Nuclear Iran

A Glossary of Terms

Simon Henderson and Olli Heinonen

Policy Focus 121 | May 2013 Update

THE WASHINGTON INSTITUTE for Near East Policy

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Map: Nuclear installations in Iran.

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Cover photo: Iran's president Mahmoud Ahmadinejad visits the Natanz nuclear enrichment facility. (Ho New/ Reuters)

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About the Authors

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About this Publication

INTERNATIONAL DIPLOMACY concerning Iran's nuclear program continues to center on the country's compliance with agreements designed to ensure that peaceful nuclear work is not used as a cover for the development of nuclear weapons. The challenge of discovering what may be going on in Iran is difficult not only because of Tehran's obstructionism, but also because the same technologies, particularly uranium enrichment and spent fuel reprocessing, can be used for both civilian and military purposes.

This Policy Focus is intended to improve comprehension of the main issues and important technical details surrounding the program. The core of the document explains the terms used by the International Atomic Energy Agency (IAEA), the world's watchdog in ensuring that nuclear science and technology are used for peaceful purposes only. Separate sections offer explanations of basic nuclear terms and the use of centrifuges for uranium enrichment. In addition, because some of Iran's technology came from nuclear-armed Pakistan, another section is devoted to explaining the main portions of Islamabad's program. And since media coverage often compares suspected Iranian nuclear work to initial U.S. development of atomic weapons in the mid-1940s, the basic terms often used in describing this history are defined separately.

In addition, this online report includes an interactive index that provides quick, hyperlinked access to all of the terms discussed in the various glossaries. By clicking on a term in this index, users can instantly jump to the page on which it appears, then click another link to return to the index.

Introduction

IRAN'S NUCLEAR PROGRAM dates from the late 1950s. By the 1960s, the United States had supplied the Iranians with a small research reactor. Later, the shah had ambitious plans to construct twenty-three nuclear power reactors, and initial orders were placed with West German and French companies. Iran also started to invest in nuclear fuel-cycle services, though was unable, due to U.S. pressure, to obtain reprocessing or uranium enrichment plants. It did, however, invest in the Eurodif enrichment plant in France and the Roessing uranium mine in Namibia, shareholdings it maintains today. When Iran signed the Nuclear Non-Proliferation Treaty in 1968 and ratified it in 1970, all its nuclear activities became subject to inspection by the International Atomic Energy Agency (IAEA).

The 1979 Islamic Revolution halted all nuclear construction activities in Iran. In the mid-1980s, during its war with Iraq, Tehran decided to revive its nuclear program, but sanctions and, in particular, U.S. pressure blocked Iranian attempts to acquire power plants, along with fuel-cycle technology from Germany, Brazil, Argentina, and Spain. Still, Iran registered a success when it built small nuclear research reactors in Isfahan with Chinese help. Also, work resumed on a power plant in Bushehr, with the help of Russian companies, that has been operating since 2011.

In seeking nuclear enrichment and reprocessing technologies, Iran first experienced success in the late 1980s by acquiring centrifuges from Pakistan, through a nuclear black market, and laser laboratory equipment from China for uranium enrichment. A decade later, the Iranians obtained more-advanced laser equipment from Russia.

Given its modest domestic uranium deposits, Iran obtained uranium ore concentrate from South Africa in 1984. In April 2013, Iran began the operation of a uranium mine in Saghand and a milling facility at Ardakan; it also has a small twenty-ton-per-year uranium mining/milling installation at Gchine.

Iranian cooperation with the Chinese included a contract in the early 1990s to build a uranium conversion facility in Isfahan, which the Iranians ultimately constructed themselves. Since 2004, it has produced 550 tons of uranium hexafluoride (UF_6), fueled by material from South Africa as feedstock. The present levels of UF_6 are sufficient to power Iran's planned enrichment facilities for several years.

Iran's first work on uranium enrichment dates from the 1970s, when it acquired laser laboratory equipment from the United States and Germany. In the next two decades, Iran conducted laboratory-scale uranium enrichment and other work, including acquisition of nuclear materials that went unreported to the IAEA. When these acquisitions were revealed in 2003, Iran—seeking to avoid referral to the UN Security Council—agreed with France, Germany, and Britain (EU-3) to suspend its enrichment- and reprocessing-related activities until necessary confidence on the peaceful nature of the program had been established. But implementation of the deal stumbled from the outset, and eventually, in June 2006, the United States, Russia, and China joined the discussion as part of the P5+1 (five permanent members of the UN Security Council, plus Germany).

Despite several UN Security Council resolutions, Iran has not suspended its uranium enrichment and heavy-water-related activities. In January 2006 Iran resumed uranium enrichment in Natanz, which had been paused. And in September 2009, Iran disclosed that it had started the secret construction of an additional underground enrichment plant in Fordow, near the city of Qom. By February 2013, Iran had installed some 15,800 IR-1centrifuges in its enrichment plants in Natanz and Fordow. Although the centrifuges have been operating well below the original design capacity, they have produced more than eight tons of 3.5 percent enriched UF_6. In 2013, Iran informed the IAEA that it plans to install about 3,000 IR-2m centrifuges at Natanz. Iran had earlier announced plans to build ten additional enrichment facilities.

Since February 2010, Iran has been producing 20 percent enriched UF_6 at the Pilot Fuel Enrichment

Plant at Natanz, ostensibly for the Tehran Research Reactor (TRR), which was originally supplied by the United States and has been operating since 1967. Iran had asked, in June 2009, for IAEA assistance in obtaining fuel for the reactor, but the regime could not agree to terms with the Vienna Group of negotiators in October 2009. Instead, the Iranians also began producing 20 percent enriched material at the Fordow facility and, by February 2013, had produced more than 250 kg of UF_6 there and at Natanz, of which some portion has been moved to Isfahan for the manufacture of fuel for the TRR.

Iran has relied on the IR-1 type centrifuge but has tested several more-advanced types, although reported progress so far has been slow. It is not clear whether this owes to design and manufacturing problems, lack of access to raw materials such as carbon fiber and maraging steel because of sanctions, or limited IAEA access to Iranian sites. It appears that Iran has now overcome these problems and is proceeding with the installation of IR-2m centrifuges, which are three to five times more powerful than the IR-1s.

In Arak, Iran is constructing a heavy-water reactor, the IR-40, designed to produce plutonium that could ultimately be used for a nuclear weapon; it was due to become operational in 2013. The construction of the reactor, however, as well as the completion of a fuel fabrication plant in Isfahan, and the production of heavy water, are proceeding at slower rates than originally announced. The slow progress can again be attributed to design problems and sanctions. In light of these, the IR-40 reactor is not expected to be operational before the end of 2014.

Iran has stated that it plans to build additional nuclear power plants with foreign help and is designing its own light-water reactor at Darkhovin, as well as research reactors elsewhere. Some Iranian politicians and officials occasionally mention plans to develop nuclear-powered ships. Although the Iranian uranium enrichment program still relies on special equipment and materials acquired from the black market, it has in past years invested heavily in indigenous production capabilities and is making steady progress,

The IAEA reports in June 2008 and November 2011 raised questions about Iran's activities apparently related to nuclear weapons research and development. These activities included work beginning in the early 1990s at the Physics Research Center at Lavisan, the so-called AMAD Plan (believed to be the project name for the overall nuclear weapons program), and from 2004 onward, initiatives at various institutes eventually under the umbrella of the Organisation of Defensive Innovation and Research. During the past year, the IAEA and Iran have discussed a "structured" approach to address questions related to the military dimension of Iran's nuclear program and prepare for IAEA efforts to verify correctness and completeness of Iran's declarations on nuclear material and activities. The parties have not yet been able to agree on the approach.

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Jumbo: Ch. 3, U.S. Development
Kahuta: Ch. 5, Pakistan
Kalaye Electric Company: Ch. 1, IAEA
Karaj Agricultural and Medical Center: Ch. 1, IAEA
Khan Research Laboratories: Ch. 5, Pakistan
Khondab: Ch. 1, IAEA
Khushab: Ch. 5, Pakistan
Kiloton: Ch. 4, Nuclear Physics
Kimia Maadan Company: Ch. 1, IAEA
Kolahdouz: Ch. 1, IAEA

Laboratory-scale experiment: *see* Bench-scale experiment
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Laser Spectroscopy Laboratory: Ch. 1, IAEA
Lavisan-Shian: Ch. 1, IAEA:
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Light-Water Subcritical Reactor: Ch. 1, IAEA
Limited frequency, unannounced access: Ch. 1, IAEA
Little Boy: Ch. 3, U.S. Development
Location outside facilities: Ch. 1, IAEA
Low-enriched uranium: Ch. 1, IAEA

Malek Ashtar University of Technology: Ch. 1, IAEA
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Megaton: Ch. 4, Nuclear Physics
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Milling of uranium: Ch. 1, IAEA
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Open-source information: Ch. 1, IAEA
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Orchid Scientific Research Center: Ch. 1, IAEA
Ore Processing Center: Ch. 1, IAEA
Organization of Defensive Innovation and Research: Ch. 1, IAEA

P1 centrifuge: Ch. 5, Pakistan
P2 centrifuge: Ch. 5, Pakistan
P5+1: Ch. 1, IAEA
Parchin: Ch. 1, IAEA
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Pars Trash: Ch. 1, IAEA
Passivation: Ch. 1, IAEA
Passive Defense Organization: Ch. 1, IAEA
Permissive action links: Ch. 4, Nuclear Physics
Physical inventory taking: Ch. 1, IAEA
Physics Research Center: Ch. 1, IAEA
Pilot Fuel Enrichment Plant: Ch. 1, IAEA
Pishgam: Ch. 1, IAEA
Pit: Ch. 4, Nuclear Physics
Plasma physics: Ch. 1, IAEA
Plutonium: Ch. 1, IAEA

1 | IAEA Reports on Iran

MOST OF THE NAMES and terms below are taken from International Atomic Energy Agency reports, of which there are various types. IAEA public documents are designated INFCIRC (meaning "information circular") plus an assigned number, while reports for the regular Board of Governors meetings are designated GOV. Although they are intended to be confidential, GOV documents—particularly on Iran, Syria, and North Korea—are often obtained by the media or think tanks simultaneous with their release to member states.

Many of Iran's nuclear sites, along with organizations and individuals involved in the nuclear program are designated under various United Nations resolutions. A consolidated list of such sites can be found at http://www.un.org/sc/committees/1737/pdf/1737ConsolidatedList.pdf.

Accountancy Reports: Under a comprehensive Safeguards Agreement between the IAEA and any non-nuclear-weapon state that is party to the Non-Proliferation Treaty, the state must provide the agency with reports on the status of nuclear material subject to safeguards as specified in the Subsidiary Arrangements. There are three types of accountancy reports:

- **Inventory change report:** a report to the IAEA showing changes in the nuclear material inventory.
- **Material balance report:** a report to the IAEA showing the material balance based on a physical inventory of nuclear material actually present in the material balance area.
- **Physical inventory listing:** a report to the IAEA in connection with a physical inventory-taking by the operator listing all nuclear material batches at the facility.

Ad hoc inspection: The IAEA conducts routine inspections at facilities to verify nuclear material subject to safeguards. Before a Subsidiary Arrangement including a facility-specific attachment has entered into force, the IAEA may conduct ad hoc inspections.

Additional protocol: Approved by the IAEA Board of Governors in 1997, the Model Additional Protocol (known in IAEA parlance as INFCIRC/540) provides additional measures for improving the effectiveness and efficiency of agency safeguards. Specifically, it gives the IAEA an expanded declaration containing information on all aspects of a country's nuclear fuel cycle activities and granting broader access to all relevant sites, including those where nuclear material is not customarily used. Iran signed the Additional Protocol in December 2003 and implemented it provisionally until February 2006, when the IAEA Board of Governors reported Tehran's noncompliance to the UN Security Council. Since then, Iran has not heeded IAEA or Security Council requests to implement and ratify the protocol.

Aluminum alloy: High-strength aluminum alloys are used for centrifuge rotors and casings. IR-1 centrifuge rotor cylinders are made of 7000-series aluminum alloy, a very strong metal produced via mixture with zinc. Outer casings of IR-1, IR-2m, and other centrifuges are made of 6000-series aluminum alloy.

AMAD Plan: In the late 1990s or early 2000s, Iran consolidated all military-related nuclear activities (fig. 1) conducted by its Physics Research Center under the AMAD Plan (full Farsi name: Sazemaneh Tarhe Amade Vije, or Organization for Planning and Special Supplies).

Amir Kabir University of Technology: Established in 1956 as Tehran Polytechnic, the university has close ties with the Atomic Energy Organization of Iran.

Ammonium diuranate (ADU): One of the intermediate chemical forms of uranium resulting from yellowcake production. Its chemical formula is $(NH_4)_2U_2O_7$.

Ammonium uranyl carbonate (AUC): An intermediate product in the process of converting uranium

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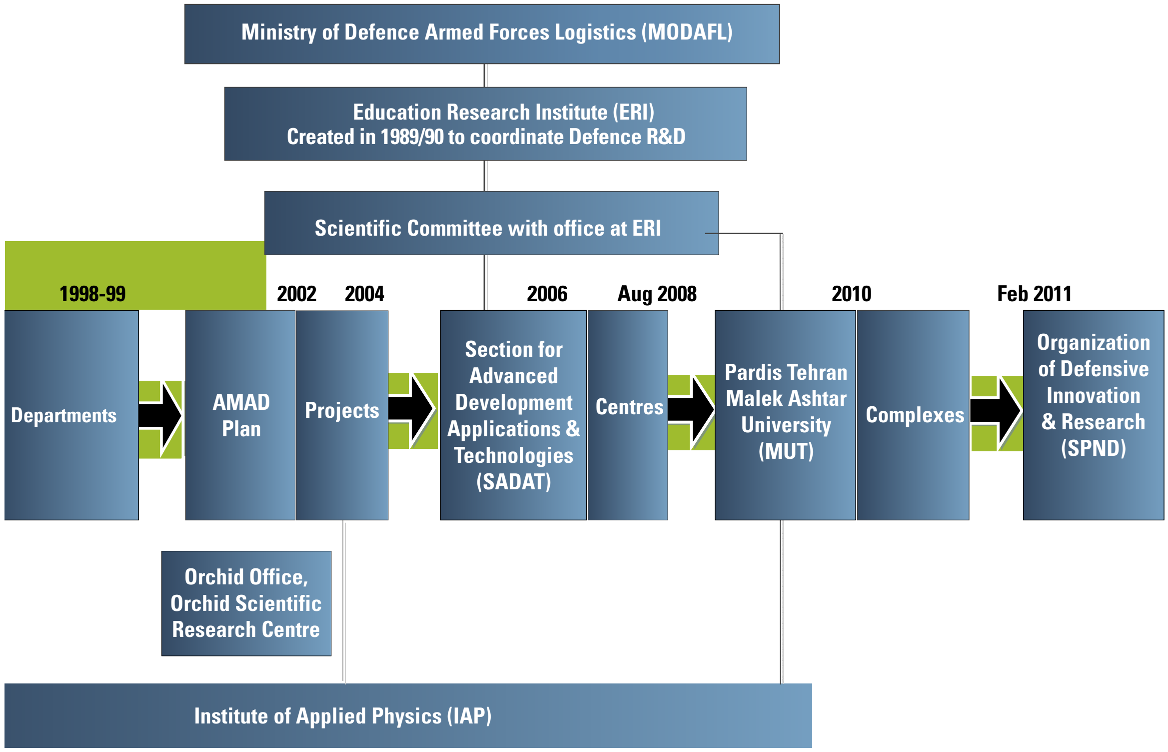

FIG. 1: Military organization and timeline of Iran's nuclear program (source: IAEA)

hexafluoride (UF_6) to uranium dioxide (UO_2). Its chemical formula is $UO_2CO_3 \cdot 2(NH_4)_2CO_3$.

Anarak: A site in central Iran, near Yazd, where nuclear waste has been stored (*see map*).

Applied Physics Institute: According to Iran, the institute was located at the Lavisan-Shian site (*see* Physics Research Center.)

Arak: The Arak area has several industrial complexes with ties to the nuclear program, in particular the reactor under construction at Khondab (*see* Khondab). In the late 1990s, one of these complexes may have manufactured a high-explosive test chamber transferred to Parchin, which the IAEA has asked to visit. The Arak area is also thought to hold factories capable of producing aluminum for IR-1m rotors and centrifuge housings.

Ardakan Yellowcake Production: A uranium mill under construction that will process the ore from the Saghand mine (*see map*). Its design capacity is fifty tons of uranium per year, which equals the planned production of Saghand. The AEOI expects the mill be operational in 2012.

Atomic Energy Council: Also known as the Supreme Atomic Energy Council or the Nuclear Energy Council, this body directs Iran's general nuclear policy. It was created by the same 1973 law that established the Atomic Energy Organization of Iran. The 15-member council is composed of the president, cabinet ministers, the head of the AEOI, and four nuclear scientists.

Atomic Energy Organization of Iran (AEOI): Established in 1973, the AEOI has operational and regulatory control over Iran's civilian nuclear program and is responsible for nuclear research and development. It also controls several companies related to the nuclear program. The president of the AEOI is one of Iran's ten vice-presidents.

Autoclave: An industrial oven in which uranium feed cylinders are heated, converting solid uranium hexafluoride into gas so that it can be fed into centrifuges.

Balancing machine: As a centrifuge rotor spins at high speeds, it experiences vibrations that, if not contained, can cause failure of the bearing and suspension system and, eventually, a crash. Therefore, the rotors are balanced horizontally and vertically to minimize vibrations. Considered dual-use items, balancing machines are subject to export controls.

Bandar Abbas: Port city in southeast Iran near the Gchine uranium mine (*see map*).

Bench-scale experiment: Testing of materials, methods, or chemical processes on a small scale, such as on a laboratory worktable or room.

Biological Study Center: Iran stated in 2004 that the activities of the Physics Research Center at Lavisan-Shian were reorganized in 1998. The Biological Study Center, which was involved in biological research and development and "radioprotection" activities, stayed in Lavisan.

Bismuth: When natural bismuth (bismuth-209 isotope) is bombarded with neutrons, bismuth-210 is created, which then decays to Po-210 via beta decay. Po-210 can be used for neutron initiators (*see* Neutron generator).

Board resolutions: Since 2003, the IAEA Board of Governors has adopted ten resolutions in connection with the implementation of safeguards in Iran. By virtue of its Relationship Agreement with the UN, the agency is required to cooperate with the Security Council in the exercise of the latter's responsibility for maintenance or restoration of international peace and security. All UN member states agree to accept and carry out the Security Council's decisions and, in this respect, to take actions consistent with their obligations under the UN Charter. Since 2006, the council has adopted six resolutions on the implementation of safeguards in Iran. In Resolution 1929 (2010), the council took the following steps: affirmed that Iran must, without further delay, implement the measures required by the IAEA Board in 2006 and 2009; reaffirmed Iran's obligation to cooperate fully with the IAEA on all outstanding issues, particularly those that give rise to concerns about the nuclear program's possible military dimensions; decided that Iran must, without delay, comply fully and without qualification with its IAEA Safeguards Agreement, including through application of the modified Code 3.1 of the Subsidiary Arrangements; and called on Iran to ratify and act strictly in accordance with the provisions of the Additional Protocol.

Bonab: A research center of the AEOI in northwestern Iran (*see map*) that specializes in nuclear applications in agriculture and manufactures laser equipment. In May 2013 the head of the AEOI announced that the site is being considered for a new research reactor.

Break-out scenarios: Circumstances in which an aspiring nuclear weapons state can break its commitments to the NPT, achieving nuclear weapons capability as fait accompli before it can be stopped by diplomati pressure or military action.

Bushehr: Iran's only civilian nuclear power reactor (*see map*). German companies began construction of the plant in 1975 but stopped in 1979 after the Islamic Revolution. In 1995, Iran signed a new contract for finishing the plant with the Russian Ministry for Atomic Energy. The 915-megawatt light-water reactor, known by its Russian acronym VVER-1000, began producing electricity for the Iranian national grid in September 2011.

Casting of uranium: Since the 1940s, vacuum induction furnaces have been used to cast uranium metal into appropriate shapes. These could be either fuel rod cores for reactors or nuclear weapon components. A more modern technique is using microwave technology to produce weapon components.

Center for Research and Development of Explosion and Shock Technology: Also known as "METFAZ," this Iranian agency conducts studies with conventional military applications (e.g., developing armor-piercing projectiles) that can also be used to develop computer codes for model nuclear explosives.

Central Islamic Revolution Committee: In the 1980s, this Iranian organization coordinated wartime strategic material acquisition and manufacturing. It also appears to have links to some nuclear-related procurement.

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Centrifuge: Machine used to enrich uranium by separating the isotope U-235 (which occurs naturally as only 0.7 percent of the metal) from U-238 (most of the other 99.3 percent). Separation is achieved by spinning at high speed. For a fuller explanation of the terms associated with this process, *see* chap. 2, "Centrifuge Enrichment."

Chamaran Building: Between 1995 and 1998, Iran carried out experiments on the purification of plutonium solution in this building, located at the Tehran Nuclear Research Center.

Chemical trap: Traps containing sodium fluoride (NaF) are used to capture uranium hexafluoride gaseous effluents at enrichment plants.

Code 3.1: Part of the Subsidiary Arrangements, this code specifies when an IAEA member state must report a new facility to the agency. According to the original version of Iran's Code 3.1, agreed in 1976, Tehran is obligated to report a new facility no later than 180 days before the introduction of nuclear material. In 2003, Iran agreed to implement the modified Code 3.1, which requires the submission of design information to the IAEA as soon as a new facility is planned. Iran unilaterally revoked its implementation of the modified code in February 2006. Iran is the only country with a substantial nuclear program that does not adhere to the modified code.

Cold trap: Also known as a desublimer, this device converts uranium hexafluoride gas to a solid so that it can be removed from centrifuge cascades.

Comprehensive Separation Laboratory (CSL): In 1991, Iran concluded a contract with a Chinese company for the establishment of this facility, where uranium enrichment was carried out on a milligram scale. The contract also supplied Iran with 50 kg of natural uranium metal in 1993, which Iran failed to report to the IAEA. The CSL was located at the Tehran Nuclear Research Center until October 2002, when the laboratory and nuclear material were moved to Lashkar Abad. The laboratory was eventually dismantled.

Concealment methods: An expression describing actions taken to reduce the probability of the IAEA detecting a country's nuclear activities or material. Such actions may include tampering with IAEA containment and surveillance measures through improper nuclear material accounting activities; falsifying records, reports, and other documents; presenting false facility operational data; and impeding IAEA inspectors so as to reduce their chances of detecting the diversion or presence of nuclear material.

Containment and surveillance measures: C/S measures such as cameras and seals are used by the IAEA to maintain continuity of knowledge on movement of nuclear material, equipment, or samples. These methods are often used to cover periods when inspectors are not present at the facility.

Copper vapor laser (CVL): Used in some machining and laser cutting applications, this technology can also be used in in atomic vapor isotope separation systems (AVLIS) a potential way of enriching uranium. Iran manufactured the CVLs used at the pilot enrichment plant at Lashkar Abad.

Correctness and completeness: Each IAEA member state's comprehensive Safeguards Agreement stipulates that all nuclear material in the state's territory must be declared "correctly and completely" to the agency.

Corrosion-resistant valves, steels, and filters: Uranium hexafluoride gas is very corrosive, so enrichment components are manufactured from materials resistant to such damage. These materials include copper, stainless steel, aluminum, aluminum alloys, nickel (or alloys containing 60 percent or more nickel), and UF_6-resistant fully fluorinated hydrocarbon polymers.

Cylinders: Uranium hexafluoride gas is stored in cylinders made of nickel (including the series of alloys called monel) or stainless steel. The cylinders are standardized and use type classifications such as 5A, 12A, 30B, or 48A, where the number refers to cylinder diameter. Typically, 5A cylinders are used for high-enriched uranium, while the others are for low-enriched, natural, or depleted uranium.

Darkhovin: Site of a future Iranian-designed

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light-water power reactor, which Tehran has described as having an output of 360 megawatts (*see map*). The construction was scheduled to begin in 2011, with commissioning to take place in 2015. The Darkhovin site is located in Ahvaz in southwestern Iran, where a French power reactor had been slated until construction was cancelled after the 1979 Islamic Revolution.

Defense Industries Organization: The DIO (in Persian: *Sasadjah Sazemane Sanaye Defa*) is a conglomerate of Iranian companies that provides the military with its own manufacturing capacity and boost its technical abilities. The DIO is controlled by Iran's Ministry of Defense Armed Forces Logistics (MODAFL), and in recent years, the DIO has also sought export markets. Some of its workshops have been involved in production of centrifuge components.

Depleted uranium: Uranium containing less than 0.7 percent of the isotope U-235 (i.e., less than the amount that occurs in natural uranium). Found in spent fuel rods from natural uranium reactors and in tails from uranium enrichment processes.

Design information: Under an IAEA Safeguards Agreement, a member state must provide the agency with design information for each nuclear site: specifically, a facility description (including layout and containment features) as well as information on the form, quantity, location, and flow of nuclear material being used.Kala The agency uses this information to design appropriate safeguards arrangements (*see* Code 3.1).

Design information verification (DIV): Process carried out by the IAEA at a given facility to verify the correctness and completeness of the design information provided by the member state. An initial DIV is performed on a newly built facility to confirm that it is as originally declared. This is followed by periodic DIVs to confirm the continued validity of the design information and the safeguards approach.

Designation of inspectors: All Safeguards Agreements stipulate that the IAEA must secure a member state's consent to the assignment of individual agency inspectors. The state can object to the designation at any time without giving specific reasons.

Destructive analysis: The means of determining the nuclear content and isotopic composition of a sample .

Destructive testing: Conducting prolonged tests under the most severe operating conditions until a given component or piece of equipment fails (e.g., a centrifuge crashes), with the purpose of determining service life and detecting design weaknesses.

Deuterium: An isotope of hydrogen that occurs naturally in water, but only in trace amounts of about 150 ppm. The highly concentrated solution known as heavy water, which contains more than 99 percent deuterium oxide (D_2O), is used as a moderator in some nuclear reactors .

Diffusion: The gaseous diffusion method of enriching uranium is based on the principle that two isotopes with the same energy (i.e., in thermal equilibrium) will have slightly different average velocities. The lighter atoms (or the molecules containing them) will travel more quickly and be more likely to diffuse through a membrane. This method is expensive due to the work needed to push uranium hexafluoride gas through a membrane, as well as the many stages required to obtain high purity given the small amount of separation achieved at each stage. In 1945, the technique required around 4,000 stages, forcing the United States to use huge amounts of electricity and house the cascades in the largest building ever constructed. By contrast, today's cascades require about 64 stages and can be assembled in a building the size of a supermarket, with comparatively minimal electricity requirements.

Diversion of nuclear material: A case of noncompliance that involves one or more of the following: undeclared removal of declared nuclear material from a safeguarded facility; use of a safeguarded facility for the introduction, production, or processing of undeclared nuclear material (e.g., undeclared production of high-enriched uranium in an enrichment plant); or undeclared production of plutonium in a reactor through irradiation and subsequent removal of undeclared uranium targets.

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Dump material: When the centrifuges are started up, or during the malfunctioning of centrifuges or cascades, the operator dumps uranium hexafluoride into cylinders. Such material is generally considered to be waste.

Education Research Institute: Established to coordinate defense research and development for Iran's Ministry of Defense and Armed Forces Logistics.

Effective kilogram (ekg): A special unit of nuclear material used in the context of safeguards, as defined by IAEA document INFCIRC/153 (Corr.). For plutonium, it corresponds directly to sample's weight in kilograms. For uranium with an enrichment of 1% or higher, the ekg is the sample's weight in kilograms multiplied by the square of its enrichment level; for uranium with an enrichment below 1% and above 0.5%, the weight in kilograms multiplied by 0.0001; and for depleted uranium with an enrichment of 0.5% or lower (or for thorium), the weight in kilograms multiplied by 0.00005.

Electric drive: The stationary part of the motor that drives a centrifuge.

Electromagnetic isotope separation (EMIS): A device called a calutron enables the separation and collection of U-235 and 238 isotopes as they pass through a magnetic field. Iran has a single calutron in Karaj, which is being used to produce stable isotopes for medical and industrial purposes. Calutrons were also used in the initial U.S. nuclear weapons program and by Saddam Hussein's program in 1980s Iraq.

Enrichment: The process of increasing the amount of the fissile isotope U-235 within nuclear material. Natural uranium contains only 0.7 percent U-235, but enrichment can increase it to 3–5 percent (the level used for nuclear reactors) or over 90 percent (used in atomic bombs). Enriching is a progressively easier process—for example, if the aim is to produce 90 percent enriched uranium, reaching the 3.5 percent level requires some 75 percent of the work. And by the time 20 percent enrichment is reached—a level Iran currently achieves—90 percent of the work has been completed (fig. 2).

Environmental sampling: The IAEA collects samples, often with cotton swipes, from certain areas to analyze them for traces of materials that can reveal information about a member state's nuclear activities. The sample could include traces of nuclear material from various surfaces (e.g., of equipment or buildings). An important part of this process is particle analysis, in which micrometer-size particles are removed from the samples for mass spectrometric isotope analysis (i.e., measurement of their size, morphology, and elemental composition).

Exemption from IAEA safeguards: Under the provisions of a Safeguards Agreement, a member state may request exemption for nuclear material up to specified limits and under certain conditions. This includes exemptions related to intended use (e.g., using nuclear material in gram quantities as a sensing component in instruments; or using it in nonnuclear activities if the material is recoverable). If exempted nuclear material is to be processed or stored together with safeguarded material, reapplication of safeguards on the exempted material is required.

Explosives testing chamber: Heavy steel vessel for containing blasts and fragments produced by explosion tests. The configuration often includes equipment such as flash x-ray and streak cameras. In January 2012, the IAEA asked Iran for permission to visit such a chamber at the Parchin complex in Taleghan, which has reportedly been used for tests of a nuclear warhead design.

Fakhrizadeh, Mohsen: The apparent leader of Iran's suspected nuclear weapons program (also known as Mohsen Fakhrizadeh Mahabadi). He has served as head of the Physics Research Center and executive officer of the AMAD Plan, the executive affairs of which were conducted by the "Orchid Office." After 2004, some AMAD activities continued under his leadership at the Section for Advanced Development Applications and Technologies (SADAT), which reported to the Ministry of Defense and Armed Forces Logistics (MODAFL). By mid-2008, he was also serving as head of the Malek Ashtar University of Technology (MUT) in Tehran. He now leads the Organization of Defensive Innovation and Research. Fakhrizadeh is named in UN Security Council Resolutions 1737 and 1747, which banned him from international travel and froze his assets.

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Farayand Technique: An Isfahan-based subsidiary of the Atomic Energy Organization of Iran that was originally intended to be a centrifuge assembly site but is now believed to be associated with centrifuge component manufacturing. The firm has since changed its name to Technology of Centrifuge of Iran.

Feed systems/product and tails withdrawal system: Process systems such as feed autoclaves (or stations) used for passing uranium hexafluoride to centrifuges or desublimers/cold traps, which in turn are used to remove UF_6 from cascades. From the desublimers/cold traps, UF_6 is moved into cylinders. Autoclaves are also used at UF_6 production plants.

Fordow Fuel Enrichment Plant (FFEP): Facility constructed under a mountain near the city of Qom (*see map*). Iran originally stated that its purpose was the production of 5 percent enriched uranium using 16 cascades and approximately 3,000 centrifuges. Since then, the facility's purpose has been changed several times. Information from June 2011 indicates that it is being used for the production of up to 20 percent enriched uranium, as well as centrifuge research and development. Built in secrecy until 2009, the plant is probably capable of withstanding most aerial bombing or missile attacks.

Frequency changers: Also known as inverters; typically used to maintain motors (e.g., for centrifuges) at a constant speed.

Fuel element chopping machine: Remotely operated equipment at a reprocessing plant that cuts, chops, or shears irradiated nuclear fuel assemblies, bundles, or rods so that nuclear material (e.g., plutonium) can be separated.

Fuel Enrichment Plant: The official name of the enrichment plant at Natanz, which is protected by a cover of cement, rocks, and earth many feet deep to protect it from airstrikes. Its large halls are designed to hold as many as 54,000 centrifuges.

Fuel Fabrication Laboratory: Facility in Isfahan where nuclear fuel R&D was conducted.

Fuel Manufacturing Plant: Facility under construction in Isfahan to produce fuel for the IR-40 heavy-water reactor in Arak and for planned light-water reactors.

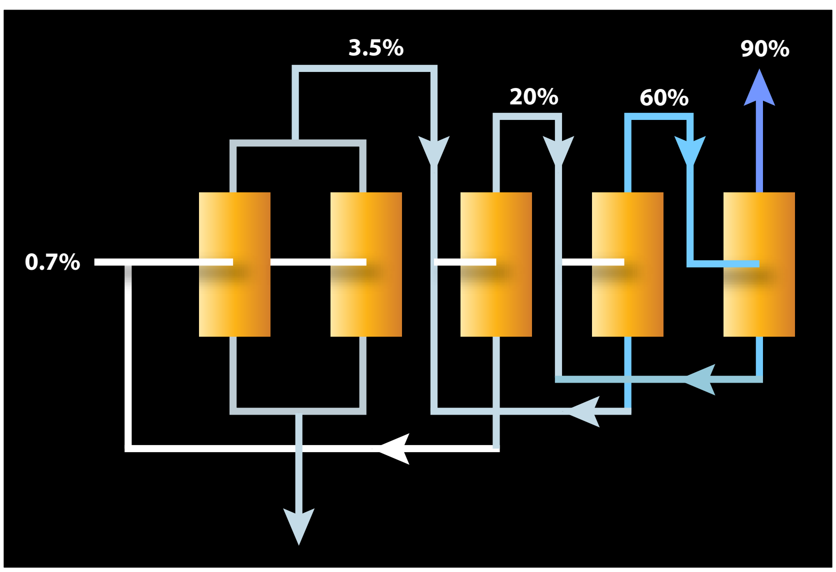

Fig. 2: Uranium enrichment

To enrich uranium so that the percentage of fissile isotope U-235 increases from 0.7% to 90%, UF6 gas is passed through four processes: (1) through two groups of 12 cascades of centrifuges, each having 164 machines, taking the enrichment level to 3.5%; (2) through eight cascades each of another 164 machines to increase the level from 3.5% to 20%; (3) through four cascades of 114 machines increase from 20% to 60%; (4) through two cascades of 64 machines each, to increase from 60% to 90%. At each stage, gas depleted of U-235 is passed back to the previous stage or out of the system completely. As the schematic suggests, the process becomes relatively easier.

Each 1,000 atoms of natural uranium contains 993 atoms of U-238 and seven of U-235. At 3.5% enrichment, the ratio becomes 193:7; i.e., 800 atoms of U-238 have been removed. Removal of just another 158 U-238 atoms effects a ratio of 35:7, or 20% enrichment— the level Iran currently achieves. Comparatively little effort, or as it is known in the jargon, "work," is needed to remove another 34 U-238 atoms to reach 90% enrichment, suitable for an atomic bomb, and a ratio of 1:8.

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Fuel Plate: A type of fuel element used in research reactors such as the TRR. An enriched uranium and aluminum alloy mixed with pure aluminum (the "meat") is sandwiched between two aluminum alloy plates (the "cladding"), which are then assembled into fuel elements. Formerly using HEU, these plates now use LEU to reduce proliferation and terrorist risks.

Fuel Plate Manufacturing Plant: A new plant in Isfahan converting up to 20 percent UF_6 into U_3O_8 and for manufacturing fuel plates for the TRR.

Gchine: The Atomic Energy Organization of Iran owns the Gchine mine near Bandar Abbas (*see map*), as well as the Gchine uranium ore concentration plant. Currently, the mine has estimated reserves of forty metric tons of uranium, and IAEA reports indicate that its annual output is around 21 metric tons. The ore concentration plant has been operating since 2006.

Girdler-sulfide (GS) process: Heavy water can be produced by two commercially viable processes: the water-hydrogen sulfide exchange (GS process) and the ammonia-hydrogen exchange. The GS process, which is used at Khondab, is based on the exchange of hydrogen and deuterium between water and hydrogen sulfide within a series of towers that are operated with the top section cold and the bottom section hot. The product of the last stage—water enriched up to 30 percent in deuterium—is sent to a distillation unit to produce reactor-grade heavy water (i.e., 99.75 percent deuterium oxide).

Graphite, nuclear-grade: Graphite capable of being used as a moderator in a nuclear reactor. Must have a purity level better than 5 ppm boron equivalent and a density greater than 1.5 g/cm^3.

Graphite Subcritical Reactor: A zero-power light-water reactor (with graphite reflector) in Isfahan, operating on uranium metal fuel. China constructed the training reactor in 1991.

Green salt: The name given, due to its color, to uranium tetrafluoride, an intermediate step in the conversion of uranium hexafluoride to either uranium oxides (U_3O_8 or UO_2) or uranium metal. The so-called "Green Salt Project" is part of an alleged secret Iranian program, which includes studies related to uranium processing, high explosives and design of a missile warhead with a nuclear payload.

Haft-e-Tir (Seventh of Tir): A workshop in Isfahan belonging to Iran's Defense Industries Organization. It is currently manufacturing centrifuge components.

Hashtgerd: An area near the city of Karaj to the west of Tehran (*see map*), where the Atomic Energy Organization of Iran has installations (specifically, in Lashkar Abad and Ramandeh).

Heavy water: Water containing more than 99 percent of the hydrogen isotope deuterium (D_2O). It is used as a moderator in reactors fueled by natural uranium.

Heavy-water production plant (HWPP): Iran commissioned the HWPP at Arak in 2006. It can produce sixteen metric tons of heavy water per year for use in the IR-40 heavy-water reactor, which is currently under construction.

Heavy-water reactor: A reactor using heavy water (deuterium) as the moderator. A prominent example is the Canadian deuterium uranium (CANDU) reactor, which is moderated and cooled by heavy water and fueled with natural uranium. Spent fuel rods from such facilities contain significant quantities of plutonium, a nuclear explosive. Iran decided in the mid-1990s to build its IR-40 heavy-water reactor, the "40" denoting its power output in megawatts. Located at Khondab in central Iran, the plant is intended for use in research and development as well as radioisotope production, at least according to Iran. It is expected to become operational sometime in 2013. Such a reactor produces weapons-grade plutonium sufficient for at least one nuclear device annually. IAEA reports indicate that Iran also tried unsuccessfully to acquire a 27-megawatt heavy-water reactor from China.

Heavy-water-reactor-related projects: UN Security Council resolutions have called on Iran to suspend all of its "heavy-water-reactor-related projects," including heavy-water production, construction of the IR-40 reactor, and manufacture and testing of fuel for that reactor.

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Hex: Slang for uranium hexafluoride gas (UF_6).

High-enriched uranium (HEU): Uranium containing 20 percent or more of the fissile isotope U-235. Weapons-grade uranium is usually enriched to 90 percent or higher levels of U-235.

High-strength aluminum: The 7000 series of high-strength aluminum is often used for centrifuge rotors. Centrifuge casings are typically made of 6000 series aluminum.

Hold-up: Nuclear material deposits remaining in process equipment, interconnecting pipes, filters, and adjacent work areas. For plants in operation, the hold-up is the amount of nuclear material contained in the process.

Imenista Andish: A private firm that had a contract with the Atomic Energy Organization of Iran to develop a rotor for a P2 centrifuge. The company concluded that carbon fiber was the best material to use given the country's industrial infrastructure. The AEOI canceled the contract in 2003, by which point the company had only built cylinder rotors and run some basic mechanical tests.

Inert gas testing of centrifuges: Xenon and sulfur hexafluoride can be used as surrogates to test the performance of centrifuges at early stages of research and development. They do not substitute, however, for testing with uranium hexafluoride gas.

Inspections: Most IAEA onsite inspections are carried out according to a defined schedule, though some are unannounced or short-notice. Inspections are limited to locations within a declared nuclear facility or other locations containing nuclear material. During onsite visits, inspectors audit the facility's accounting and operating records, verify the nuclear material inventory, take environmental samples, and apply containment and surveillance measures such as seals and cameras. The frequency of inspections depends on the type of facility and its inventory of nuclear material. A light-water reactor (e.g., Bushehr) is typically inspected quarterly, while an enrichment plant (e.g., Natanz) has monthly announced inspections as well as additional unannounced visits at least once a month. The IAEA's annual inspection effort in Iran totals about 500 person-days.

Institute of Applied Physics (IAP): Part of Iran's Physics Research Center.

Isfahan Nuclear Technology Center: Iran's largest nuclear research center, established in 1975 with French assistance (*see map*). Although France eventually ceased cooperation, work continued, particularly with Chinese assistance. The site is home to research reactors, numerous laboratories, the Uranium Conversion Facility, and Zirconium Production Facility.

IR-1 centrifuge: This Iranian model is based on the early Dutch SNOR design acquired by Pakistani scientist Abdul Qadeer Khan, who developed it further and called it "P1." The design was subsequently given to Iran, Libya, and North Korea.

IR-2 centrifuge: Iran's original IR-2 was made of carbon fiber, without bellows. A more advanced model, the IR-2m, uses two carbon fiber rotors and a maraging steel bellows. Both models are based on the Pakistani P2 centrifuge, a German design acquired by A.Q. Khan, which uses a maraging steel rotor.

IR-3 centrifuge: One of the prototype centrifuges tested at Iran's Pilot Fuel Enrichment Plant.

IR-4 centrifuge: An Iranian design based on Pakistan's P2 centrifuge, but believed to use carbon fiber for both the rotor and bellows.

IR-5 centrifuge: One of the prototype centrifuges tested at Iran's Pilot Fuel Enrichment Plant.

IR-6 centrifuge: One of the prototype centrifuges tested at Iran's Pilot Fuel Enrichment Plant.

Isotope: Any of two or more species of atoms of a chemical element with the same atomic number and nearly identical chemical behavior but with differing atomic mass or mass number and different physical properties. *See also* Atomic weight.

Jabr Ibn Hayan Laboratories: Part of the Tehran Nuclear Research Center, this facility has been involved in laser uranium enrichment, uranium conversion, and metallurgy research and development. The facility was named after Jabr Ibn al-Hayan, a ninth-century Shiite Muslim chemist.

Kalaye Electric Company: A subsidiary of the Atomic Energy Organization of Iran that has been involved in research and development as well as construction of uranium gas centrifuge enrichment facilities in Tehran and Natanz.

Karaj Agricultural and Medical Center: An Atomic Energy Organization of Iran research center west of Tehran (*see map*) that has been storing waste from the nuclear program and equipment dismantled from atomic vapor laser isotope separation experiments in nearby Lashkar Abad.

Khondab: Site, near Arak (*see map*), where Iran's IR-40 heavy-water research reactor is still under construction. The spent fuel rods from this type of reactor contain significant amounts of plutonium, a potential nuclear explosive. Khondab is a also the location of a heavy-water production plant.

Kolahdouz: An industrial site in western Tehran belonging to the military industries. In 2003, the IAEA visited three locations on this site to clarify allegations related to uranium enrichment activities.

Laser enrichment: Separating uranium isotopes by using a laser of a particular wavelength, which "excites" U-235 atoms to the point that they can be segregated from U-238. Such systems use one of two types of process medium: atomic uranium vapor or the vapor of a uranium compound. The first category includes atomic vapor laser isotope separation (AVLIS), for which Iran has built a pilot plant in Lashkar Abad (*see map*). Tehran never completed equipment for the second category, however (molecular laser isotope separation, known as MLIS or MOLIS). AVLIS technology was obtained from Russia and China, and some of the MLIS equipment from the United States.

Laser Spectroscopy Laboratory (LSL): In 1991, the Atomic Energy Organization of Iran concluded a contract with a Chinese supplier for establishing this facility to study the spectroscopy of uranium metal on a milligram scale. The LSL was used until October 2002, when the laboratories and nuclear material were moved to Lashkar Abad. None of these activities were reported to the IAEA. The equipment was eventually dismantled.

Lavisan-Shian: A site in Tehran where the Physics Research Center was once located. Iran razed the site after November 2003; the IAEA visited it in June 2004.

Light-water reactor (LWR): A power reactor that is both moderated and cooled by ordinary (light) water. LWR fuel assemblies usually consist of Zircaloy-clad fuel rods containing uranium oxide pellets of low enrichment (generally less than 5 percent). There are two types of LWR: boiling water reactors and pressurized water reactors. The LWR at Bushehr is the second type.

Light-Water Subcritical Reactor: A Chinese-made zero-power reactor in Isfahan, used for train-ing purposes.

Limited frequency, unannounced access (LFUA): An IAEA safeguards measure developed for gas centrifuge plants whose stated output is uranium enriched to 5 percent or less. LFUA inspections of cascade areas are designed to help detect diversion of one "significant quantity" (SQ) of uranium (including the production of material at an enrichment level higher than that declared) while protecting sensitive technical information related to the enrichment process.

Location outside facilities (LOF): Any location that is not a designated nuclear facility, but where nuclear material is customarily used in amounts of one effective kilogram or less. All of Iran's LOFs are hospitals, which use uranium in radiation shielding.

Low-enriched uranium (LEU): Uranium containing between 0.7 and 20 percent of the isotope U-235 found in the natural metal. At 20 percent the material becomes known as high-enriched uranium.

Malek Ashtar University of Technology (MUT): A Iranian public university dedicated to engineering,

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science, and the military. Opened in 1986, it has campuses in Tehran and Isfahan, with funding provided by the Ministry of Defense. In 2005, the German government identified MUT as a mainly civilian institution that also conducts military research and development. The university is also linked with key Iranian nuclear figure Mohsen Fakhrizadeh, who merged the SADAT Center into MUT, where it is known as "Pardis Tehran."

Manipulator: Remotely controlled device (sometimes known as a "master slave") for handling highly radioactive materials inside specially constructed thick-walled containers known as "hot cells."

Marivan: Area of Iran close to the Iraqi border (*see map*) where the IAEA has reported large-scale high-explosive experiments.

Mass spectrometry: Isotope analysis technique in which small quantities of a sample are ionized, formed into a beam, and passed through a strong magnetic field-where they deflect differently depending on their masses.

Material unaccounted for (MUF): The difference between the material balance at the end of an accounting period compared to what it was at the beginning, given by the equation MUF=(PB+X+Y)-PE,

where PB = the beginning physical inventory,

X = the sum of increases in inventory,

Y = the sum of decreases in inventory,

PE = the physical ending inventory.

MUF is generally not zero, due to measurement uncertainties, but these have internationally accepted target values. Using these values, statistical tests are conducted to confirm whether the MUF declared by the operator is acceptable and if nuclear material has been diverted.

Medical isotopes: Iran produces several radioisotopes for medical and industrial purposes at the Tehran Nuclear Research Center. The most common such isotope is molybdenum-99. *See also* MIX facility.

Meeting in 1984: The IAEA has asked Iran for information about a high-level 1984 meeting to discuss reviving the country's pre-revolution nuclear program. Iran denied that any such meeting took place.

Military workshops: According to information Iran gave the IAEA in 2004, most of its centrifuge components are manufactured in workshops belonging to defense industries organizations.

Milling of uranium: A process in which uranium is extracted from crushed fine ore by leaching. The uranium is then precipitated and removed from the solution. After drying and, usually, heating, a concentrate referred to as "yellowcake" undergoes a conversion process. Iran has uranium mills at Ardakan near Yazd and in Gchine and near Bandar Abbas (*see map*).

Miniature Neutron Source Reactor: A small research reactor in Isfahan of Chinese origin.

Ministry of Defense and Armed Forces Logistics: Established in 1989, MODAFL encompasses the regular military (Artesh) and the Islamic Revolutionary Guard Corps (IRGC or Pasdaran). MODAFL also controls Iran's Defense Industries Organization and its subsidiary, the Aerospace Industries Organization, both of which are involved in the nuclear program.

MIX facility: Acronym for the Molybdenum, Iodine, and Xenon Radioisotope Production Facility at the Tehran Nuclear Research Center.

Modality: An understanding on specific measures or conditions agreed between the IAEA and a member state to accomplish the objectives of a given site visit or inspection.

Molecular laser isotope separation (MLIS or MOLIS): A type of laser enrichment that Iran has considered but not pursued.

Monte Carlo methodology: A lgorithms now widely used in science and business but originating in work on the design of the first U.S. nuclear weapons. This methodology is used to simulate physical and mathematical systems.

Moallem Kalayeh: A site northwest of Tehran that IAEA officials visited in 1992. The Atomic Energy

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Organization of Iran has a training and recreation facility there, but it was originally considered as a possible nuclear research center.

Najafabad: An alleged nuclear site in Isfahan province, stated to be a chemical plant. Also called "Velayat 1."

Natanz: The site of Iran's main uranium enrichment plant in the central part of the country, north of Isfahan (*see map*).

Natural uranium: Uranium as it occurs in nature contains about 0.7 percent U-235 and 99.3 percent U-238, as well as minute quantities of U-234 .

Neutron: An atomic particle that is present in every material except the element hydrogen. In fissile materials, neutrons can cause the nucleus of an atom to split, releasing more neutrons and creating a chain reaction.

Neutron generator: Also known as an *initiator* or *neutron source*, this device is capable of producing a burst of neutrons upon activation. It is a crucial component of any implosion device aimed at kickstarting a chain reaction when a nuclear device goes critical. The initiator is typically placed in the center of the device and is activated by the impact of the converging shockwave. IAEA reports indicate that Iran worked on a polonium-beryllium neutron source around 1994, and more recently with deuterium sources, but it has been unable to conclude whether the experiments were peaceful or not. Pakistan is thought to have used a uranium deuteride initiator known as a D-D for its nuclear weapons, a type developed in China.

Noncompliance: When a state is found to be in violation of its Safeguards Agreement with the IAEA, such as by diverting nuclear material from declared nuclear activities, failing to declare nuclear material that must be placed under safeguards, violating agreed recording and reporting systems, obstructing IAEA inspectors, interfering with safeguards equipment, or otherwise preventing the agency from carrying out its verification activities. In the event of noncompliance, the IAEA director-general must report the matter to the agency's Board of Governors, which then calls upon the member state to remedy the problem. The board must also inform other IAEA member states, the UN Security Council, and the General Assembly. The Security Council may take additional actions, including sanctions, to reinforce the compliance.

Nondestructive assay (NDA): Measuring the nuclear material content or elemental/isotopic concentration of an item without producing significant physical or chemical changes in the item.

Nondestructive testing (NDT): A wide group of analysis techniques used in science and industry to characterize the properties of a material, component, or system without damaging it.

Nuclear material: Uranium, plutonium, or thorium (a possible nuclear fuel). Often subdivided into "source material" and "special fissionable material."

Nuclear Nonproliferation Treaty (NPT): A global treaty designed to halt the spread of nuclear weapons, promote the spread of peaceful nuclear technology, and further the goal of disarmament. The NPT, which went into force in 1970, divides its signatories into two categories: nuclear weapons states and non-nuclear weapons states. The five official nuclear weapons states are the United States, Russia, Britain, France, and China. The non-nuclear weapons states—which include Iran—agree not to pursue nuclear weapons in exchange for access to peaceful nuclear technologies. The nuclear weapons states are obligated to assist in the development of nuclear energy while also working in good faith toward nuclear disarmament.

Nuclear-powered vessels: In June 2012, the Iranian navy announced that it was considering construction of nuclear-powered submarines. Shortly afterward, Tehran stated that it was also considering nuclear-powered oil tankers. Although naval reactors typically use high-enriched uranium (HEU) as a fuel in order to reduce reactor size (e.g., U.S. Navy submarines use 97 percent HEU, and Russian icebreakers up to 75 percent), there have been exceptions. The French navy uses low-enriched uranium (LEU) "caramel" fuel (around 7.5 percent) in its submarines, enabling

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it to enrich and manufacture fuel rods at its civilian plants. Brazil's planned nuclear submarine is also expected to use LEU fuel. Experimental merchant ships such as the *Savannah* (U.S.), *Otto Hahn* (Germany), and *Mutsu* (Japan) used LEU fuel, but they no longer exist. In terms of international nuclear safeguards, the issue is complicated. Non-nuclear weapon states with a Comprehensive Safeguards Agreement are allowed to remove certain material from IAEA safeguards—in this case, nuclear material intended for nonproscribed military use such as submarine fuel can be exempted under arrangements reached with the agency.

Offer in 1987: A handwritten one-page document given to Iranian officials in Switzerland by a foreign intermediary believed to be a business associate of Pakistani nuclear scientist A.Q. Khan. The offer included: a disassembled centrifuge; drawings, descriptions, and specifications for centrifuge production; drawings and specifications for a "complete plant"; materials for the manufacture of 2,000 centrifuge machines; auxiliary vacuum and electric drive equipment; and uranium reconversion and casting equipment. The latter item provides some details on how to make uranium components for a nuclear weapon. Iran has repeatedly stated that the intermediaries offered the reconversion unit with casting equipment on their own initiative, and that the Atomic Energy Organization of Iran never actually received any such items.

Offer in early 1990s: Sometime in 1993–1994, associates of Pakistani nuclear scientist A.Q. Khan made a new offer to Iran concerning the transfer of centrifuge technology. Iran maintains that no documentation exists on the offer apart from shipping documents confirming the delivery of P1 centrifuge components in 1994–1995. The deal included provision of the P2 centrifuge design, but Iran claims it did not pursue any work on that design between 1995 and 2002. Some reports indicate that documentation related to nuclear weapons design may also have been passed to Iran as part of the deal. The genesis of the deal itself is unclear—Tehran claims that it was offered on the initiative of Khan and his associates, but Open-source information: Information generally available to the public from sources such as scientific literature, government releases, commercial satellite images, and releases issued by public organizations, commercial companies, and the media.

Orchid Office: Executive office of the AMAD Plan, located on Orchid Street in Tehran.

Orchid Scientific Research Center: Part of Iran's Physics Research Center.

Ore Processing Center: An installation at the Tehran Nuclear Research Center that performs bench-scale tests to recover uranium from ore.

Organization of Defensive Innovation & Research: An entity headed by Mohsen Fakhrizadeh, suspected of being associated with Iran's military nuclear research.

P5+1: The group currently leading international nuclear negotiations with Iran. Led by European Union High Representative Catherine Ashton of Britain, it includes the five permanent members of the UN Security Council (the United States, Britain, China, France, and Russia) plus Germany. It is also known as the E3+3.

Parchin: A large military-industrial site near Tehran that is believed to have conducted nuclear experiments, particularly high-explosives testing allegedly related to warhead design.

Pardis Tehran: Organization created by Mohsen Fakhrizadeh through the merger of the SADAT Centers and Malek Ashtar University of Technology.

Pars Trash: One of the subsidiary companies of the Kalaye Electric Company, focusing on centrifuge component manufacturing. The workshop is located in east Tehran.

Passivation: The process of flushing newly installed uranium enrichment equipment (e.g., piping or centrifuges) with depleted uranium hexafluoride to coat the surfaces, which must be done before the equipment can be used.

Passive Defense Organization: Created in response to perceived threats of military attack against Iran, the Passive Defense Organization designed and established contingency centers for various organizations and activities. The Atomic Energy Organization of Iran requested that one of these centers be designated as a contingency enrichment plant, so that the country's enrichment activities do not need to be suspended in the case of an attack. According to Iran, this was the basis for establishing the enrichment plant at Fordow.

Physical inventory taking: A given nuclear facility's physical inventory is determined by the facility operator and reported to the IAEA in the physical inventory listing. The agency then verifies the report during a physical inventory verification inspection.

Physics Research Center (PHRC): The Tehran-based organization believed to have been at the center of Iran's military nuclear research. It was created with the purpose of ensuring "preparedness for combat and neutralization of casualties due to nuclear attacks and accidents (nuclear defense)," as well as providing "support" and "scientific advice and services to the Ministry of Defense." Iran has stated that those activities ended in 1998, but between the late 1990s and early 2000s, the PHRC's efforts were consolidated under the "AMAD Plan." In late 2003 and early 2004, Iran completely cleared the PHRC site in Lavisan-Shian outside Tehran.

Pilot Fuel Enrichment Plant: An enrichment research and development facility in Natanz. Unlike the site's main enrichment plant, it is located above ground. Currently, it is being used for tests involving single centrifuges as well as small and full cascades, including Iran's next-generation centrifuges. Some of these tests involve nuclear material.

Pishgam: An Iranian engineering firm known by several names, including Pishgam Energy Industries Development Co. and Pioneer Energy Industries Development Company (PEI). It has been providing engineering and technical support for various Atomic Energy Organization of Iran projects, including the Zirconium Production Plant, the Uranium Conversion Facility, and the Fuel Manufacturing Plant—all located in the Isfahan Nuclear Technology Center—as well as the Yellowcake Production Plant at Ardakan. The company is listed in UN Security Council Resolution 1803 (2008).

Plasma Physics: A department at the Tehran Nuclear Research Center that housed the uranium enrichment program during the early 1990s.

Plutonium (Pu): A radioactive element that occurs in only trace amounts in nature. When produced by irradiating uranium fuels, plutonium contains varying percentages of the isotopes Pu-238, 239, 240, 241, and 242. Plutonium containing any Pu-239 is considered a special fissionable material. The International Atomic Energy Agency has defined 8 kg of plutonium as a "significant quantity," that is, the amount sufficient for a nuclear bomb.

Project 3: Believed to be an Iranian program for weapon system design, including several sub projects, one of which is Project 3.12, the development of a hemispherical high-explosive initiation system, including detonators.

Project 4: The name of the Iranian program for uranium enrichment using gas centrifuges.

Project 5: The Iranian program for uranium mining, concentration and conversion, including subproject 5.13, the so-called Green Salt Project, and subproject 5.15 the Gchine mine.

Project 110: The project responsible for the design of a new nuclear payload for the Shahab-3 missile.

Project 111: The Iranian project preliminary studying the integration of a nuclear payload into a reentry vehicle of the Shahab-3 missile.

PUREX reprocessing: Around the year 2000, the Pishgam company was involved in the design of a PUREX-based reprocessing method for the Atomic Energy Organization of Iran. The PUREX is an industrial process used to separate uranium and plutonium from spent nuclear fuel.

Pyroprocessing: In 2010, the IAEA noted that the Jabr Ibn Hayan Multipurpose Research Laboratory (JHL) in Tehran had initiated pyroprocessing research and development activities to study the electrochemical production of uranium. Iran stated that the experiments were

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aimed at studying the electrochemical behavior of uranyl ion in ionic liquid. Pyroprocessing is an alternative to PUREX reprocessing and can also be used to produce high-purity uranium metal. Pyroprocessing, however, has only been used on an experimental scale.

Qom: A holy city in central Iran, south of Tehran (*see map*), near the Fordow uranium centrifuge enrichment plant built deep inside a mountain.

Radioisotope batteries: Radioisotope thermoelectric generators (RTGs or RITEGs) are electrical generators in which the heat released by the decay of a suitable radioactive material is converted into electricity. They have been used as power sources in satellites, space probes, and unmanned remote facilities such as lighthouses. Most applications have used Pu-238, but Iran has stated that it studied Po-210 for that purpose. Po-210 can also be used as part of an initiator in an atomic bomb.

Recycled uranium: When low-enriched uranium has been irradiated in a reactor and removed for reprocessing, it still contains more than 1 percent U-235, along with an additional isotope (U-236) not present in natural uranium. High U-236 content has been found in samples taken from Iranian centrifuge equipment that originated in Pakistan. For its part, Pakistan likely received such uranium from China.

Remote monitoring: A technique whereby safeguards data collected by unattended monitoring and measurement systems (e.g., camera images) is transmitted to IAEA headquarters or a regional office via communication networks, where it is then evaluated. The IAEA currently has around 200 such systems deployed worldwide. The benefits are that evaluation and equipment checks can be performed without visiting a site. This approach includes often-unannounced inspections to ensure that the state is not tampering with the remote-monitoring equipment. Iran has not agreed to allowing remote monitoring at its facilities.

Reprocessing: Chemical separation of nuclear material from fission products. Usually refers to obtaining plutonium from irradiated uranium fuel rods. The most common reprocessing process is PUREX.

Resolutions of the UN Security Council: The relevant Security Council resolutions on Iran—adopted under Chapter VII of the UN Charter, making them mandatory—are 1696 (2006), 1737 (2006), 1747 (2007), 1803 (2008), 1835 (2008), and 1929 (2010). *See also* Board resolutions.

Routine inspections: The most frequent type of IAEA inspection. They may be carried out according to a defined schedule or with little or no notice.

SADAT Centers: Some of the military nuclear activities that Iran had carried out under the AMAD Plan were resumed after 2004 under a new organization known as the Section for Advanced Development Applications and Technologies (SADAT), which continued to report to MODAFL. The organization inludes the Center for Readiness and New Defense Technologies, reponsible for the activities of the Lavisan-Shian site; the Center for Industrial Research and Construction; the Center for R&T (2) of Advanced Materials–Chemistry; the Center for R&T of Advanced Materials–Metallurgy; the Center for R&D of New Aerospace Technology; and the Center for Laser & Photonics Applications.

Safeguards Agreement: Each non-nuclear-weapons state that is party to the Nuclear Nonproliferation Treaty must conclude a Comprehensive Safeguards Agreement (CSA) with the IAEA. The model Safeguards Agreement, laid out in IAEA document INFCIRC/153 (Corr.), serves as the basis for negotiation of each state's CSA. The details of how these safeguards will be applied are contained in the agreement's Subsidiary Arrangements. Under a CSA, a member state must accept IAEA safeguards on all source or special fissionable material in all peaceful nuclear activities within its territory, under its jurisdiction, or carried out under its control. The IAEA has a corresponding right and obligation to ensure that safeguards are applied on all such material, for the exclusive purpose of verifying that it is not diverted to nuclear weapons. Iran's agreement with the IAEA entered into force on May 15, 1974 (*see* http://www.iaea.org/Publications/Documents/Infcircs/Others/infcirc214.pdf).

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Saghand: A uranium mine under construction in Yazd in central Iran (*see map*). It has an annual estimated production capacity of 50 metric tons.

Satellite imagery: The IAEA uses commercially available satellite imagery to support its work. Available from various vendors, such high-resolution imagery is useful in following construction of nuclear sites over long periods of time.

Separative work unit: A way of measuring the efficiency of different centrifuge designs, relating to both the amount of material processed and the degree of enrichment achieved.

Shahab-3: Persian for "meteor," the Shahab is a medium-range (800 miles) ballistic missile developed by Iran and based on the North Korean Nodong missile. As indicated in documentation and other information obtained by the IAEA, the Shahab-3 nose-cone reentry vehicle is designed to accommodate a nuclear payload.

Shahid Beheshti University: A senior SADAT official solicited assistance from this university on a matter related to nuclear weapons—specifically, complex calculations related to the state of criticality of a solid sphere of uranium being compressed by high explosives.

Shahid Hemmat Industrial Group: A subordinate of Iran's Aerospace Industries Organization (AIO), which is responsible for the country's liquid-fueled ballistic missile programs.

Shariaty Building: Between 1987 and 1993, Iran conducted plutonium separation experiments in a laboratory in this building, located at the Tehran Nuclear Research Center. In 1993, plutonium solutions produced from these activities were transferred to the center's Chamaran Building, where experiments continued.

Sharif University of Technology: One of the largest engineering schools in Iran, SUT was established in 1966 under the name Aryarmehr University of Technology, then renamed after the 1979 Islamic Revolution. Since 2004, the IAEA has asked Iran to explain nuclear-related equipment procured by the former head of the Physics Research Center, who was also a professor at SUT. The equipment—only some of which he was able to obtain—included balancing machines, mass spectrometers, magnets, and fluorine handling equipment, all of which could be useful in uranium enrichment.

Shielded window: Hot cells, in which work involving plutonium or other highly toxic materials is conducted, have thick windows made of lead glass, which absorbs radiation.

Shielding material: Heavy, high-density metals such as lead, tungsten, and uranium are used for radiation shielding (e.g., in gamma-cameras at hospitals and radioactive source transportation casks).

Shockwave software: Software that is useful in understanding and modeling detonations; has nuclear, military, and nonmilitary applications.

Significant quantity: The approximate minimum quantity of nuclear material required for the manufacture of a nuclear explosive device. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses. The IAEA has defined 25 kg of U-235 for high-enriched uranium (U-235≥20 %), 75 kg U-235 for low-enriched uranium (U-235<20%), or 8 kg of Pu-239 or U-233 as a "significant quantity." Some outside experts argue that an aspiring nuclear weapons state could construct a simple fission weapon with as little as 3 kg of weapons-grade plutonium, or between 2 and 7 kg of HEU. (U-233 is a fissile isotope but has only been used experimentally in reactors, and not as a nuclear explosive.)

Source material: Uranium in its natural isotopic composition, uranium depleted in isotope U-235, and thorium, inluding metals, alloys, and chemical compounds or concentrates of uranium and thorium.

Special fissionable material: These materials are defined by their ability to sustain a chain reaction and include Pu-239, U-233, U-235, and any material

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that contains them. (U-233 is a fissile isotope but has only been used experimentally in reactors and not as a nuclear explosive.)

Special inspection: Site visit that may be carried out under certain circumstances and according to defined procedures. The IAEA may order a special inspection if it believes that information made available by a member state—including direct explanations or information obtained from routine inspections—prevents the agency from fulfilling its responsibilities under the Safeguards Agreement. This need for information has to be considered essential and urgent, and is envisioned for use only when other avenues to obtain necessary information have been exhausted.

Starting point of IAEA safeguards: Refers to the point in a nuclear fuel cycle after which the full requirements specified in a Comprehensive Safeguards Agreement begin to apply to nuclear material. Specifically, the application of safeguards begins when any nuclear material of a composition and purity suitable for fuel fabrication or isotopic enrichment leaves a plant or completes the process stage in which it has been produced. It also applies when nuclear material is imported into a state.

State Organization for Planning and Management: According to Tehran, a business associate of Pakistani nuclear scientist A.Q. Khan approached an employee of this Iranian organization at a meeting in Dubai sometime in 1993–1994, making an oral offer for the delivery of P1 centrifuge documentation and components. The information was then passed to the Atomic Energy Organization of Iran. Tehran claims that the Khan network never made a written offer.

Structured approach: The document listing unresolved issues related to the military dimension of Iran's nuclear program, and the IAEA requirements to verify the correctness and completeness of Iran's declaration on nuclear material and activities. The three-page document, which has been discussed since late 2011 by the IAEA and Iran with little progress, includes topics to be addressed and modalities in relation to the IAEA access to relevant information, documentation, people, sites, and material..

Stuxnet: A computer virus reportedly developed jointly by the U.S. and Israeli governments, designed to interfere with centrifuges. The Thunderstruck and Flame viruses also targeted Iran's nuclear program.

Subsidiary Arrangements: A document containing the technical and administrative procedures for implementing an IAEA member state's Safeguards Agreement. Under an INFCIRC/153-type Safeguards Agreement, both the state and the agency are required to agree on such arrangements. The document typically consists of a General Part, applicable to all of the state's common nuclear activities, and Facility Attachments prepared for all of the state's nuclear sites and describing arrangements specific to each one.

Supreme National Security Council: The body that formulates Iran's nuclear policy, though its decisions do not become effective until they are confirmed by the Supreme Leader. The president presides over this body and selects its secretary, who in turn serves as Iran's chief nuclear negotiator. More broadly, the council's responsibilities include: determining national defense and security policies within the framework of the Supreme Leader's general policies; coordinating political, intelligence, social, cultural, and economic activities that affect general defense and security policies; and exploiting national resources in order to confront internal and external threats.

Suspension: In November 2003, Iran decided to suspend all enrichment-related and reprocessing activities to rebuild confidence after their two-decade failure to report nuclear activities to the IAEA became known. This included halting the installation of new centrifuges, the production of uranium hexafluoride feed material for enrichment processes, and the importation of enrichment-related items.

Tails: A waste stream of depleted uranium produced when enriching material to reactor grade. Tails typically contain only 0.3 to 0.4 percent of the fissile isotope U-235, compared to 0.7 percent in natural uranium.

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Technical cooperation: The IAEA provides technical assistance to developing member states, including funds for a wide variety of projects. Such funding covers research and projects related to the peaceful use of nuclear technology in the areas of medicine, agriculture, and nuclear energy, safety, and security. The assistance does not cover the transfer of sensitive technologies such as reprocessing or uranium enrichment. UN Security Council Resolution 1737 called for halting any IAEA aid that might help Iran develop nuclear weapons; as a result, the agency's technical assistance to Tehran is limited and carefully vetted.

Tehran Research Reactor: Initially, the TRR was a five-megawatt thermal-pool-type light-water research reactor that ran on 93 percent high-enriched uranium. Supplied by the United States, it became operational in 1967. In 1987, with IAEA assistance, Iran paid Argentina's Applied Research Institute to convert the reactor to run on 19.75 percent enriched fuel. The reactor is located at the Tehran Nuclear Research Center in the north of the city.

Transparency: Throughout the discussions on the scope and content of its nuclear program, Iran has repeatedly offered "transparency" to build international confidence in its intentions. Transparency and open availability of information would allow other IAEA member states to see Iran's activities and capabilities more clearly. Openness also entails giving the IAEA access to information, which in broader terms means access to people, equipment, documents, and sites. Hence, merely inviting inspectors to locations where they have access under the Safeguards Agreement cannot in of itself be considered transparency. At times, Iran has offered to "show" a location that it previously defined as off limits, regardless of the IAEA's own view on the site. Inspections conducted under such conditions can have meaning only if substantially new information is given, including in-depth discussions and explanations of the nuclear program's scope and content.

Unannounced inspection: An IAEA inspection for which no advance notice is provided to the member state before the arrival of inspectors.

Uranium: A naturally occurring radioactive element with atomic number 92. Natural uranium contains the isotopes U-234, 235, and 238; the isotopes U-232, 233, and 236 are produced by radioactive decay.

Uranium alloy: Metallic uranium can be cast, formed, and welded by a variety of processes. Since uranium metal oxidizes easily, many processes use uranium alloys that retain or enhance most of the natural metal's desirable characteristics while reducing the potential for oxidation.

Uranium Chemistry Laboratory: The Atomic Energy Organization of Iran established this facility in Isfahan to study the chemistry of uranium compounds.

Uranium Conversion Facility (UCF): This facility, which began operation in Isfahan in 2006, converts yellowcake into uranium dioxide, uranium metal, and uranium hexafluoride. Iran has informed the IAEA that it intends to build production lines for the conversion of natural and 20 percent enriched uranium for use in its reactors. The UCF's annual capacity is 200 metric tons UF_6. UCF started as a joint project with the Chinese, who withdrew from the project in the mid-1990s.

Uranium dioxide: Processed natural or enriched uranium used for fuel rods, particularly in light-water and heavy-water reactors.

Uranium hexafluoride (UF_6): The gaseous feedstock used in the uranium enrichment process that produces fuel for nuclear reactors and weapons. Referred to as "hex" in the nuclear industry.

Uranium metal document: A fifteen-page document describing the generic procedures for reducing uranium hexafluoride to uranium metal and casting it into nuclear weapon components. Iran claims that the document came with the P1 centrifuge documentation provided by the A.Q. Khan network in 1987. It has also stated that the Iranian government did not pursue the reconversion unit with casting equipment mentioned in the offer, and that it received only centrifuge-related information and components.

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Uranium tetrafluoride (UF_4): Generally used as an intermediate in the conversion of uranium hexafluoride (UF_6) to either uranium oxides (U_3O_8 or UO_2) or uranium metal. It is formed by the reaction of UF_6 with hydrogen gas, or by the action of hydrogen fluoride (HF) on uranium dioxide. Due to its color it is often called "green salt."

Vanak Square Laboratory: An Atomic Energy Organization of Iran facility located in Tehran, which the Iranian government claims was used to repair vacuum equipment. In 2007, the IAEA found enriched uranium particles in samples taken from the Sharif University of Technology. Iran explained the presence of the particles at the university as a result of cross-contamination of equipment that had been sent for repair to the Vanak lab.

Veracity checking: When the IAEA receives information about a member state from third parties, it vets the data against other agency information to ensure its credibility. This includes reconciling the data with the IAEA's own findings, declarations made by the accused state, procurement information, relevant publications, and so forth.

Virtual nuclear weapon state: This term, first used by then IAEA head Muhammad el-Baradei, applies to any state that has the capacity to manufacture plutonium or HEU and design a nuclear device, without actually making a nuclear weapon.

Waste Disposal Facility, Qom: A location at Qom marsh land where the Atomic Energy Organization of Iran disposes low level radioactive and nuclear wastes.

Waste Handling Facility: A site at the Tehran Nuclear Research Center used for solidification and storing of radioactive and nuclear waste.

Waste Storage Facility, Karaj: Run by the Atomic Energy Organization of Iran, this facility is located in the Karaj Agricultural and Medical Center (*see map*).

Whole Body Counter (WBC): Device used to measure radioactivity within the human body, generally applicable only to materials that emit gamma rays.

Workplan: In August 2007, Iran and the IAEA agreed on a document titled "Understandings of the Islamic Republic of Iran and the IAEA on the Modalities of Resolution of the Outstanding Issues." Generally referred to as the "workplan," which was distributed as INFCIRC/711. By February 2008, the agency determined that the four items identified in the workplan as "past outstanding issues" and the two items identified as "other outstanding issues" were either closed, completed, or no longer outstanding. The remaining issues that need to be clarified by Iran relate to the circumstances of Iran's acquisition of the uranium metal document, procurement and research and development activities of military related institutes and companies that could be nuclear related, and the production of nuclear equipment and components by companies belonging to defense industries.

Yazd: Iran's Yazd (*see map*) Radiation Processing Center is equipped with a Rhodotron TT200 accelerator supplied by Belgium. The center carries out geophysical research to analyze nearby mineral deposits.

Yellowcake: Semi-processed ore containing a variety of oxides of uranium but principally triuranium octoxide, U_3O_8. The yellowcake produced by most modern uranium mills is actually brown or black, not yellow; the name comes from the color and texture of the concentrates produced by early mining operations.

Zirconium: Metal used to clad uranium fuel rods in a nuclear reactor.

2 | Centrifuge Enrichment

WHILE AUSTRIAN SCIENTIST Gernot Zippe is responsible for the basic design of the centrifuge currently used for uranium enrichment, which he developed while as a war prisoner for the Soviet enrichment program, the concept and application of centrifuges for that purpose was pioneered during the 1930s and 1940s by American scientist Jesse Beams. In the early 1940s, he and his colleagues at the University of Virginia conducted the first known successful use of centrifuges to separate uranium isotopes. Yet when the United States began the Manhattan Project during World War II in order to make an atomic bomb, it selected gaseous diffusion as the method for uranium enrichment.

In a gas centrifuge (fig. 3), gaseous uranium hexafluoride (UF_6) is fed into a thin-walled cylindrical rotor that spins at high speed (typically more than 300 meters per second). Air resistance is reduced by spinning the rotor inside a casing in which a vacuum has been created. Centrifugal forces cause the heavier UF_6 molecules containing U-238 isotopes to move closer to the wall than the lighter UF_6 molecules with U-235 isotopes, thus partially separating the uranium isotopes. The separation is increased by an axial countercurrent flow of gas within the centrifuge that concentrates the relatively lighter enriched gas (U-235) at the top of the centrifuge and the relatively heavier depleted gas (U-238) at the other end. This flow can also be driven mechanically (by scoops and baffles) or thermally (by heating the bottom end cap).

The separating capacity of a single centrifuge increases with the length of the rotor and the rotor wall speed, though longer rotors are subject to greater stress at high speed. Centrifuge design is therefore a compromise between length and speed, both of which depend on the material used. Individual centrifuge components must be manufactured to very close tolerances in order to minimize any imbalances.

The output of a centrifuge is measured in terms of separative work units (SWU), a function of the amount of uranium processed and the degree to which it is enriched.

A typical centrifuge comprises approximately 100 different components. This section lists the most important components and related terms.

Baffles: These disc shapes with holes are placed inside a centrifuge rotor tube to isolate the takeoff chamber from the main separation chamber and control UF_6 circulation. Baffles must also be manufactured from high-strength materials.

Bearings: The bottom bearing of the centrifuge consists of a thin metal pin attached to the rotor, which widens to a ball at its end, a few millimeters wide. Special lubrication systems, using Fomblin oil, prevent wear and ensure smooth operation. The know-how of the bottom bearing is in the etching of the necessary grooves and the lubrication. Pakistani scientist A.Q. Khan was prosecuted in absentia in the Netherlands for trying to obtain classified information about the etching process.

The top bearings consist of ring magnets that hold the top of the rotor steady without any physical contact.

Bellows: Short cylinders that support and connect rotor tubes. As with other components, they are manufactured from high-strength materials. In the Iranian IR-1 centrifuge, a four-section aluminum rotor is separated by three bellows made of maraging steel. In the Pakistani P2 centrifuge, the rotor is made of maraging steel, with the bellow effect created by machining a groove into the rotor at its midpoint.

Carbon fiber: An alternative to aluminum or maraging steel for a centrifuge rotor. The separative power of a gas centrifuge increases rapidly with rotor speed and is proportional to its length, and a rotor's peripheral speed is limited by the strength-to-density ratio of the material from which it is made. Aluminum alloys can reach maximum peripheral speeds of up to 425 meters per second, compared to around 525 m/s for

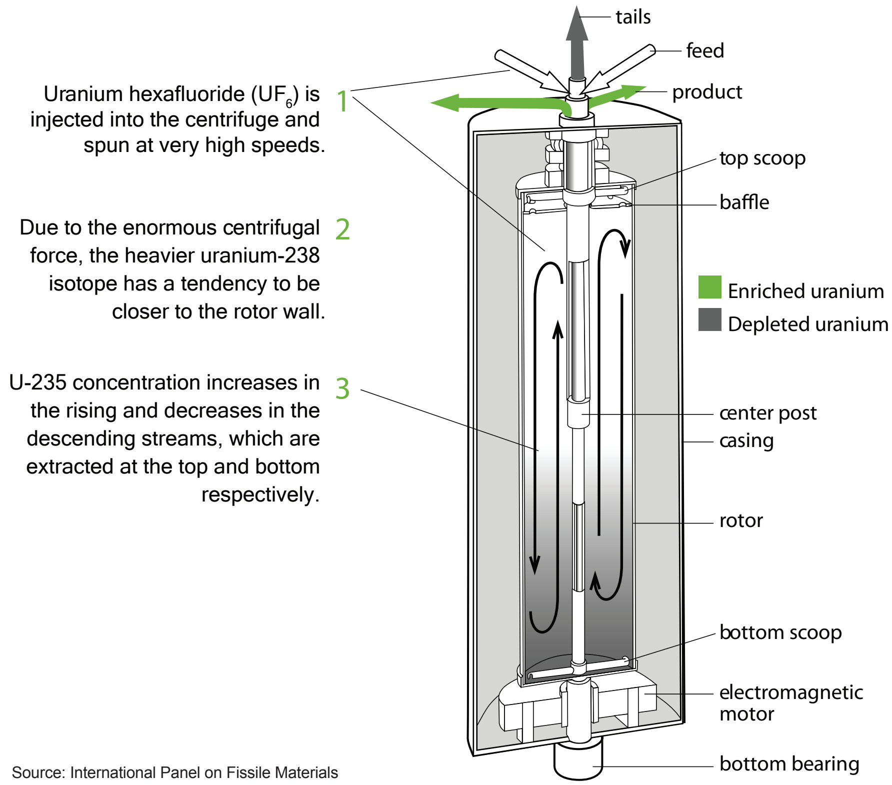

FIG. 3: Gas centrifuge.

maraging steel and 700 m/s for carbon fiber. Other components, such as baffles, bellows, and top and bottom end caps, can also be manufactured from carbon fiber. Iran recently announced that it could produce carbon fiber, but experts do not believe that the quality and strength of its materials meet the requirements for gas centrifuges.

Cascade: Arrangement of groups of centrifuges to produce successively higher concentrations of U-235. Each stage enriches the product of the previous step further before being sent to the next stage. Similarly, the "tails" from each stage are returned to the previous stage for further processing. Since the enrichment factor of a single centrifuge is generally below 1.2, more than a dozen stages are required to produce 3.5 percent enriched uranium. To produce 90 percent enriched uranium more than 65 stages are required, which are split for process control reasons into several units. In a scheme to produce weapons-grade enriched uranium, passed to Libya in the 1990s by businessmen associated with the Pakistani scientist A.Q. Khan, a 164-centrifuge cascade enriches uranium from 0.7 percent to 3.5 percent. Then another 164-machine cascade enriches the material from 3.5 to 20 percent, a 114-machine cascade enriches from 20 to 60 percent, and a final 64-machine cascade enriches from 60 to 90 percent.

Casing: Contains the rotor tube assembly of a gas centrifuge. Also called a housing, it typically consists of a rigid aluminum cylinder with up to 30 mm thick walls, with precision-machined ends to locate the bearings as well as one or more flanges for mounting.

Critical speed: Speed at which a centrifuge rotor will begin to shake or resonate, endangering the equipment until that speed is surpassed. Critical speeds vary, depending on a rotor's design and material.

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End caps: Components placed at the ends of a rotor tube to contain the UF_6 within. The top end cap supports the upper bearing while the bottom cap carries the rotating elements of the motor and lower bearing. End caps must be manufactured from high-strength materials.

Enrichment factor: A way of describing enrichment level at a given stage. It is calculated by dividing the product U-235 concentration with that of U-235 feed concentration.

Expanding mandrel: A key component of the flow-forming and spin-forming machines used to produce centrifuge rotors with very precise inside diameters. Such mandrels grip the metal being worked on and can change their grip as the cylindrical rotors are formed. In the 1980s, British authorities confiscated an expanding mandrel that Pakistan had ordered from a British company. Rather than risk any chance of it getting to Pakistan, the Royal Navy dumped it at sea.

Flow forming: Also called spin forming, this is an incremental technique in which a metal rotor or bellow is formed over a mandrel by one or more rollers using tremendous pressure. The roller deforms the work piece, forcing it against the mandrel and generating thin, precise wall thicknesses.

Fomblin oil: Special oil used for vacuum pumps in a centrifuge plant, able to withstand the corrosive environment associated with uranium hexafluoride.

Maraging steel: Metal known for its toughness and malleability, which makes it ideal for use in centrifuges, where both strength and slight flexibility are required (in contrast with other toughened steels, which are often brittle). Most steel is strengthened using carbon, but maraging steel is principally alloyed with nickel (though other metals are also used). It then undergoes extended heat treatment. Maraging steel is used to form the joins (known as bellows) in the P1 and IR-1 centrifuges. In the P2 centrifuge, the entire rotor is made of maraging steel, with additional flexibility created by a narrow groove halfway up the rotor.

Rotor: A spinning rotor cylinder encounters a series of critical speeds as it accelerates; the greater its length, the more quickly it reaches these points. When it reaches the first critical speed, a cylindrical rotor tends to bend outward like a bow. At the second critical speed, it bends like an "S." As additional critical speeds are achieved, the rotor bends into more and more curves.

There are ways of overcoming the problems caused by critical speeds. The first is to use short, low-diameter "subcritical" rotors in which critical speeds are not encountered—a solution favored in Russian designs. The output of such rotors is small, approximately 1 SWU per year or less. Most commercial enrichment plants use "super-critical" rotors. To overcome the challenges of resonance at critical speeds, they use two methods. First, the rotors are built with flexible joints called bellows so they can absorb the dynamic forces and adopt new shapes as they go through each critical speed. Second, new high-strength materials such as carbon fiber are used to achieve much higher speeds; other viable materials are high-strength aluminum and maraging steel.

Scoops: Small-diameter tubes for the extraction of UF_6 gas from the rotor tube.

Tandem cascade: A method used by Iran to more efficiently enrich from 3.5-percent LEU. The first cascade of IR-1 centrifuges enriches to almost 20 percent, while the second takes the tails of the first and enriches them to 10-percent LEU, which is fed into the first. The tails of the second are natural, unenriched uranium.

Vacuum system: Centrifuges typically include built-in molecular pumps to reduce air resistance on the rotor.

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3 | Initial U.S. Development of Nuclear Weapons

Alamogordo: The military range in New Mexico where the United States carried out its first nuclear weapons test in July 1945. The test was needed because the designers of the Fat Man bomb wanted to be confident that it would work when dropped on its target. Conventional high explosives imploded on a plutonium core, producing an explosion equivalent to 20,000 tons of TNT. The same type of plutonium bomb was dropped the following month on the Japanese city of Nagasaki; in contrast, the bomb dropped on Hiroshima contained high-enriched uranium.

Device: Jargon term for nuclear bomb.

Fat Man: The name given to the implosion-type bomb (fig. 4) dropped on Nagasaki on August 9, 1945. It contained about 6.1 kg (or about 13 lbs) of plutonium, and was based on the design tested previously in the New Mexico desert.

Gadget: Nickname for the world's first atomic bomb, tested by the United States in July 1945.

Hiroshima: The Japanese city destroyed on August 6, 1945, by an American atomic bomb containing high-enriched uranium, the first military use of a nuclear weapon.

Jumbo: Name given to a giant steel containment vessel (25 feet long and weighing 214 tons) built in 1945, intended to allow testing of a plutonium-based implosion device. If the test was successful, "Jumbo" would be destroyed, but it was designed to be strong enough to withstand a less than completely successful test, thereby allowing the plutonium to be recovered. This type of vessel can also be used for testing of components or subsystems of nuclear devices, which the IAEA believes might have been done at Parchin.

Little Boy: The name given to the nuclear bomb dropped on Hiroshima in August 6, 1945. It used a previously untested gun-type design (fig. 5) in which one mass of high-enriched uranium was fired into another, bringing the total amount of high-enriched uranium to 64 kg. The explosion was equivalent to around 15,000 tons of TNT.

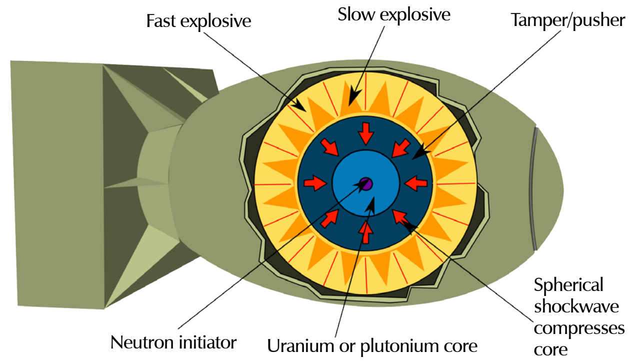

FIG. 4: Implosion-type atomic bomb.

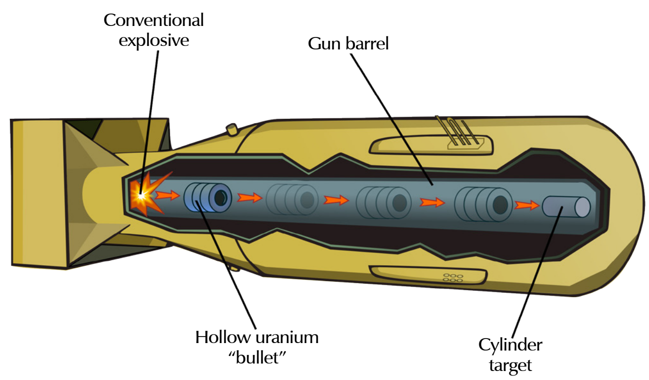

FIG. 5: Gun-type atomic bomb.

Manhattan Project: The name of the secret program to develop the atomic bomb, led by the United States, with participation from Britain and Canada.

Nagasaki: The Japanese city destroyed by an American plutonium bomb on August 9, 1945.

Trinity: The code name or the first nuclear test, carried out at the Alamogordo military range in the New Mexico desert in 1945.

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4 | Basic Nuclear Physics and Weapons Design

IN ADDITION TO the specific technical definitions listed below, a general note about nuclear explosives is in order. Both U-235 and Pu-239 are potential nuclear explosives—the former is obtained by enriching natural uranium, while the latter is a product of reprocessing spent uranium fuel rods (fig. 6). The proliferation of low-tech centrifuges such as Pakistan's P1 model and subcritical designs has made high-enriched U-235 more easily obtainable, and many of the materials and components of these centrifuges are widely used in other industries. Due to their relatively small sizes and lack of visible signatures such as chimneys of reactors, centrifuge facilities are easy to conceal. Nevertheless, the preferred nuclear explosive for bomb designers is Pu-239, since it requires as little as a third of the amount of material needed for a U-235 weapon, enabling the development of nuclear warheads that are more easily carried in the nose cone of a missile or by an aircraft. In addition, reprocessing technology, which is used to separate plutonium, is easier to master.

Alpha decay: When an alpha particle (two protons and two neutrons) is emitted from an atomic nucleus, the atom is transformed into a different element. Po-210 emits alpha particles, a characteristic that can be used in the neutron initiator to trigger an atomic weapon.

Atomic bomb: A nuclear bomb using either plutonium or high-enriched uranium and relying on the principle of fission. See Gun-type nuclear device and Implosion device.

Atomic number: The number of protons in the nucleus of one atom of a given element. Uranium's atomic number is 92, and plutonium's is 94.

Atomic weight: Uranium, like many other elements, has several isotopes. Natural uranium consists of 99.27% U-238, 0.72% U-235, and 0.005% U-234. The nucleus of these isotopes are different: U-238 has 146 neutrons and 92 protons, and U-235, 143 neutrons and 92 protons. Hence their masses differ slightly. The atomic weight of natural uranium is 238.03.

Beryllium: Element used as a neutron reflector for nuclear research reactors due to its unique combination of structural, chemical, and nuclear characteristics. Intimately mixed with high-energy alpha radiation emitters such as Po-210, it has also been used to produce neutron sources. Some nuclear weapon designs have "neutron pushers" made of beryllium surrounding the fissile material core. (*See* Neutron generator.)

Boosted nuclear weapon: Enhanced design of an implosion-type atomic bomb that involves timely injection of tritium or deuterium into the center of a fissile core just after it has begun to fission. When fission begins, temperature and pressure rise, causing a fusion that releases a burst of neutrons, which speed up, or boost, the fission chain reaction. As a result fissile material is used more efficiently. A boosted atomic weapon can be several times more powerful than the types dropped on Hiroshima and Nagasaki.

Cage: The metal framework that holds the high-explosive lenses of an implosion-type atomic bomb.

Chain reaction: A self-sustaining nuclear reaction in which the energy and neutrons produced by the fission (splitting) of a U-235 or Pu-239 nucleus causes another nucleus to fission, and so on. If kept under control or "moderated," the heat resulting from the reaction can be used in a civil power reactor to produce electricity. If left uncontrolled, the result is a nuclear explosion, unless the critical mass splits apart too early and leads to a "pre-detonation" or "fizzle."

Cold test: A means of testing a nuclear bomb with nuclear material and high-explosives, but without causing a fission reaction, This is a vital part of the development of a nuclear weapon, which must be perfected without consuming difficult-to-obtain plutonium or HEU. Such a test, which is also called a subcritical test, is difficult to detect by others.

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Conversion time: The time required to convert different forms of nuclear material to metallic form and manufacture them further into the components of a nuclear bomb. If nuclear material is already in the form of a metal, the estimated conversion time is typically 7–10 days. If high-enriched uranium is in the form of UF_6 or pure uranium oxide, the time is on the order of 1 to 3 weeks.

Critical mass: The amount of fissionable material needed to achieve a self-sustaining chain reaction. A critical mass depends on several factors, including the material's shape, composition, purity, and density. By using a neutron reflector, a reaction can reach critical mass with about 11 pounds (5 kg) of nearly pure or weapons-grade Pu-239, or about 33 pounds (15 kg) of U-235.

Criticality: The point at which the neutron population in a reactor remains relatively constant, achieved by the reactor operator using control rods to absorb neutrons.

Detonator: The trigger that sets off a conventional explosive. In a gun-type atomic bomb, the detonator fires one subcritical mass of U-235 into another. In a typical implosion-type bomb, thirty-two shaped high-explosive charges are simultaneously fired, squeezing a core of U-235 or Pu-239 into a critical mass. Such simultaneous firing can be achieved by using components known as electric bridge wire or spark-gap detonators.

Dirty bomb: a device combining radioactive material and conventional high explosive, leading to contamination of an area, creating panic and terror. The radioactive material could be strontium, cesium or cobalt sources, used widely in industry and medicine.

Elevated pit: A way of suspending a fissile core within a spherical implosion device, thereby improving the implosion shockwave and ensuring a more complete fissioning of the core.

Exploding bridge wire detonator (EBW): Used to simultaneously fire multiple explosive charges. It uses a small electrical conductor (bridge, bridge wire, or foil) that explosively vaporizes when a fast, high-current electrical pulse passes through. EBWs also have applications outside nuclear weapons that require precisely timed multipoint detonations (e.g., commercial blasting in mines).

Explosive control system: The procedures for arming, fusing, and firing nuclear devices in a manner that protects the population from explosions caused by accidents or the actions of adversaries.

Explosive lenses: When detonated simultaneously, these specially shaped high explosives cause an implosion that squeezes a high-enriched uranium or plutonium core into a critical mass. The charges are shaped in interlocking patterns to form a perfect sphere. Typically, a nuclear device has thirty-two explosives lenses—twenty-two shaped as hexagons and ten as pentagons, or the basic pattern of a traditional soccer ball.

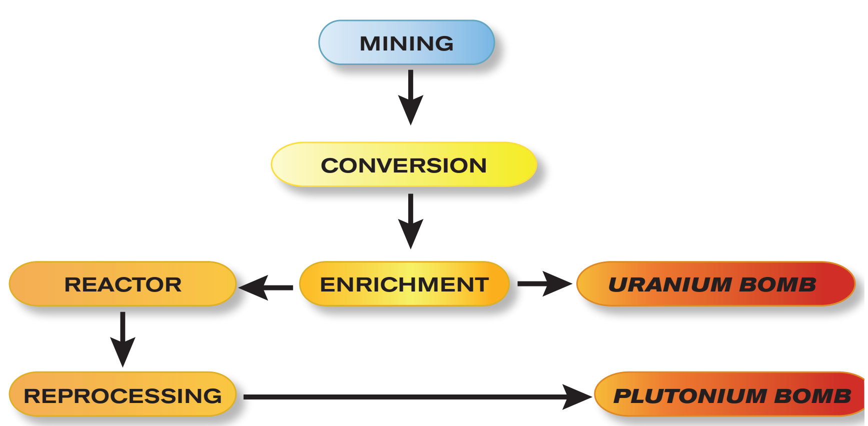

FIG. 6: Alternative routes to a nuclear weapon. Atomic bombs can use either highly-enriched uranium or plutonium as a nuclear explosive. Both can be obtained via civilian nuclear power and research programs.

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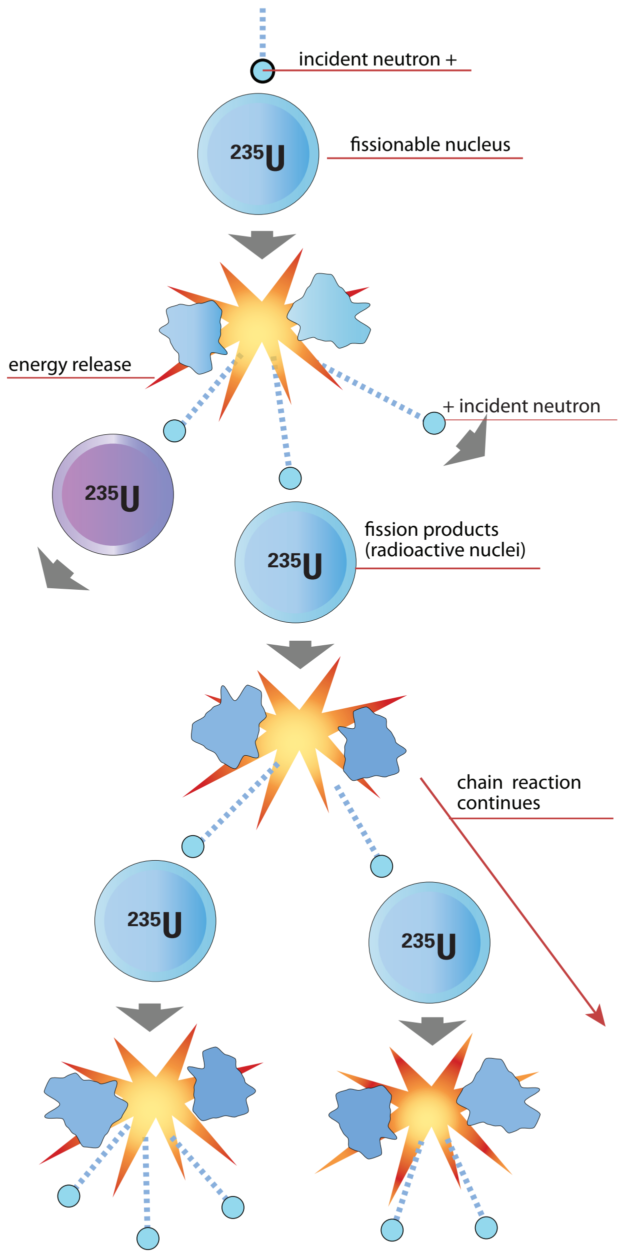

FIG. 7: Nuclear fission

Fission: A nuclear reaction or radioactive decay process in which the nucleus of an atom splits into smaller parts, often producing free neutrons and gamma rays, and releasing a very large amount of energy (fig. 7). Fissionable nuclides are U-235, U-233, and Pu-239.

Flash x-ray machine: Flash x-ray generators or pulsed electrons are used in nonnuclear hydrodynamic experiments to study the behavior of a nuclear weapon from ignition to the beginning of the chain reaction. Such experiments could consist of wrapping inert (nonfissile) material (i.e., natural uranium or tungsten) in a high explosive shell that is then detonated, replicating the effects in the core of a nuclear device. High-speed radiographic images of the implosion process are taken with the flash x-ray machine. Flash x-rays are also used to study conventional high-speed events (e.g., the use of kinetic energy penetrators, explosively formed projectiles, and shaped charges).

Flying plates: A component of an implosion-type atomic bomb. Also known as "driver plates" and "dished plates."

Fusion: Process whereby two or more atomic nuclei are combined into heavier nuclei, accompanied by the release of energy, and the principle of the hydrogen bomb, which is much more powerful than an atomic bomb. Fusion requires extremely high temperatures and pressures, achieved by using an atomic bomb at the outset.

Gun-type nuclear device: Device in which one piece of fissile uranium is fired at a fissile uranium target at the end of the weapon (similar to firing a bullet down a gun barrel), achieving critical mass when the two pieces are combined. The gun method uses uranium only; plutonium is considered impractical because of premature triggering due to Pu-240 contamination. Another reason is that plutonium samples must be brought together even faster than uranium samples to achieve critical mass.

Hemispherical shell: Component of an implosion-type atomic bomb. Two hemispherical shells cover the U-235 or Pu-239 nuclear core, serving as a reflector to bounce back neutrons from the initial stages of fission and improve the likelihood of an explosive chain reaction. The performance of the reflector depends on the materials used to form the shell and its inside coating; an effective reflector can dramatically lessen the amount of fissile material needed.

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High explosives: In an atomic bomb, these are the shaped charges used to compress high-enriched uranium or plutonium into a critical mass. Three types of explosives associated with nuclear weapons are HMX (high melting point explosive), RDX (rapid detonation explosive), and TATB (triaminotrinitrobenzene). They generate shockwaves of very high pressure, speed, and temperature. TATB is favored for nuclear weapons because it is particularly insensitive to accidental detonation.

High-speed electronic switches: High-voltage/high-current electrical switches operating at very high speeds are essential components for a nuclear weapon. The detonators that fire high-explosive implosion systems (i.e., exploding wire or exploding foil detonators) require voltages up to 20 kilovolts and draw currents from 10 to 100 kilo-amperes. Pulse neutron tubes, used to control the initiation of fission chain reactions, require voltages of 100 to 200 kilovolts and currents in the ampere range. These currents must be turned on rapidly and precisely—timing accuracies of tens to hundreds of nanoseconds are required.

High-speed streak camera: Used to photographically record fast-moving objects in a manner that allows for slow-motion playback. A normal motion picture is filmed and played back at 24 frames per second; high-speed cameras can film up to a quarter-million frames per second.

Hydrodynamic experiments: Designed to simulate the first stages of a nuclear explosion. In such experiments, high explosives are detonated to study the effects on specific materials. The term "hydrodynamic" is used because material is compressed and heated with such intensity that it begins to flow and mix like a fluid.

Hydrogen bomb: Sometimes known as a thermonuclear bomb, it relies on the concept of hydrogen fusion. It is much more powerful than a fission-based atomic bomb; in fact, a fission explosion is used to trigger a fusion bomb.

Implosion device: The method of causing a nuclear explosion by squeezing a core of U-235 or Pu-239 into a critical mass. In personal correspondence with one of the authors, Pakistani nuclear scientist A.Q. Khan described his country's implosion-type bomb in the following terms: "First the outside cover, then the cage holding lenses (explosives), then the main explosive sphere and…the steel liner, inside the steel liner the depleted uranium reflector, then the HEU core. Inside the core is a ball of about one inch diameter containing uranium deuteride as the neutron source. Between the liner and the reflector is a gap maintained by three steel studs, for acceleration of shock waves. The high explosive lenses initiate the main explosive sphere, which then squeezes the depleted uranium, which squeezes the core, which has a neutron initiator inside. The total diameter is about 850 mm (33.5 inches)."

Kiloton: A measure of the explosive power of an atomic bomb, equivalent to one thousand tons of TNT. The bomb tested at Alamogordo, New Mexico, in July 1945 was 20 kilotons. The one dropped on Hiroshima was 12 to 15 kilotons; the one dropped on Nagasaki was 20 to 22 kilotons. The destructive power of the much more powerful hydrogen bomb is rated in megatons, equivalent to millions of tons of TNT.

Megaton: A measure of the explosive power of a hydrogen bomb, equivalent to one million tons of TNT. Atomic bombs are much less powerful and are therefore rated in kilotons.

Moderator: Substance, such as graphite or heavy water, used to help control a nuclear chain reaction in a reactor.

Multiplex initiation system: a method of detonating conventional high explosive in an implosion device, compressing the fissile material core into a supercritical mass. The detonations have to be simultaneous at multiple points with a high degree of precision.

Neutron bomb: A fission-fusion thermonuclear weapon (hydrogen bomb) in which the burst of neutrons is generated by a fusion reaction. The enormous neutron radiation released kills by penetrating through thick, protective materials such

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as armor rather than relying on destructive explosive force.

Neutron initiator or neutron generator: Neutron source capable of producing a burst of neutrons, which, like the pilot of a gas stove, ignites the chain reaction at the optimal moment when the configuration is prompt critical. An internal initiator, e.g. a polonium-beryllium source or a small sphere containing deuterium and tritium, is placed in the center of the device, where it is activated by impact of the converging shock wave. Po-210 particles hit beryllium, releasing neutrons, and deuterium and tritium release neutrons though fusion. External initiators, neutron generators, are pulse neutron tubes, which work like a linear accelerator. In the tube a deuterium atom collides with tritium, generating neutrons through fusion. Other types of neutron initiators are available, such as uranium tritide or D-D accelerators. Documents show A.Q. Khan lecturing on nuclear weapons with a UD_3 initiator in the background.

Nuclear device: Term used to describe both atomic bombs and much more powerful hydrogen bombs.

Permissive action links (PALs): Safety devices built into nuclear weapons to prevent their use without permission from the designated chain of command.

Pit: American term for the fissile-material core of an implosion-type atomic bomb, named after the pit or stone in a fruit.

Polonium-210: Material used in a neutron initiator, in combination with beryllium. The materials are separated and then pushed together by a shockwave, which results in a burst of neutrons that initiates a chain reaction.

Reactor: A device where a controlled fission chain reaction can be sustained. The reactor has a specially constructed steel vessel containing nuclear fuel, usually uranium.. Depending on the design, the reactor can use uranium that is either in its natural state or enriched to contain various percentages of the fissile isotope U-235—for example, 3–5 percent (as in some power reactors), 20 percent (as in a research reactor), or much higher levels (as needed to power a nuclear submarine or aircraft carrier).

Reflector: Material or coating in an implosion-type atomic bomb that reflects neutrons back into a fissioning core, reducing the amount of fissile material needed for a critical mass. With a beryllium reflector, the critical mass of Pu-239 is reduced from 15 kg (about 31 pounds) to 4 kg (nearly 9 pounds). With U-235, the equivalent figures are 50 kg (110 pounds) and 15 kg (33 pounds). Using a natural uranium reflector, the critical mass for a U-235 implosion device is 18 kg (39 pounds).

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5| Pakistan's Development of Nuclear Weapons

Dished plates: Also known as "driver plates" or "flying plates," these shaped pieces of metal are placed on the inside of similarly shaped high-explosive charges in an implosion-type atomic bomb. In all, 32 pieces are used—22 hexagons and 10 pentagons that together make a perfect sphere, as in a traditional soccer ball. The momentum given to the plates by the detonating explosives facilitates the squeezing of the U-235 or Pu-239 nuclear core into a critical mass. When British authorities intercepted an order from Pakistan for the manufacture of such plates in the early 1980s, they were able to calculate the precise dimensions of the atomic bomb that Islamabad was trying to build, using a design supplied by China (fig. 8). U.S. authorities subsequently built a mockup of the bomb, which they showed Pakistani officials as part of their negotiations to slow or even halt the country's nuclear weapons program.

Expanding mandrel: A key component of the flow-forming and spin-forming machines used to produce centrifuge rotors with very precise inside diameters. Such mandrels grip the metal being worked on and can change their grip as the cylindrical rotors are formed. In the 1980s, British authorities confiscated an expanding mandrel that Pakistan had ordered from a British company. Rather than risk any chance of it getting to Pakistan, the Royal Navy dumped it at sea.

Ghauri: Pakistan's 800-mile-range nuclear-tipped ballistic missile, based on the North Korean Nodong missile. It is also known as the Hatf-5. North Korea has supplied the same missile to Iran, where it is known as the Shahab-3.

Inverter: Also known as a frequency changer, this component ensures that the electricity supply to a centrifuge is stable. Today, inverters are subject to international export controls. Pakistan's first orders for inverters, made in Europe in the late 1970s, initially went undetected because such devices are also used in textile mill spinning machines.

Materials and Equipment that Pakistan Sought from Overseas for its Nuclear Program

GAS CENTRIFUGE COMPONENTS
Rotors
Bellows
Top and bottom end caps

MATERIALS FOR GAS CENTRIFUGE PRODUCTION
Aluminium alloy (AISI 7075 and equivalents)
Maraging steel (all grades)

EQUIPMENT FOR GAS CENTRIFUGE PRODUCTION
Expanding mandrels for holding centrifuge rotors
Flow forming machines

COMPONENTS FOR CENTRIFUGE PLANT CONTROL
Frequency changers (inverters)

NUCLEAR EXPLOSIVE DEVICE DEVELOPMENT AND PRODUCTION
Hemispherical shells
Dished plates
(Materials may be aluminium alloy or steel)

Detonators
Detonator circuit power supplies

Neutron generator systems

High speed cameras
Flash X-ray equipment

FIG. 8: Excerpts from 1980s British intelligence document about Pakistan

Kahuta: The site of Pakistan's main uranium enrichment facility, built among hills close to the capital. Pakistan assembled its arsenal of Ghauri missiles at this site as well. The official name for Kahuta and related locations is "Dr. A.Q. Khan Research Laboratories."

Khan Research Laboratories (KRL): Shortened form of the name given to Pakistan's clandestine uranium enrichment site in 1981 by then president Muhammad Zia-ul-Haq, intended to honor Abdul Qadeer Khan, the Pakistani scientist who had worked on uranium centrifuge technology in Europe. Previously, it was called Engineering Research Laboratories (ERL) and had the military designation Project 706. Despite Khan's retirement in 2001 and televised confession of proliferation activities in 2004, the name of the facility has been retained.

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Khushab: Site of Pakistan's heavy-water production plant and 50-megawatt heavy-water reactors, which produce plutonium for compact atomic bombs. The site includes three completed reactors and a fourth still under construction. It is operated by the Pakistan Atomic Energy Commission, which in the past competed with Khan Research Laboratories to produce nuclear explosives and rival missile designs.

Nuclear weapon designs: Investigations into the A.Q. Khan network have revealed it also had detailed information on various designs of Pakistani nuclear weapons and gave some of the information to its clients. Some of this digital information included more modern designs such as the device tested by Pakistan in 1998.

P1 centrifuge: Pakistani centrifuge based on early Dutch designs designated SNOR and CNOR (short for scientific and cultivated nuclear orbital rotor), which had been developed in the initial phases of the Urenco project and used in a Dutch enrichment pilot plant in the mid-1970s.

P2 centrifuge: The Pakistani P2 is a slightly modified version of the supercritical G2 centrifuge, a German design made prior to the Urenco project and utilizing a maraging steel rotor with two segments. The A.Q. Khan network distributed detailed designs and manufacturing instructions to its clients in digital form. P2 information was, at least, proliferated to Iran, Libya and North Korea.

Urenco: A Dutch-British-German consortium established by treaty in 1970, responsible for developing centrifuge enrichment techniques intended to make low-enriched uranium for use in civil nuclear power reactors. Pakistani scientist A.Q. Khan worked for a subcontractor of the Ultra Centrifuge Nederland (UCN) during the early 1970s and became familiar with the technology and component suppliers needed to establish a centrifuge plant.

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