Challenges of Hazardous and Harmful Materials to Release from Destroyed Iran Nuclear Reactors and to Reach Iraqi Cities

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Abstract
Iraq faces significant risks if nuclear reactors in Iran were to explode, due to its geographical proximity and shared environmental systems. These risks would largely stem from the release of radioactive materials and could have severe consequences across various sectors. In the following, a brief overview on the hazardous and harmful materials those may release and reach Iraqi cities beyond bombing of three nuclear reactors in Iran, Fordow, Natanz, and Isfahan, on Sunday 22nd June 2025.

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1. Introduction

A nuclear reactor is a complex engineering device that controls a nuclear fission chain reaction to produce thermal energy, which can then be converted into electricity. Its design relies on precise physical principles to ensure safety and efficiency. The key physical components of a nuclear reactor are:

(i) Fuel: This is the fissile material that produces energy. It's typically enriched uranium (Uranium-235) or plutonium-239. The fuel is fabricated into small pellets, which are then assembled into long rods known as fuel rods. These rods are grouped together into bundles called fuel assemblies.

(ii) Moderator: A material used to slow down the neutrons released from fission. Fast neutrons are less effective at causing new fissions. Common moderator materials include light water, heavy water, and graphite.

(iii) Control Rods those are made of materials that effectively absorb neutrons, such as cadmium or boron. They are used to control the rate of the chain reaction throughout inserting them into the reactor core reduces the number of neutrons available for fission, slowing down or stopping the reaction. Then, withdrawing them allows the number of neutrons to increase, thus accelerating the reaction and increasing power output. They are also used to shut down the reactor in emergencies.

(iv) Coolant: A substance (liquid or gas) that absorbs the heat generated by nuclear fission within the reactor core. Common coolants include pressurized water, boiling water, carbon dioxide gas (CO_2), or liquid metals like sodium. The coolant transfers this heat out of the reactor vessel to produce steam.

(v) Reactor Vessel: A large, high-pressure, thick steel container that houses the reactor core (fuel, moderator, control rods, and primary coolant). It's designed to contain radioactive materials and the high pressure generated during operation.

(vi) Steam Generator (in Pressurized Water Reactors): A heat exchanger where heat is transferred from the primary (radioactive) coolant to a secondary, non-radioactive water system. Water in the secondary system is boiled to produce high-pressure, high-temperature steam.

(vii) Containment Structure: An extremely strong, massive concrete and steel structure that encloses the reactor vessel and steam generators. It is designed to contain any release of radioactive materials in the event of an accident and to protect the reactor from external impacts.

2. Operational Mechanism of a Nuclear Reactor

The operational mechanism of a nuclear reactor involves converting nuclear energy into thermal energy, and then into electrical energy, through several steps. The first step is the nuclear fission chain reaction. Operation begins by partially withdrawing control rods from the reactor core. Free neutrons strike the nuclei of Uranium-235 (or Plutonium-239) atoms in the fuel rods, causing them to fission (split). Each fission releases thermal energy and new neutrons. These new neutrons are slowed down by the moderator to become effective "thermal neutrons," which then strike other uranium nuclei, continuing the process in a controlled, self-sustaining chain reaction.

The second step is the heat generation. The energy released from fission is converted into immense heat within the reactor core. The coolant (such as water) flows through the reactor core and absorbs this heat, causing its temperature to rise.

The third step is the steam production. In Pressurized Water Reactors (PWR) (the most common type), the hot coolant travels from the reactor vessel to the steam generator. In the steam generator, heat is transferred to a secondary (non-radioactive) water loop, causing the water in this loop to boil and produce high-pressure steam. (In Boiling Water Reactors, steam is generated directly within the reactor vessel).

The fourth step is the electricity generation. The high-pressure steam is directed to a turbine, causing it to spin at high speed. The turbine is connected to an electrical generator, which converts the mechanical energy of the turbine's rotation into electrical energy.

The fifth step is the cooling and recycling. After passing through the turbine, the steam is condensed (cooled back into water) in a condenser, typically using cold water from a river, sea, or a cooling tower. The condensed water is then recycled back to the steam generator (or reactor vessel in Boiling Water Reactors) for reuse in the steam production cycle.

Through this mechanism, a nuclear reactor can produce vast amounts of electricity from a very small quantity of fuel, all while maintaining strict control to ensure safety.

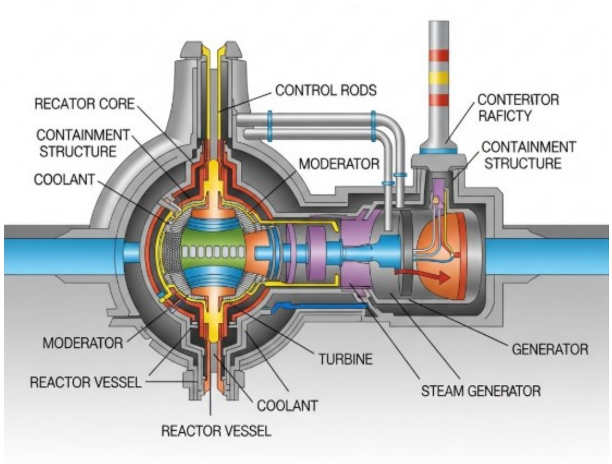

Fig. (1) Schematic explanation of a nuclear reactor and its components

3. Main Materials in Nuclear Reactor

3.1 Radioactive Fission Products

These are the primary products of nuclear fission within the reactor fuel and are highly radioactive and dangerous. They include:

Iodine-131: Highly volatile and poses a significant risk to the thyroid gland, especially in children, as it accumulates there. It has a relatively short half-life (about 8 days), so its danger is immediate but diminishes quickly.

Cesium-137: A long-lived radioactive isotope (half-life of about 30 years). It behaves chemically like potassium, making it easily absorbed into living tissues (muscles) and able to spread in the environment for long periods.

Strontium-90: A long-lived radioactive isotope (half-life of about 29 years). It behaves chemically like calcium and accumulates in bones and teeth, increasing the risk of bone cancer and leukemia.

Xenon-133 and Krypton-85: Radioactive noble gases. They can spread rapidly in the atmosphere. Although less dangerous in terms of biological accumulation, they can cause external radiation exposure.
Barium-140 and Lanthanum-140: Short-lived radioactive isotopes.
Tellurium-132 and Ruthenium-103/106: Can contribute to radioactive fallout.

3.2 Actinides

These are heavy elements present in the original reactor fuel or produced by neutron absorption. They have very long half-lives and pose a long-term risk:
Plutonium-239/240: Highly radiotoxic, especially if inhaled. It can cause lung and bone cancer. Plutonium-239 has a very long half-life (about 24,000 years), making it a persistent contaminant.
Uranium: The primary fuel for the reactor. Enriched isotopes (like Uranium-235) would be present. In addition to radiation, uranium can have chemical toxicity to the kidneys if ingested in large quantities.
Americium-241: Produced from the decay of plutonium. Extremely dangerous if inhaled or ingested.

3.3 Neutron Activation Products

These materials are formed when structural components of the reactor (like steel and concrete) absorb neutrons and become radioactive themselves. They include:
Cobalt-60: Produced by the activation of naturally occurring cobalt in steel. It emits powerful gamma rays and has a half-life of about 5.3 years.
Iron-55: Produced by the activation of iron.
Carbon-14: Can be produced by the activation of carbon in the reactor and surrounding air.
Tritium (Hydrogen-3): A radioactive isotope of hydrogen. It can be produced in the water within the reactor (heavy or light water used as a coolant).

3.4 Radioactive Dust and Particles

When a reactor is destroyed, these radioactive materials aerosolize into fine dust and particles, which can travel long distances by wind and form radioactive fallout. These particles can enter the body through inhalation or ingestion, or contaminate surfaces, vegetation, and water.

3.5 Non-Radioactive Chemical Contaminants

In addition to radioactive materials, the destruction of a reactor can release other hazardous chemical substances that were used in reactor operations or were part of its structure, such as chemicals from coolants if the reactor used chemical coolants, and materials from secondary fires, as fires can ignite within the facility due to the destruction, releasing dangerous combustion pollutants.

The quantities and types of materials released depend on several factors, including the type of reactor, the amount of fuel present, the extent of the damage, and the atmospheric conditions at the time of the incident. Managing these materials requires massive efforts to control contamination and mitigate risks in both the short and long term.

4. What is the situation in Iraq?

The geographical extent of the spread of hazardous and harmful materials resulting from the destruction of a nuclear reactor is highly variable and depends on a complex set of factors. There isn't one fixed "range," but rather a wide spectrum that can extend from a few kilometers to thousands of kilometers, with impacts potentially lasting for decades or even centuries.

The key factors influencing geographical extent of hazardous and harmful materials resulting from the destruction of a nuclear reactor are severity of destruction and scale of emissions, meteorological conditions, nature of radioactive materials, and topography and vegetation.

With respect to severity of destruction and scale of emissions, there are two main considerations. The first one is the amount of radioactive material as the greater the amount of damaged nuclear fuel and activated structural materials released, the larger the contamination and the wider its spread. The second consideration is the form of release, whether it was a massive explosion that launched a giant cloud into the upper atmosphere (like Chernobyl), or a gradual leakage of gases and liquids (like Fukushima)? Powerful explosions propel materials much farther.

With respect to the meteorological conditions, there are three considerations: wind speed and direction, precipitation (rain, snow), and atmospheric stability. Wind speed and direction is the most crucial factor in determining the path of the radiation cloud. Strong winds can carry particles hundreds or even thousands of kilometers within hours or days. Rain can "wash" radioactive particles out of the atmosphere, causing them to fall to the ground more quickly and in higher concentrations (known as "black rain"). This can create highly contaminated spots far from the source. During temperature inversions (where cold air is near the ground and warm air above it), radiation can be trapped close to the surface, increasing exposure levels in nearby areas. Conversely, unstable atmospheric conditions help disperse pollutants.

With respect to the nature of radioactive materials, there are other three considerations; particle size, half-life, and material form. Larger, heavier particles fall closer to the explosion site. Smaller, lighter particles can remain suspended in the atmosphere for longer periods and travel greater distances. Materials with short half-lives (like Iodine-131) pose an immediate danger but diminish quickly. Materials with long half-lives (like Cesium-137, Strontium-90, Plutonium) can contaminate areas for decades or centuries, requiring long-term evacuation or extensive cleanup efforts. Materials can be gases, solid particles, or liquids. Gases spread faster and farther.

With respect to the topography and vegetation, mountains, valleys, and bodies of water can influence wind patterns and, consequently, the distribution of radioactive fallout. As well, radioactive particles adhere more easily to plants and trees, leading to the contamination of forests and agricultural areas.

4.1 Estimated Geographical Range

Based on past incidents and simulation studies, the geographical range can generally be categorized as follows:

Immediate Vicinity of the Reactor (Several Kilometers): This area experiences the most severe radiation levels and destruction and could become uninhabitable for very long periods (decades to centuries).

Near Zone (Tens to Hundreds of Kilometers): Affected by heavy radioactive fallout that can render these areas uninhabitable or unsuitable for agriculture for years to decades. This would require large-scale evacuation and extensive cleanup.

Intermediate Zone (Hundreds to Thousands of Kilometers): Lighter radioactive particles can reach these areas, leading to contamination that can affect agriculture, groundwater, and food industries. This might not require immediate evacuation but necessitates strict monitoring of food and water.

Global Reach (Thousands of Kilometers): Very fine radioactive particles can spread into the upper atmosphere and disperse globally, albeit at very low concentrations that typically do not pose a significant direct health risk. For example, Chernobyl radiation reached parts of Europe and North America at detectable concentrations.

In the event of an attack on Iranian nuclear reactors, given Iran's geographical location and proximity to Iraq, Iraq could be significantly affected. If winds blow from Iran towards Iraq (which is common), the geographical extent of radioactive contamination could stretch for hundreds of kilometers into Iraqi territory, particularly affecting the southern and western regions of Iraq, and possibly deeper areas depending on meteorological conditions. This could lead to widespread contamination of water, soil, and food, with catastrophic long-term health, environmental, and economic consequences.

It is crucial to emphasize that a reactor destruction scenario differs from an accidental leak (like Fukushima), as the volume of released materials would be much larger and more dangerous.

Fig. (2) Map of the Middle East

The Bushehr plant is the facility that poses the greatest and most immediate risk to Iraq in the event of an attack or accident, due to its massive quantities of radioactive materials produced during reactor operation. As for enrichment facilities like Natanz and Fordow, their primary risk comes from the release of enriched uranium and toxic chemicals, with potential radiological contamination but far less severe and widespread than from a power reactor. The Arak reactor, in its current non-operational and fuel-free state, does not pose an immediate radiological threat.

Fig. (3) Geographical explanation of the locations of Iran three bombed nuclear reactors

Iraq must remain vigilant and continue to enhance its capabilities for radiological monitoring and emergency response, in cooperation with international organizations and regional countries. Given the regional tensions, Iranian nuclear facilities pose a significant concern for Iraq due to their geographical proximity and the potential for a radioactive release if they are targeted or experience major accidents. The most important Iranian nuclear reactors and facilities that could pose a real threat to Iraq are:

(i) Bushehr Nuclear Power Plant

It is located on the Persian Gulf coast, approximately 450 kilometers (280 miles) directly (as the crow flies) to the city of Basra (the closest major Iraqi point), approximately 500 kilometers (310 miles) directly to the city of Amarah (Maysan Governorate), and approximately 700 kilometers (435 miles) directly to Baghdad, the capital.

Bushehr is Iran's only operational nuclear reactor. This means it contains thousands of kilograms of radioactive nuclear materials (such as uranium, cesium, strontium, and plutonium produced during operation). Should it be subjected to a direct attack or a major malfunction leading to a core meltdown, the release of very large quantities of radioactivity into the environment would have widespread catastrophic consequences.

Given its proximity to the Persian Gulf and the prevailing winds that often blow towards Iraq, any radioactive leak from Bushehr would directly threaten southern Iraq, including its water supplies, agriculture, and population. This is the site about which GCC countries, including Iraq, have expressed strong concerns to the International Atomic Energy Agency (IAEA).

(ii) Natanz Fuel Enrichment Plant

It is located in central Iran, approximately 400 kilometers (250 miles) directly to the nearest point on the Iraqi border, and approximately 650 kilometers (405 miles) directly to Baghdad.

This is Iran's largest uranium enrichment facility. Although enrichment typically takes place underground and the radiation levels from the uranium itself (which hasn't been used in a reactor yet) are far less dangerous than fissionable materials in an operational reactor, the destruction of the facility could lead to release of uranium hexafluoride (UF_6): A toxic chemical compound derived from uranium. Its reaction with water vapor in the air produces harmful chemical substances. The destruction of the facility could also lead to limited radiological contamination. While some radiological contamination might occur at the site itself or its immediate vicinity due to the presence of uranium isotopes, the risk of widespread radioactive release would be significantly lower than from the destruction of a power reactor. However, the risk could be higher if areas storing higher-enriched uranium are targeted.

Although the direct radiological risk is less than from the Bushehr reactor, potential airborne radioactive particles could reach governorates like Diyala, Wasit, and possibly Baghdad, especially with favorable winds.

(iii) Fordow Fuel Enrichment Plant

It is located near the city of Qom, approximately 550 kilometers (340 miles) directly to Baghdad, and approximately 775 kilometers (480 miles) to Sulaymaniyah in the Iraqi Kurdistan Region.

Fordow is a heavily fortified facility built inside a mountain, used for enriching uranium to high levels (sometimes exceeding 60%). Like Natanz, its primary danger doesn't come from a "radioactive reactor core" but from the materials used in enrichment. Due to its deep fortification, it might be difficult to completely destroy, but any significant damage could lead to the release of enriched uranium and toxic chemicals that could spread with winds and reach Iraq, with effects similar to Natanz but possibly at lower concentrations due to the greater distance.

(iv) Arak Heavy Water Reactor (Khondab)

It is located near the city of Arak (now known as Khondab), about 250 kilometers southwest of Tehran, approximately 250 kilometers (155 miles) directly from the Iraqi border (near the border with Diyala or Wasit governorates). The city of Arak itself is about 1281 kilometers (796 miles) by road from Baghdad, but the aerial distance of the reactor from the nearest border point is much closer.

This is a research heavy water reactor. It was originally designed to be capable of producing plutonium, a material that can be used for nuclear weapons. Under the 2015 nuclear deal, its design was modified to reduce proliferation risks, with its core removed and filled with concrete. According to recent reports (June 2025), this reactor has been targeted by strikes aimed at the "component designated for plutonium production" to prevent its restoration. The IAEA has stated that the reactor was not operational and contained no nuclear material at the time of the strikes, meaning “there were no direct radiological effects” from these recent attacks.

The potential risk if this reactor has been operational and contained nuclear fuel, its destruction would pose a significant risk due to the potential release of plutonium and other fission products, which could contaminate the region for thousands of years.

4.2 Key Measures to Avoid Damage and Risks from Materials Reaching Iraq Due to the Destruction of Iranian Nuclear Reactors

The potential destruction of Iranian nuclear reactors poses significant and complex challenges for Iraq, given its close proximity. Protecting the population and environment from the resulting harmful materials requires a multi-faceted approach, focusing on preparedness, immediate response, and long-term mitigation.

4.2.1 Pre-Emptive Measures and Preparedness

Establish a Robust Early Warning System: Iraq needs a highly sensitive and rapidly deployable **radiation monitoring network** across its eastern borders, particularly in southern and central regions. This system should be capable of detecting even minute levels of radiation in air, water, and soil, providing real-time data to decision-makers.

Develop Comprehensive Emergency Response Plans: These plans must clearly outline roles and responsibilities for all government agencies (civil defense, health, environment, military) at national and provincial levels. They should include:

- Evacuation routes and safe zones: Pre-identified and regularly rehearsed for potentially affected populations.
- Shelter-in-place protocols: Clear instructions on how citizens should seal their homes, turn off ventilation, and stay indoors.
- Public communication strategies: Pre-prepared messages and clear channels (radio, TV, social media, SMS alerts) to disseminate timely and accurate information.

Educate the Public: Conduct widespread public awareness campaigns on nuclear emergency preparedness. This includes:

- Understanding basic radiation protection: Explaining concepts like "shelter-in-place," "staying informed," and "following official instructions."
- Importance of potassium iodide (KI): Educating about its specific use (thyroid protection from radioactive iodine only), correct dosage, and that it should “only be taken upon official directive”.

- Emergency kit essentials: Encouraging families to prepare kits with bottled water, non-perishable food, first-aid supplies, and battery-powered radios.

Stockpile Essential Supplies: Ensure a strategic reserve of:

- Potassium Iodide (KI) tablets: Sufficient quantities to cover populations in high-risk areas.
- Personal Protective Equipment (PPE): Respirators, protective clothing for first responders and essential personnel.
- Decontamination equipment: Sprayers, specialized cleaning agents, and waste disposal materials.

Enhance Medical Capabilities: Train medical personnel in treating radiation sickness, managing contaminated patients, and providing psychological support. Ensure hospitals have necessary equipment and protocols.

International Cooperation: Engage actively with international bodies like the **IAEA (International Atomic Energy Agency)** and neighboring countries to share information, coordinate response efforts, and conduct joint drills. This includes advocating for stricter international oversight of all nuclear facilities in the region.

4.1.2 Immediate Response During an Incident

Activate Early Warning System: Upon confirmed or suspected incident, immediately activate all radiation monitoring stations.

Issue Immediate Public Alerts: Disseminate clear instructions via all available channels:

- "Shelter-in-Place" order: For **populations** in predicted fallout zones.
- Evacuation orders: If radiation **levels** are too high for sheltering.

Direct KI Distribution and Administration: If radioactive iodine is detected, issue precise instructions for taking **Potassium Iodide**, emphasizing correct dosage and who should take it.

Restrict Movement and Access: Establish checkpoints and control zones to limit movement into and out of affected areas.

Secure Food and Water Supplies: Immediately test and, if necessary, halt the consumption of local food (crops, livestock, fish) and water supplies in affected areas. Distribute pre-stocked safe supplies.

Protect First Responders: Ensure all emergency personnel are properly trained, equipped with adequate PPE, and operate under strict radiation safety protocols.

4.1.3 Long-Term Mitigation and Recovery

Continuous Monitoring: Maintain long-term environmental monitoring of air, water, soil, and food products for radioactive contamination.

Decontamination Efforts: Implement strategic decontamination plans for affected areas, which could involve:

- Washing down surfaces.
- Removing contaminated topsoil.
- Managing contaminated waste.
- These efforts would be massive, costly, and potentially span decades.

Agricultural and Livestock Management: Develop strategies for managing contaminated farmlands and livestock, potentially including crop destruction, animal culling, or long-term restrictions on agricultural use.

Public Health Surveillance: Establish long-term health registries to monitor the health of exposed populations, tracking potential increases in cancer rates and other radiation-related illnesses. Provide ongoing medical care and support.

Economic Rehabilitation: Develop plans for the long-term economic recovery of affected regions, which will suffer immense losses in agriculture, tourism, and overall economic activity. This will likely require significant international aid.

Implementing these measures requires substantial financial investment, political will, and robust technical capabilities. It's a national priority to minimize the catastrophic potential impact of such an event.