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The Potential Development of Nuclear Weapons Technology and Materials by Iran

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Part I: Constructing a Nuclear Arsenal

A nuclear warhead is a complex, precision assembly, dependent upon very high quality refined materials. These technological and material demands call for a sophisticated societal and industrial infrastructure capable of bringing together a diverse range of scientific and engineering knowledge, advanced means of production and the co-operation, or at least approval of other nation states.

However, the technologies of nuclear weapon design and fissile material production have not been well safeguarded by nuclear weapons capable nations over the last 40 to 50 years.[1] Indeed with the intellectual know-how needed to design and assemble a nuclear warhead now some 60 years old, the theoretical capability to produce nuclear warheads is no longer exclusive.. Moreover, this once exclusive technology has slipped through the non-proliferation safeguarding system, and is now available to those countries aspiring to nuclear weapon empowerment.

Nuclear Warheads: Physics and Mechanics

A nuclear warhead may take the form of an atomic fission device (the atomic or A-Bomb) or a hydrogen fusion device (the thermonuclear or H-Bomb).[2] The fission warhead achieves nuclear detonation by either firing together (*gun* type) or uniformly compressing (*implosion* type) a core of fissile material. This fissile material comprises either highly enriched uranium (HEU), or a core of plutonium metal. Until the moment of detonation the fissile core of the warhead is held in a subcritical spatial arrangement as two separate subcritical masses (*gun*) or as a shell assembly (usually a hollow sphere or fissile pit – *implosion*). To initiate nuclear detonation, conventional but high brisance explosive charges are fired to either propel the subcritical masses together or to uniformly compress the fissile pit down to supercritical volume, at which instance neutrons are generated within the core. In turn, these neutrons interact and generate more neutrons to seed a very rapid chain reaction, with each link of the chain liberating energy.

A number of tricks involving engineering, materials and physics are necessary to ensure that this process occurs sequentially, very rapidly and successfully. In the implosion warhead, the conventional explosive charges are arranged into a series of composite lenses facetted around the fissile core, all of which are individually triggered to produce an inward coalescing shock front to push or squeeze on the core. The fissile core itself is encased within shells of zirconium alloy, beryllium and depleted uranium which serve respectively to maintain the fissile pit geometry; contain and reflect back the soaring neutron flux; and initially, for an instant, tamp the nuclear process. Within the assembly is an initiator that, at the moment the detonation sequence occurs, provides an abundance of neutrons to boost the nuclear process.

A fusion (H-Bomb) warhead includes and is built around a fission device. Essentially, the inner primary stage (an atomic bomb) is in close proximity to a secondary stage of fusion fuel, composed of deuterium, tritium and lithium wrapped in a blanket of depleted uranium. The nuclear process commences when the conventional high

explosive lenses are detonated, starting the compression process and prompting fission of the atomic primary stage. The fissioning atoms vaporize the interior of the warhead casing, forming a very hot and dense gas (plasma) which, in turn, first compresses a plutonium spindle, causing it to fission that in turn sparks fusion in the secondary stage by transforming lithium into tritium. The tritium fuses with the deuterium, producing a great abundance of neutrons which ignite and irradiate the uranium blanket, trapping expanding fusion fuel between two blankets of exploding uranium in a fission-fusion-fission process which liberates enormous fusion/fission energy. The entire thermonuclear process of fission-fusion-fission in these two stages, and in repetitive blanket stages if incorporated in the warhead, occupies only a few hundred nanoseconds.

Nuclear Warheads: Materials

Thus, the nuclear physics package – or innards – of either a fission or fission–fusion warhead consists of a relatively simply but highly integrated assemblage of precision components. Some of these components are naturally radioactive (the fission core and the blankets) and other components are in concentrated form (the tritium). Also within the nuclear physics package are materials that are highly corrosive (lithium) and highly toxic (beryllium), and others that are unstable in chemical (the high explosive lenses), and persistently radiotoxic (plutonium) senses.[3,4]

The general consensus is that any country developing a nuclear warhead would first obtain a small arsenal of fission or A-Bombs before it gained sufficient know-how and competence to develop a thermonuclear or H-Bomb arsenal. That said, the inclusion of tritium to fusion-boost a fission warhead within a few years of becoming nuclear weapons capable should not be entirely discounted.

A single fission warhead may be constructed using 15–30 kg of highly enriched fissile uranium (HEU). This requires an enrichment plant to raise the low natural level of the fissile isotope of uranium (U-235 at 0.7%) to a very high level of concentration (> 90%) by displacing the normally non-fissile isotope U-238. Large quantities of natural uranium, in the form of milled uranium, refined to yellowcake and then converted to the gaseous state of uranium hexafluoride (UF_6), are required for this process. The depleted uranium (DU or U-238) by-product can be used as part of the fissile core of a fission nuclear warhead (A-Bomb), first to contain the nuclear process and, an instant later, contributing to the fission energy release.

To increase the yield and reliability of an A-bomb, the enriched uranium fissile core can be replaced with a few kilograms (~5kg) of highly fissile plutonium. Plutonium is produced by reprocessing natural or low-enriched uranium spent fuel that has been irradiated in a nuclear reactor. Reprocessing or chemical separation of the U-238 component of the spent fuel involves dissolving the intensely radioactive spent fuel into a solution from which a very small fraction of plutonium is extracted. Breeding and isolating plutonium requires a fuel fabrication plant, a heavily moderated (thermal) reactor, and a spent fuel reprocessing or chemical separation plant.

To advance the design of an A-bomb, the initial fissioning of the plutonium is boosted. This is achieved by introducing a spurt or abundance of neutrons to the fissile heart of the warhead, either with a small pea-sized source of radioactive polonium combined with beryllium, or by creating neutrons from fusing a few grams of radioactive tritium and deuterium (heavy water). These techniques require a nuclear reactor to generate the radioactive materials, and conventional chemical plants to isolate either the deuterium or beryllium, and to provide lithium as a source of tritium.

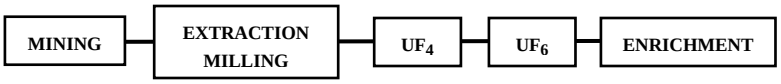
Nuclear Fuel and Weapon Materials: Dual Capability

As previously discussed, the essential fissile components of a nuclear warhead can be made from either highly enriched uranium-235 or a smaller quantity of plutonium which is rich in the plutonium-239 isotope.

For both plutonium and uranium designs, a few kilograms of depleted uranium are required to tamper and contain the early stages of detonation; a few grams of tritium–deuterium or, alternatively, polonium to initiate the nuclear sequence; some conventional beryllium in sintered ceramic form; high explosives; and, if the warhead is to include a fusion stage, a fuel pack of lithium-deuteride, a few more kilograms of plutonium or enriched uranium, and a further 20 kg or so of depleted uranium for the fusion-fission mantle. The industrial-scale procurement of these materials requires the following materials and processes:

Enriched Uranium: For a moderate yield nuclear detonation of 10 to 20 kilotons (kt) fuelled by uranium, the fissile mass at the heart of the warhead needs to comprise uranium metal enriched to a level in excess of 90% U-235. This applies to the *gun* configuration of the warhead fissile pit—it should also be possible to construct a *gun* warhead with fissile core components enriched to between 70% and 80% U-235, only with considerable loss of detonation efficiency, say perhaps achieving a 0.5 to 2.5 kt yield.

There are a number of means of enriching natural uranium to higher levels above the natural occurrence of about 0.7% U-235.[5] The primary means used for civil fuel production are cascaded gaseous diffusion and, increasingly, centrifuge plants. The uranium-bearing ore first has to be milled, processed and separated to form yellowcake (U_3O_8), and then converted into uranium hexafluoride gas (UF_6) with the intermediate stage of uranium tetrafluoride (UF_4).



The general rule is that the efficacy of the uranium enrichment process reduces at both extremes, i.e., enrichment becomes increasingly more difficult the higher the enrichment of the product and the lower the content of U-235 in the feedstock.[6] Another difficulty is that as the enrichment level rises, the stages have to be reduced in volume to avoid criticality, this generally requires that processing through the final cascade

comprising hundreds or more individual (centrifuge) stages has to be continuous and not batched.

Nevertheless, apart from the difficulties of scale of both the enrichment and the associated uranium hexafluoride feed plants, uranium enrichment to nuclear warhead levels is entirely practicable in plants designed to produce moderately low levels of enrichment for civil power station and research and development (R&D) reactors (2 to 4% and up to 20% respectively). Essentially, increasing the enrichment level is a matter of batching the process by stretching and/or recycling—at the penalty of rendering an already lengthy cycle even lengthier.[7] For example, a civil gas diffusion type plant of 5,000 stages, capable of producing, say, 500 kg of 20% enriched uranium for research reactor fuel annually, could be readily adapted to yield 25 kg or so of 90% enriched uranium per year—this is sufficient for the manufacture of a single, enriched uranium A-bomb warhead.

Depleted Uranium: Depleted uranium arises in very large quantities as a by-product of the enrichment process. All that is needed is to reduce the uranium from the uranium hexafluoride to a uranium oxide and, finally, finish this in a metalizing plant by converting it to its most dense elemental metal form.

Plutonium: Again, for a ~20 kt yield atomic warhead, a core or fissile pit containing between 3–5 kg of plutonium is required which, for an *implosion* type warhead, comprises a hollow plutonium sphere with an external diameter of about 80 mm.[8] Plutonium is produced in a nuclear reactor by the U-238 capture of a neutron. The nuclear sequence requires, first, fission of U-235 in the reactor fuel to release a neutron, capture by U-238, and transformation of this through a short-lived decay chain to the relatively stable Pu-239 with a half-life of ~24,300 years.[9] Ideally, the plutonium required for a nuclear warhead should have a very high Pu-239 content,[10] so subsequent fissioning of Pu-239 has to be inhibited by either removing the plutonium yielding fuel from the reactor at a very low burn-up and/or by constraining this fission whilst the plutonium bearing fuel remains in the active core of the reactor.[11]

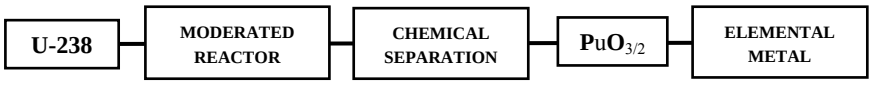
Selective fuel channel withdrawal can be achieved by using reactors that are capable of refueling whilst "on-load," such as the UK Magnox power station reactors that, in the past, contributed strongly to the UK's plutonium production program. Other reactor core configurations, such as on-load refueling, heavy water moderated reactors are also suited to maximize Pu-239 production. The second objective of constraining plutonium fissioning can be met, to a limited extent, by control of the neutron absorption window at which Pu-239 is more amenable to fission, although this is not a practical proposition in a larger electricity-generating power station in which the reactor is also utilized for plutonium breeding.

Generally, both graphite-moderated gas-cooled and heavy water-moderated reactors with on-load refueling are *dual-capable*, in that these reactors are designed (or may be adapted) for breeding plutonium as well as power production. It is these types of reactors (both research and civil power) that strongly feature in the reactor inventory of countries with nuclear weapons programs underway.

Plutonium Recovery: Unlike enriched uranium, which only requires conversion to its elemental metal form for use in a nuclear warhead, the plutonium has to be extracted from the spent reactor fuel by chemical separation or reprocessing. In brief, a reprocessing plant[12] receives irradiated and intensely radioactive fuel withdrawn from nuclear reactors, mechanically breaks down the fuel, dissolves it in nitric acid, and then sets about separating the three constituent parts of depleted uranium, plutonium and highly radioactive waste fission products, by passing the fluid mix between aqueous and solvent phases in batches. Of the three products, the fission waste is sent to storage for ultimate disposal, the depleted uranium to storage and possible re-use as fuel blend for reactors, and the plutonium recovered as an oxide powder. The processes of chemical separation cannot distinguish the various isotopes of plutonium, so plutonium extracted by reprocessing comprises the plutonium isotopic signature generated in the reactor core and is referred to as *reactor-grade* plutonium.

To form the fissile core or *pit* of a nuclear warhead, the isotopic content of the reactor-grade plutonium is radiochemically polished to remove those isotopes of high radioactivity (which would make fabricating and handling the warhead components radiologically difficult), together with those that absorb neutrons or those that fission early in the nuclear detonation sequence. This first post-reprocessing stage yields a *weapons-grade* plutonium dioxide (PuO_2) dominated by the Pu-239 isotope.[13]

The plutonium oxide is reduced to its extremely dense elemental metal form, yielding small buttons which are then cast into ingots of plutonium alloyed with a trace metal, such as gallium, to ease subsequent machining.[14] Generating, extracting and finishing the plutonium components for a warhead fissile pit therefore requires:



Development Pathway to Nuclear Weaponry

In an atomic nuclear warhead the uranium and plutonium fissile materials are highly enriched and refined, and the process of fission is achieved very rapidly for the nuclear detonation. In comparison in civil applications, notably in the fuel cores of nuclear power plants and research reactors, the process (intensity) of fission is drawn out, and the enrichment of uranium relatively modest, although the refined purity of both uranium and plutonium in civil nuclear fuel is very high.

The processes of procuring, refining and enriching these materials are much the same for both military and civil needs. It is only the level of enrichment of the U-235 fissile isotope of uranium and the degree of isotopic refinement of plutonium that distinguishes between military and civil uses. Essentially, this means that the same industrial plants can be used to isolate and process these materials, it being only the extent of processing and the controls applied that distinguishes between military and civil grades. Moreover, the larger the plant throughput capacity, it follows, the easier it is to mask a stream of weapons grade material that might be diverted from the audited output. Another

possible ruse is for a plant to produce extra quantities of civil grade materials only to later convert these stocks to military grade.

In the past, the convention has been for a country to choose whether to separate its nuclear weapons program from its civil nuclear activities, or to combine the two. For example, the United States continues to completely isolate its military and civil nuclear programs, whereas both the United Kingdom and France chose a dual-use route that sustained their military nuclear activities within their respective civil nuclear power programs until separation was required under the Nuclear Non Proliferation Treaty (NPT) of 1968.[15] Even so, some argue that separation between *safeguarded* and *unsafeguarded* plants was not entirely transparent in the UK for a decade or more following its ratification of the NPT.[16]

Israel's acquisition of its nuclear warhead arsenal developed during the 1960s – which it neither confirms nor denies under its stance of nuclear ambiguity – was entirely a military expedient with no civil power involvement. Likewise but more recently, North Korea achieved its current status as a nuclear weapons state with its test of October 2006 via a development program focused entirely on the military imperative. However, unlike Israel, throughout much of its program North Korea was confronted with quite severe sanctions and trade embargoes that aimed to impede if not entirely block the procurement of the necessary fissile and associated materials required.

In fact, throughout North Korea's period of development the effectiveness of international sanctions has eked away because of a vast black market in clandestine nuclear trade, much of which was established under the ingenuity of the former head of Pakistan's research laboratories, Abdul Qadeer Khan. This trade, perpetrated by middle men and shell companies, prospered on under-the-counter procurement techniques, false end-user certifications, as well as the transfer of detailed specifications and blueprints from one country to be manufactured in another and consigned to a third, before delivery to their final destination. Khan's involvement seems to have been central to the development of Iranian and Libyan (now abandoned) centrifuge-based uranium enrichment efforts, primarily through the provision of detailed engineering drawings, design specifications, components, and complete assemblies of Pakistan's P-1 and P-2 centrifuge models,[17] including the specifications of a nuclear warhead from Pakistan's stockpile.[18]

Therefore, countries intent on achieving nuclear weapons status might choose to adopt one of two strategies. The first is the *go-it-alone* strategy whereby, like North Korea, the requisite technologies and information are acquired and pieced together into an industrial–science based infrastructure. This fast track strategy has the risk of early discovery, running foul of the NPT and attracting immediate sanctions before a sufficiently large, stand-alone arsenal of nuclear warheads can be secured—a non-negotiable situation that now confronts North Korea.

The second strategy is for countries who have, or who are developing a civil nuclear power industry. As advanced civil nuclear technology is traded from the established nuclear civil power nations, countries developing nuclear power are striving for

independence in the fuel cycle, building up their own domestic nuclear fuel industries. These plants, including uranium conversion and enrichment facilities, research and power reactors, and reprocessing plants, are all capable, that is *dual-capable*, of producing the military grades of fissile materials required for nuclear warheads.

This second approach is sometimes referred as *smart* proliferation, a scheme by which the necessary dual-capable uranium conversion and enrichment, and/or plutonium breeding and extraction facilities are developed within the civil nuclear power limits of the NPT, until, that is, the stockpile of fission materials is sufficient to switch and upgrade to nuclear weapons use. This juncture is the *pre-breakout* point at which the proliferating country might serve its 90-day notice period required to quit the NPT, thereafter converting its fission material stocks to warheads without contravening any international agreement.[19] The time period required to switch nuclear production facilities from civil to military use is relatively short (a few years or less depending on the capacity of the plants), so any country that has the means of production and nuclear weapons know-how can pose a proliferation threat at some point in the future.

Smart proliferation, especially when coupled with clandestine international trading in knowledge, technology, parts and nuclear materials, is particularly challenging to the efficacy of the IAEA in policing such clandestine actions, particularly within the bounds of NPT intelligence and detection resources. Moreover, since the IAEA is also charged with encouraging and facilitating the peaceful use of nuclear technology, the dual-capability of nuclear programs may indeed compromise its monitoring and reporting on the military ambitions of states who aim to breakout at some future juncture.

Part II: The Shaping of Iran's Nuclear Program

Examining the history and recent development of Iran's nuclear activities provides an insight into which, if any, of these two strategies towards nuclear weapon status Iran has been pursuing. During the 1950s and 60s there was considerable cooperation between Iran and the United States, including the establishment of the Tehran Nuclear Research Centre (TNRC) in 1959, which was operated by the Atomic Energy Organization of Iran (AEOI). Cooperation with the United States continued under the US Atoms for Peace program with – in 1967 – the commissioning of a US-sourced $5MW_t$ pool-type research reactor fuelled with highly enriched uranium (HEU). This reactor remains in operation at the TNRC, but now with a moderately enriched (~20%) uranium core.

Iran signed the NPT in 1968, ratifying in 1970 and subsequently agreeing to the inspection regime of the Additional Protocol in 2003 (although this has never been formally ratified by Iran).

Iran's civil nuclear power program commenced in earnest in 1975 with a contract awarded to Kraftwerk Union to construct two 1,200 MW_e pressurized water reactors (PWRs) at Bushehr on the shores of the Arabian Gulf. At about the same time the United States entered a series of agreements and cooperation pacts that enabled the sale and transfer of nuclear technology to Iran, going so far as to offer an irradiated fuel

chemical (reprocessing) plant for the procurement of plutonium from the nuclear fuel cycle.

However, come the Islamic Revolution of 1979, Iran's nuclear ventures were halted and partially dismantled. The two nuclear power plants (NPPs) under construction at Bushehr which should have been finished and commissioned in 1981/2 were abandoned[20] with Kraftwerk withdrawing in July 1979, leaving one NPP 50% complete and the other about 80% complete. Other foreign agreements and technical cooperation programs also collapsed following the Revolution with, amongst others, France reneging on a contract to supply enriched uranium[21] and the United States withdrawing from its pledge to supply new fuel cores for the TNRC research reactor.

Since 1973 Iran's nuclear activities have been centrally organized and overseen by the government agency AEOI, although the organization has since undergone several revisions in its mission and structure since its inauguration. After the 1979 Revolution Iran faltered along an uncertain route to recover its fledgling nuclear development program, although by the mid-1980s a distinctive pattern had begun to emerge.

Structure and Organization of Iran's Nuclear Program

This pattern has been organized by the AEOI in operating numerous facilities throughout the country, including the TNRC, the Esfahan Nuclear Technology Centre (ENTC), the Nuclear Research Centre for Agriculture and Medicine (NRCAM), and the Beneficiation and Hydrometallurgical Research Centre (BHRC). Operational facilities include: uranium mines and yellowcake production in central Iran; uranium conversion and fuel fabrication at Esfahan; uranium enrichment at Natanz; operational research reactor facilities in Tehran; and a recently commissioned heavy water plant at Arak in preparation for the natural uranium fuelled, heavy water reactor now under construction at Arak. In addition, the Bushehr nuclear reactor, when completed and commissioned later this year (currently scheduled for commissioning and reactor start up in September 2007), will be Iran's first commercial-sized nuclear power plant. The locations and capabilities of the plants involved in Iran's nuclear program can be summarized as follows:[22]

Tehran Nuclear Research Centre: Founded in 1968, the TNRC facilities include a $5MW_t$ research reactor;[23] a facility for producing radioisotopes; trial production facilities for uranium yellowcake production and laboratory-scale chemical separation of plutonium from irradiated fuel—although this is now likely to have been dismantled; the Ebn-e Qasem technology laboratory—that may have been used for small-scale laser enrichment trials; and a radioactive waste handling facility. The TNRC is located in Amirabad suburb, approximately 5 km north of the centre of Tehran, with this residential suburb spreading a further 6 km to the north and 10–15 km to the east and west.

Kalaye Electric Company (a.k.a. Kala-Electric): Located in the southern suburb of Tehran, this is the alleged manufacturing and testing facility for Iran's centrifuge enrichment program, and the location of the IAEA's discovery of the presence of HEU

in its environmental samples in 2003. It is likely that all past enrichment trials at Kalaye have now been transferred to a very much larger, custom-built uranium enrichment facility at Natanz, which has been provided under the supervision and management of Kalaye Electric.

Bushehr: Following its troubled beginnings, one of the two NPPs commenced by Kraftwerk Union at Bushehr is now nearing completion and commissioning. The Bushehr contract[24] provides for the Russian Federation to provide, commission, and then supply and manage the operational spent fuel for a single PWR incorporated into the existing structures on site that were mostly completed by Kraftwerk Union before the contract was abandoned. If commissioning goes according to schedule, new, Russian-fabricated, unirradiated uranium fuel will be delivered to the Bushehr NPP in or around March 2007. The new fuel consignment will involve about 80 tU of 2–3.5% enriched PWR fuel assemblies, thereafter about 25 to 30 tU of fresh fuel will be delivered to the Bushehr site each year of its anticipated 30 to 40 years of operation. Until reactor start-up, the radiological hazard at Bushehr will be limited to the new and unirradiated uranium fuel inventory.

Following reactor start-up, the fuel in the reactor core becomes progressively more radioactive as it burns-up over the, on average, three-year cycle. The (radioactive) reactor fuel inventory in the operational reactor will, providing commissioning adheres to the scheduled program, reach its maximum level[25] at the end of year 3, say by 2010/11. Equivalent amounts of intensely radioactive irradiated (spent) fuel will be stored in a water-filled storage pool at the NPP pending return to the Russian Federation.

Arrangements for the transfer of irradiated fuel from the fuel storage pond are uncertain, but as a result of proliferation issues the European (EU-3) stance is that this fuel should be returned to the Russian Federation in batches following about 5 years of post-reactor core cooling. If fuel returns are delayed for, say fifteen years, the radioactive inventory of interim- and long-term (half-life) radionuclides in the fuel accumulating in the storage pond will exceed that of the active fuel core of the reactor.

Front-End Uranium Fuel Activities: In developing an independent domestic nuclear fuel industry Iran has established uranium ore mining, conversion and enrichment plants and facilities across the country, all linked together to provide for the ultimate enrichment of uranium. Uranium is mined, milled and processed to yellowcake stage at the sites at Gchine and Saghand (and possibly at Anarak), converted to uranium hexafluoride at Esfahan with enrichment intended at Natanz.[26] The main mining resource seems to be at Saghand, which has been under development from the early 1990s and was scheduled for completion in 2005,[27] and there is limited uranium milling currently being undertaken at Ardakan. The short-term objective of this uranium fuel cycle is to achieve annual production capacities of 11.3 tons of natural uranium dioxide (UO_2) and 34 tons of up to 5% enriched UO_2 which will require about 280 tons per annum of uranium hexafluoride (UF_6) feedstock with an initial material feed of 300 tons per annum of yellowcake. The Esfahan Nuclear Technology Center (ENTC) includes a number of related nuclear facilities including small research reactors, zirconium production

facilities, a fuel fabrication plant, and other R&D activities jointly operated with the University of Esfahan.

The main uranium enrichment activity is presently being developed at the Natanz facilities, much of which are underground. The IAEA first became aware of the scale of these enrichment facilities in February 2003, and went on to conduct a number of inspections of the site during September of that year. The facilities include a pilot fuel enrichment plant (PFEP) and a yet to be fully equipped commercial-scale enrichment facility comprising a 100,000 m^2 covered complex which has the capability to house between 30,000 and 50,000 P-2 centrifuges[28]—although, to date, Iran does not seem to have been able to build and successfully operate a P-1/P-2 line of 100 to 160 cascaded units.[29] If and when the Natanz enrichment facility becomes operational at a commercial scale – and depending on its production throughput and the degree of enrichment undertaken – the demand for uranium hexafluoride feedstock will increase markedly, perhaps outpacing the mining and reduction to yellowcake facilities to the extent that imports of ore/yellowcake may be sought by Iran.

Arak Heavy Water Production and the IR-40 Reactor: A heavy water (D_2O) production plant at a specialized facility located at Khondab, near Arak, was commissioned in mid-2006. The plant has an initial production capacity of around 8 to 10 tons per year, expanding to about 15 tons per year, for which it will require a considerable amount of electrical power (~10 MW_e). Construction of the heavy water moderated IR-40 (40 MWt) reactor[30,31] is thought to have commenced at Arak by the Mesbah Energy Company in or around 2004 and the completion date is believed to be around 2010-2012.

This type of moderated reactor will be a very efficient plutonium breeder. If plutonium production is one of its intended functions, once the reactor is commissioned and in operation the radiological sources at Arak will comprise:

- the nuclear-fuelled core of the reactor with a maximum burn-up of about 5–7 GWd/tU over a three to four year operating period;[32]
- plutonium breeding cartridges (if installed): these will be removed from the core in batches following about 3 months of irradiation exposure in the blanket sections of the reactor, and irradiated fuel and cartridges will be stored in the reactor pond;
- beyond the reactor containment building, a chemical separation (plutonium reprocessing)[33] facility which, if Iran is developing a plutonium-core warhead, would be most probably sited at Arak; and
- quantities of plutonium dioxide (PuO_2) held in storage at Arak (or possibly at Esfahan).

Radioactive Waste Management: There is a centralized radioactive waste facility capable of receipt and interim storing of low- and intermediate-level wastes[34] located at Karadj which was reported to be about 50% complete in 2003.[35] However, as of that year there seems to be no substantive regulations for waste management in Iran, including for the regulation of discharges from the nuclear power plant at Bushehr. The

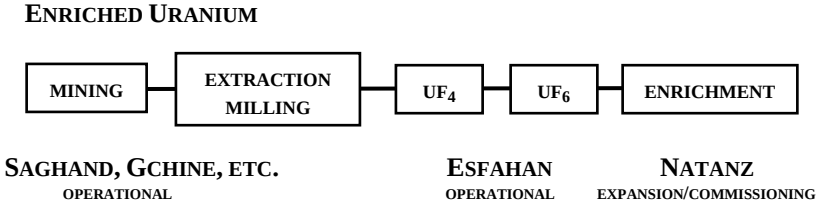
categorization of wastes and a national radioactive waste strategy, although prioritized as urgent in 2003, have yet to be published.[36]

When operational, the Bushehr NPP will be the largest single source of radioactive wastes in Iran, producing radioactive material – so it is claimed – that could be stored and/or discharged into the environment within authorized limits, although the authorized limits do not seem to have been specified (or are not publicly available) at present.[37,38,39]

Fitting Together the Nuclear Jigsaw

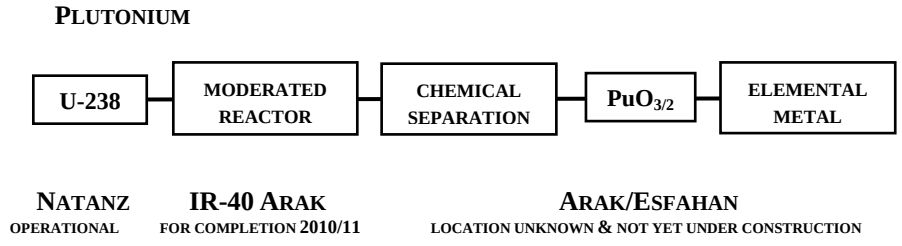
All the necessary components for a viably-sized uranium fuel program are in place with mining, ore conversion to yellowcake, production of uranium hexafluoride feed and, at Natanz, a very large facility for the actual enrichment process. When completed and operational, these various *dual-capable* facilities will knit together to provide for both civil and military fissile materials production.

First, the uranium enrichment activities are claimed by Iran to be solely to establish its capacity to produce nuclear fuel for its single (yet to be commissioned) civil electricity generating reactor at Bushehr. However, the single PWR NPP currently near completion at Bushehr would not, on its own, provide sufficient demand to commercially justify the sheer scale of Iran's ventures into the uranium enrichment and nuclear fuel manufacturing fields. The IAEA concern is that hidden within the capacity of the front-end fuel processes, especially at the Natanz enrichment plant, it could be possible to divert a sufficient stream of highly enriched uranium (HEU) to supply the HEU fissile pits for a moderately sized nuclear weapons arsenal.



Also, there seems to be a second and quite independent fissile materials acquisition program underway at Arak.[40] This will involve the heavy water, highly moderated reactor (IR-40) presently under construction which, claims Iran, is solely to support its general nuclear research and development program (including radio-isotope production) replacing the very much smaller and ageing R&D reactor at the TNRC.

Once consignments of U-238 rich fuel (or specially prepared short-burn targets) have been irradiated in the reactor, their chemical separation provides for the extraction of highly fissile plutonium for the fissile pit of a compression-type nuclear warhead.



Although the Bushehr PWR will be generally unsuited for breeding the high quality grade of plutonium required for a reliable warhead, the international community is, nevertheless, insisting that all future fuel cores (as well as the spent fuel) for Bushehr be provided and managed by the Russian Federation as a safeguards requirement.

Progress of Iran's Program to Date

The inspection and reporting activities of the IAEA from the 1990s provide an insight into the development of Iran's nuclear program. For example, IAEA inspectors visited Iran's uranium mines in 1992; there was IAEA involvement in securing safeguards in the deal with the Russian Federation to complete one of the abandoned Kraftwerk PWR NPPs at Bushehr in 1995;[41] and in 1996 there was reported IAEA unease when Iran contracted the People's Republic of China to supply a gaseous conversion plant to produce the uranium hexafluoride feedstock (at Esfahan) for uranium enrichment.

In 2003 a significant international spat was caused when the IAEA reported on its finding of 36% enriched uranium particles of types which were not then declared in Iran's safeguarded inventory;[42] between 1991 and 2000 Iran had run a laser enrichment program, in the course of which it had used 30 kg of uranium metal not previously declared to the Agency; and between 1988 and 1992 it had irradiated 7 kg of UO_2 targets and extracted small quantities of plutonium.

After the Kalaye HEU discovery (2003) the IAEA adopted a much more strenuous and examining approach to Iran's nuclear activities but it has, in the opinion of some, still failed to uncover substantive evidence of a nuclear weapons program. Even so, the IAEA believes that it has proven, albeit much in hindsight, that Iran's nuclear development has been dominated by the military imperative. This is quite contrary to Iran's claim that, at least until 2000 or thereabouts, the development of uranium enrichment was entirely restricted to achieving its independence in the civil nuclear power fuel cycle.[43]

In its report of February 2006,[44] the IAEA detailed what it considered to be a number of non-compliances with the NPT and the Additional Protocol,[45] referring to:

- Iran's procurement of P-1 centrifuge technology and hardware dating from 1987;

- acquisition of P-2 centrifuge technology for which it received detailed engineering drawings and specifications for P-2 components in 1995 and, thereafter, development work being carried out in 2002–2003;
- the construction of the heavy water research reactor (IR-40) at Arak which Iran had been asked to reconsider in the IAEA resolution[46] noted in its previous report;[47]
- the fact that the source of the irradiated uranium used in the plutonium separation trials could have been derived from sources other than those declared by Iran;[48]
- trials producing the radioisotope polonium previously reported by the IAEA;[49] and
- Iran's possession of a document related to the procedural requirements for the reduction of UF_6 to metal in small quantities, and on the casting and machining of enriched, natural and depleted uranium metal into hemispherical forms.[50]

The IAEA has presented "evidence" that Iran has ventured outside what the IAEA considers would be necessary to support a civil nuclear power program, giving examples of finds, albeit in minute quantities, of highly enriched uranium and plutonium, the development of multiple cascade centrifuge technology, and the ability of Iran to generate and isolate fission initiating substances such as polonium. Iran argues that there is no substantive evidence of a nuclear weapons program but, even so, what seems to trouble the IAEA is the scale and persistence of Iran's nuclear venture, going so far as to report in 2006 its conclusion that it "did not fully understand the twenty years of undeclared nuclear activities undertaken by Iran."[51]

The self-evident conclusion to be drawn from the IAEA's assertions about uranium enrichment to very high levels is that Iran is progressing towards a nuclear arsenal of gun-type, highly enriched uranium-cored geometry. However, during the last five or so years, Iran's nuclear program has diversified to include a capability to produce sufficient heavy water moderator for a 40 MW_t research and development reactor (IR-40) now under construction and due for commissioning in 2010/11. Iran claims that this heavy water moderated reactor is intended to be used for the production of medical and industrial radioisotopes but the reactor will also be capable of producing not insignificant quantities of fissile plutonium which, if it so desires, would enable Iran to venture along the route of acquiring a plutonium-cored nuclear weapons arsenal, like North Korea.

This apparent late conversion to, or adoption of, a plutonium warhead strategy may be the result of difficulties experienced in operating a sufficient number of centrifuges in cascade in the now parallel uranium enrichment program at Natanz. Building the heavy water plant and IR-40 reactor at Arak, together with the development of chemical separation (reprocessing) capabilities for extracting the plutonium, may be seen as a surer and quicker route than procuring and setting the several thousands of centrifuges required for uranium enrichment to HEU.

Breaking Out of the NPT

None of the evidence produced by the IAEA so far demonstrates that Iran has achieved a nuclear weapons capability. Indeed, and more to the point, reading between the lines suggests that Iran has encountered considerable technical and logistical difficulties and setbacks in its endeavors to establish itself as a nuclear power in the region.

In terms of being an emergent *civil* nuclear power, it remains wholly dependent upon the Russian Federation for the completion and commissioning of the single, electricity generating PWR at Bushehr. When completed, it is not at all certain that Iran will be capable of competently operating the power plant without continuing dependence upon the Russian Federation, particularly now that international sanctions have been applied because of suspicions over its military nuclear activities. The present technical difficulties at Natanz – including the slow rate of manufacturing and assembling of centrifuge units, the reliability of the individual centrifuges and the problems associated with operating these in meaningfully-sized cascades – seem to be such that it is unlikely that Iran possesses the wherewithal to enrich uranium in sufficient quantities up to a level suitable for use in the Bushehr PWR plant and certainly not up to the 20%+ level required for a fuel core recharge of the small Tehran research reactor.

Much the same applies to the alleged nuclear weapons development program, which would seem to be marooned in its HEU enrichment strand, particularly in developing multi-centrifuge P-2 production.[52] Similarly, there must now be considerable doubt that Iran will be able to finalize and commission the IR-40 reactor and put in place a fuel reprocessing plant to enable it to proceed with the plutonium compression type warhead strand by 2010–11.

So, if as it is claimed by the protagonists voicing against Iran, a nuclear weapons program is underway this, in itself, seems to have failed to run to its own intended timelines. That said, it is not clear whether this (and most probably future) slippage has been the result of Iran's clandestine nuclear activities being rumbled by the IAEA and/or by the withdrawal of technological assistance from a surreptitious partner or, perhaps, by increasingly tighter restrictions being placed internationally on the transfer of dual-capable nuclear plants and technology to Iran.

Regardless, if Iran's intention has been to pursue a smart proliferation strategy before breaking-out from the constraints of the NPT, then in this it has failed. Now, with the recently declared (December 2006) United Nations Security Council sanctions[53] in place and, providing Iran is unable to elicit hidden technological and manufacturing assistance from some international partner, its procurement of both HEU and weapons grade plutonium fissile materials will be subject to close international scrutiny, as well as impeded by sanctions.

If Iran's HEU program had progressed according to plan the breakout year would possibly have been 2007/8. Now – and if the UN sanctions are effective – that HEU breakout date is unachievable, so the expectation is that Iran will shift emphasis to its second proliferation strand based on plutonium. For this, and assuming Iran can, on a go-it-alone basis, overcome the considerable technological difficulties of scaling up its

past laboratory-sized plutonium separation trials, the next breakout year might be around 2011/12.

Part III: Conclusions

Civil or Military Program?

Iran claims that it is its inalienable right to develop and operate its own uranium enrichment facilities for civil nuclear power applications. It claims that its present industrial-scale uranium enrichment operations at Esfahan and Natanz are solely in support of its desire to fabricate moderately enriched uranium (2–5% U-235) and that these facilities are not involved in enrichment to nuclear warhead levels (>90% U-235). Similarly, it argues that the recently commissioned heavy water plant and IR-40 reactor under construction at Arak are solely for its future nuclear R&D which will also provide radio-isotopic production to replace the limited capacity of the ageing Tehran reactor.

The IAEA claims otherwise, presenting evidence and its conclusions that Iran's nuclear activities are aimed at acquiring sufficient quantities of fissile materials – very certainly HEU and possibly in a few years' time plutonium-239 – in sufficient quantities to provide it with a modest nuclear warhead arsenal. It has shown that, particularly over this past decade, there has been an ongoing nuclear R&D program extending beyond that normally expected in support of a civil nuclear interest, including laboratory-scale trials in high levels of enrichment, separation of plutonium, and the procurement of radioactive materials essential for triggering a nuclear device.

In December 2006, the United Nations Security Council unanimously concurred with the IAEA, agreeing to apply a series of sanctions forthwith. The sanctions are detailed in Resolution 1737[54] which, essentially, calls for:[55]

- suspension of all enrichment and reprocessing activities, including research and development in these areas;
- suspension of all heavy-water projects, including the construction of the IR-40 reactor at Arak;

and for all States of the international community take necessary measures to

- prevention of the supply, sale or transfer directly or indirectly of all items or materials, goods, equipment, etc., that could be of use or benefit to Iran's enrichment, reprocessing or heavy-water related activities, or the development of nuclear weapon delivery systems, thereby restricting the transfer of nuclear technology and materials to Iran.

Iran's Present State of Preparation

All of the evidence suggests that Iran now has sufficient confidence in its knowledge of warhead design – both *gun* and *implosion* types – to move forward and acquire the

necessary fissile materials for their construction. Unlike other countries that have recently developed a nuclear weapons capability by confining their effort to a single warhead type (i.e., Pakistan: HEU/*gun*; and North Korea: plutonium/*implosion*), the IAEA evidence and the nature of the UN sanctions strongly suggest that Iran has been developing both *gun* and *implosion* warhead strands simultaneously.

However, in terms of HEU enrichment Iran seems to have encountered considerable difficulties in transferring the necessary technology from laboratory-scale tests to the industrialized process required to procure even a few kilograms of HEU per annum, with the enrichment processes at Natanz being held back by the lack of progress in building centrifuge cascades of the number and complexity necessary. It is not certain why Iran has run into this apparent difficulty, although it may be a result of a number of factors, including the break up of the A.Q. Khan network; the withdrawal of overseas technology transfer in light of the developing IAEA concerns from 2002; and, quite possibly, a lack of the experience and knowledge required to organize and meet the demanding quality assurance and production demands of an industrial-scale enrichment program, including the manufacture, assembly and commissioning up to or more than 100 centrifuge units per year.[56]

The IR-40 reactor at Arak, scheduled for completion in 2010/11, may also encounter similar difficulties and delays because it is a unique hi-tech venture for Iran. Progressing from the few milligrams of plutonium known to have been separated to the kilogram quantities required for each implosion type warhead may present technological and quality assurance challenges, thereby introducing further delays before Iran is able to confidently breakout of its NPT commitments.

Iran's two-stranded approach to acquiring nuclear weapons, as alleged by the IAEA and accepted as fact by the UN Security Council, seems to have been uncovered before it has sufficiently advanced to warrant a breakout from the NPT. However, while international sanctions may set back progress, they are unlikely to entirely prevent a determined government proceeding along a route to becoming a nuclear weapons power at some future date.

International Sanctions: Associated Radiological Risks

Military Dimension: The application of UN sanctions signifies that the international community has recognized that Iran could pose – at some time in the near future – a nuclear threat. This threat might be construed to be either locally within the region, or globally via delivery by advanced ballistic missiles and/or, indirectly, by transfer of the technology or hardware to a sub-national entity.[57, 58]

Putting aside the complex geopolitical reasoning that might be applied in justifying or, possibly, deterring such military action, the most obvious objective would be to halt Iran's progress on the route to nuclear weapons acquisition. In such circumstances key elements of both the enrichment and plutonium strands might be targeted, perhaps focusing on the Natanz and Arak facilities. Striking Natanz would have little radiological significance beyond the locality of the facility, perhaps spreading no more

than a few kilometers downwind. Striking the Arak heavy water plant and yet-to-be completed IR-40 reactor would have no radiological outcome.

However, if a punitive strike was made against the NPP at Bushehr – even though the Bushehr nuclear power plant would be of little significance to an Iranian military program – the state of the reactor fuelling and operation would be critical to the potential radiological consequences.[59] Key dates are around March 2007 when the first consignments of new (unirradiated) uranium fuel are scheduled to be received at the plant, and from around September 2007 when the reactor is due to become critical.[60]

Until reactor start-up the radiological hazard at Bushehr will be limited to the new fuel inventory (of a minimal radiological risk). Once the reactor is operational, the reactor fuel (radioactive) inventory will reach its maximum[61] at the end of year 3 or 4, say by 2010/11, at which point – and continuing thereafter – the potential radiological consequences will be at their maximum. Arrangements for the transfer of irradiated fuel from the fuel storage pond are uncertain, although because of proliferation issues the European Union stance is that this fuel should be returned to the Russian Federation in batches following about 5 years of post-core cooling. If fuel returns are delayed for, say fifteen years, the radioactive inventory of interim- and long-term (half life) radionuclides in the fuel accumulating in the storage pond will exceed that of the active fuel core of the reactor.

A number of assessments have been published on the potential consequences of a ~1,000 MW_e PWR reactor incident involving a release of the radioactive products of the reactor core. One such study[62] predicts that about one-thousandth of the total core activity being released over a 4 hour period would result in 1,680 fatal cancers in the short term dispersed over a land area of about 1,500km^2 (within a few weeks and months) and 14,400 fatalities in the longer term (over the remaining lifetime of those exposed).[63] Of course, it is not at all reliable to superimpose analysis undertaken for a NPP located in one region onto one in another because quite different consequence-significant parameters of climate, population habits and lifestyles, demography, etc., will apply. That said, this and other assessments of the radiological impact of an untoward radioactive release from a commercially-sized nuclear power plant indicate the scale of the consequences that could arise in the region.

When applied to the Gulf region, the radiological aftermath of an extreme radioactive release at Bushehr – either as the direct result of a military strike or a severely damaging accident – resulting in the dispersal of a radioactive plume downwind could require rapid implementation of population protection measures (sheltering and evacuation); restrictions applied to the distribution of food; closure of water desalination plants; and interim-term decontamination of tracts of land and the built-environment, in part or throughout the United Arab Emirates territories. Appendix 3 outlines the potential radiological consequences of military strikes on a number (but not all) of the nuclear sites in Iran.

Nuclear Safety: As sanctions will halt, or at least impede the transfer of knowledge, information and safety systems, they might affect the safety of Iran's uranium

enrichment and heavy water related undertakings. Even though the Security Council sanctions specifically exclude and allow for information and technology transfer relating to the Bushehr NPP nearing commissioning, the dual-capability of the other projects will practicably result in a starvation of information, education and joint ventures between Iran and the wider international nuclear community.

The irony here is that perhaps the culture essential to maintaining nuclear safety will be left wanting, which with the impending commissioning of the largest radioactive source term in the region at Bushehr, might result in an untoward release of radioactivity accompanied by intolerable health and economic impacts across the region.

Appendices

Appendix 1

Key Dates in Iran's Nuclear Program

DATE	ACTIVITY	DUAL ROLE	IAEA/POLITICAL ACTION, ETC
1967	United States installs Tehran research reactor		
1970			Iran Ratifies NPT
1975	Kraftwerk signs contract for two PWRs at Bushehr		
1979/82	Construction of Bushehr PWR units successively abandoned		
1985	Iran commences nuclear warhead development activities		
1988-92	Laboratory quantities of plutonium-239 extracted	✓	
1991	Iran procures 1,800kg of uranium yellowcake from China	✓	
1993	Samples of polonium-210 are irradiated and extracted	✓	
1995	Russian Federation contracted to complete one of the Bushehr PWRs		
1996	China supplies UF_6 plant at Esfahan	✓	
2002			**Aug** National Council of Resistance opposition group exposes extent of Iran's nuclear program
2003	IAEA Environmental sampling at Natanz detects two types of HEU		**Feb** IAEA visits Natanz enrichment plant **Aug** IAEA reports HEU discovery at Natanz **Sep** IAEA calls for Iran to cooperate fully regarding past activities **Oct** Iran agrees with EU-3 to resolve past safeguards violations and suspend enrichment and reprocessing activities **Dec** Iran signs but does not ratify the NPT Additional Protocol
2004	UF_6 conversion of 37t uranium commences at Esfahan in September IR-40 reactor construction commences at Arak	✓ ✓	**Jun** IAEA resolution deplores Iran's continuing non-compliance **Sep** IAEA calls for suspension of nuclear activities and threatens to refer Iran to the UN Security Council **Nov** Iran agrees to restore full suspension of enrichment and reprocessing activities
2005			**Jun** Presidential elections put President Ahmadinejad in power **Sep** Ahmadinejad confronts World Summit
2006	UF_6 conversion recommenced at Esfahan Uranium enrichment preparations recommence at Natanz Heavy water plant at Arak commissioned into operation	✓ ✓ ✓	**Mar** Russia proposes limited concession for Iran to undertake small-scale enrichment **Apr** IAEA gives Iran 30 days (28 April) to comply and suspend enrichment activities, IR-40 reactor construction and ratify the Additional Protocol—Iran continues with enrichment and IR-40 construction **Dec** UN Security Council agrees to take

			sanctions measures against Iran

Appendix 2

Nomenclature

brisance: The measure of rapidity with which an explosive develops to its maximum pressure (with a high brisance indicating a fast explosive). By careful selection of levels of brisance (slow, medium, fast), lenses of explosive can be shaped to direct or coalesce the detonation pressure wave.

burn-up: The level of irradiation (by neutrons) of the fuel, measured in GWd/tU (Giga Watt day per ton of uranium).

cascade: An assemblage or train of individual centrifuge units coupled together so that the following centrifuge receives the slightly enriched U-235 output of the preceding centrifuge.

critical mass: The critical mass of fissile material is the amount needed for a sustained nuclear chain reaction wherein the neutrons released in each fission are just sufficient to maintain *criticality* or the chain reaction. The critical mass of a fissionable material depends upon its nuclear properties and physical properties (in particular its density), its shape, and its enrichment or isotopic purity. Surrounding fissionable material by a neutron reflector such as beryllium or tungsten carbide reduces the needed mass. *Subcritical* is a state wherein there is an inability to sustain a fission or chain reaction and *supercritical* is a situation wherein there is an increasing rate of fission.

delta-phase plutonium: Plutonium undergoes a number of metallurgical phase states (ie crystal structure) when heated. Use of moderate density (16.9 $g.cm^3$) *d-phase plutonium* for the fissile pit components is important because, first, this phase readily alloys with traces of gallium or indium which improve stability and malleability and, second, during the compression stage of nuclear detonation, the d-phase undergoes a rapid transition to the denser (19.2 $g.cm^3$) *α-phase* increasing the reactivity insertion for nuclear criticality.

EU-3: The team of France, Germany and the United Kingdom negotiating with Iran to resolve the outstanding difficulties with the IAEA.

fissile: A fissile element is capable of *fission*, that is the splitting of the (usually) uranium atom into parts by collision with a neutron which releases fission products and further neutrons, thereby creating a chain reaction—each fission event releases energy which can be dissipated as heat to raise steam and power turbines to generate electricity.

fusion: The fusing together of light atoms, hydrogen in the deuterium-tritium fusion reaction which liberates energy—tremendous levels of energy are required to establish and maintain conditions conducive to successful fusion so, in a H-Bomb, fusion is induced by the first stage atomic (fission) nuclear detonation.

gun type: The simplest technique for assembling a supercritical mass, achieved by shooting one piece of fissile material as a projectile against a second piece as a target, which, when combined, produce a critical mass. Because of the relatively long amount of time it takes to combine the materials, this method of combination can only be used practically for U-235—predetonation is likely when using Pu-239 which has a higher spontaneous neutron release due to Pu-240 contamination.

GBq/m^3: Giga Becquerel per cubic meter, where Giga is x10^9 or one thousand million disintegrations of Becquerel (Bq)—this is a specific radioactivity used to define the radioactivity of substances—in this case radioactive waste.

See also *TBq* where *T* is tera or x10^{12}

GWd/tU: The amount of energy extracted from the fuel in terms of Giga-Watt days per tonne Uranium which is a measure of the amount of electrical energy (GWd in x10^9 Watt-day) generated from per tonne of uranium fuel (tU) – this is the extent of irradiation of the fuel, sometimes referred to as *burn-up*

Half-life: The half-life is the amount of time it takes for the radioactivity of an element to decay to one-half half of its (radio)activity. The half-life for a given isotope is always the same at whatever state of decay it is at. For example, the half-life of beryllium-11 is 13.81 seconds, so commencing with a mass of 16 grams of Be-11 after 13.81 seconds the mass of Be-11 will have decayed to 8g, in another 13.81 seconds the Be-11 mass would have decayed to 4g, then 13.81 seconds later to 2g, then 1g, 0.5g and so on.

Radioactive half-lives range from fractions of a second, seconds (oxygen-22 at 2.25 seconds) to thousands (plutonium-239 at 24,400 years) to millions of years (Uranium-235 at 704 million years)

HF_6: Uranium hexafluoride is a gaseous stage required for the enrichment process.

implosion type: The compressing process where a hollow sphere of subcritical plutonium-239 is externally compressed by conventional high explosive lenses to a supercritical size to achieve a nuclear detonation.

kt: Kiloton or 1000 tons equivalent of TNT explosive energy, generally used as a crude measure of the power of a nuclear detonation.

LEU: low-enriched uranium that has been enriched with the fissile U-235 isotope over and above the natural level of ~0.7% and usually adopted when referring to uranium enriched up to 4–5% for use in commercial power nuclear reactors, compared to *HEU* or highly enriched uranium which is adopted for levels of greater than 60% U-235 enrichment (with U-235 enrichment at greater than 90% being referred to as *weapons-grade HEU*).

moderated: A *moderated* reactor is one in which the neutrons released in the chain reaction are slowed in a moderator from fast to slow or thermal velocity, thereby

increasing the chance of fission and capture in the fertile U-238—resulting in greater production of plutonium. Effective moderator materials are graphite and heavy water.

MW_e: Expression of power usually adopted to define the electricity generating capacity of a nuclear power or electricity generating plant, expressed in electrical units generated (e). In terms of the steam cycle, to generate electricity about two-thirds of the total thermal energy produced is dissipated to the environment, so the plant capacity expressed in electrical units is about one-third the heat or thermal rating of the same plant, i.e. a 1000 MW_e plant is roughly equivalent to a 3000 MW_t plant.

MW_t: Expression of power capacity expressed as Mega (million) Watts of thermal (t) energy.

nanosecond: one thousandth millionth of a second, ie $x10^{-9}$ second.

NPP: Nuclear power plant.

pool reactor: Typically a low powered research and development reactor where the reactor operates at a low pressure and is immersed in a calandria tank of water which acts as radiation shielding and a low level heat exchange to dissipate the thermal energy produced as a by-product of nuclear fission underway in the reactor core.

radioactivity: Overall, the various processes by which unstable atomic nuclei emit sub-atomic particles (radiation). Decay occurs in the *parent nucleus* and produces a *daughter nucleus*. The unit for measuring radioactivity is the *Becquerel* (Bq). If a quantity of radioactive material produces one decay event per second, it has an activity of one Bq. Since any reasonably-sized sample of radioactive material contains many atoms, one Becquerel is a tiny level of activity; numbers expressed in *gigabecquerels* are seen commonly. For example the *curie* (Ci), which was originally defined as the radioactivity of one gram of pure radium, is 37 *gigabecquerels* (GBq).

safeguarded: a process, plant or materials store that is safeguarded under the terms of the NPT. This is usually undertaken by inspection and physical accountancy (measuring and auditing of material stocks, equipment and plant capacities, etc) by IAEA personnel.

source term: The total about of radioactivity which, in this case, refers to the radioactivity of the fuel core of the Bushehr reactor which will change (increase) as the fuel is irradiated or burnt-up within the reactor core. The source term is the total amount of radioactivity available for release in an accident or incident in which the reactor containment (enclosure) is bypassed or damaged from which radioactivity is released – the amount or fraction of radioactivity released is referred to as the Release Fraction.

tritium: Tritium (^3H) occurs naturally (due to cosmic rays interacting with the atmosphere) and it is also produced in the nuclear reaction process when deuterium captures a neutron, with a half-life of 12.3 years. Used in nuclear weapons tritium

provides the source initiation in a fission bomb by producing an abundance of neutrons from its fusing during the late compression stage and it can be used to predetermine the yield of the weapon (ie *dial a yield*). In earlier fusion bomb designs tritium was used as the fusion fuel, although this is now commonly replaced with lithium.

tU: Tons of uranium—neglects the weight of the fuel assembly grids and braces, etc.

U-235: The fissile isotope of uranium which naturally occurs at levels of about 0.7% compared to the fertile U-238 which makes up most of the remainder of naturally occurring and abundant uranium.

UO_2: Uranium dioxide is the form of most commercial nuclear reactor fuel which is sintered into fuel pellets.

yellowcake or *urania*: The first concentrate of the process of mining and milling uranium-bearing ore, mainly comprising the oxide U_3O_8 (triuranium octaoxide) which is the precipitate of leaching the uranium-bearing ore by acid.

Appendix 3

Potential Consequences of Military Strikes and Accidents

NUCLEAR FACILITY	TIME WINDOW/FUNCTION	IMPACT
Tehran 5 MW_t reactor	Small R&D pool reactor, introduced 20% enriched uranium core, 1960s containment design	Relatively small source term but radiological impact mainly determined by location in residential area of Tehran. Low energy core so accident-related dispersion energy relatively low but military strike could result in high energy (lofted plume) release and higher consequences—risk of potable water supply and watercourse contamination.
Bushehr PWR NPP	Nuclear fuel to be delivered to site in March 2007	Strike before March 2007 results in no radiological impact.
	Reactor start-up expected September/November 2007	Strike between March and start-up in September 2007 results in minimal radiological impact, comprising unirradiated uranium fuel dispersion. This is because the reactor fuel core has not been irradiated and so the radioactive source term is that of the low enriched uranium without any significant fission products content.
	Post reactor start-up	Increasing potential radiological consequences following reactor start-up to a maximum at about year 3 to 4 when reactor radioactive inventory is at a maximum – significant radioactive inventory begins to accumulate in water cooling pond irradiated fuel, depending on arrangements to return the irradiated fuel to the Russian Federation – radiological consequences could spread beyond Iran's territory and include Gulf states and restrict shipping movements through the Arabian Gulf.
Arak $\underline{D_2O}$ plant	Continuous from 2006 (possibly not fully operational)	Strike prior to IR-40 reactor start-up (~2010) disrupts accumulation of stocks of heavy water production, delays start-up of IR-40 reactor. Strike after reactor start-up may sufficiently disrupt heavy water supplies for reactor annual replenishment (up to 8 tons $\underline{\mathbf{D_2O}}$ per year).
Arak IR-40 reactor	Scheduled commission/ start-up in 2010–2011	Strike prior to reactor commissioning will have no significant radiological impact—UN sanctions likely to significantly delay completion of construction and equipping, commissioning most probably will be set back considerably.
Arak plutonium chemical separation	From reactor commissioning + 3 to 6 months to receipt of first fuel batches	Assumed, yet to be built at Arak – if built, most probably a batch plant dealing with a few kilograms of irradiated fuel – no significant impact until batch reprocessing commences then downwind contamination and longer term (lifetime) health consequences could be significant.
Natanz	Continuous: enrichment facilities, apparently located underground within earthed, bunded bunker but not believed to be operational at anything other than prototype trial stage	Structural damage to underground centrifuge halls, disruption of power supplies. Uranium contamination and general toxicity risk associated with uranium and, particularly, UF_6 airborne dispersal and reaction into uranyl fluoride (UO_2F_2) and hydrogen fluoride (HF)—radiological impact limited to workforce and immediate local population from uranium dispersion and uranium hexafluoride release and contamination.
Esfahan	Continuous: operational UF_6 plant – main human resource in Iran's nuclear program	Disruption of UF_6 conversion—uranium contamination and general toxicity risk associated with uranium and, particularly, UF_6 airborne dispersal and reaction into uranyl fluoride (UO_2F_2) and hydrogen fluoride (HF). Could also result in a release of other sources of radioactivity at Esfahan. Military strike could have significant impact on human scientific and

		engineering resources.

About the Author

John Large is the Chief Executive of Large & Associates, a company of consulting engineers based in London that specializes in the nuclear field. He is a Chartered Engineer, a Fellow of the Institution of Mechanical Engineers, a member of the Institution of Civil Engineers, a member of the British Nuclear Energy Society and a Fellow of the Royal Society of Arts.

Prior to founding Large & Associates, from the late 1960s through to the early 1990s, John Large was a full time member of the research and teaching academic staff of Brunel University, where he undertook research for the United Kingdom Atomic Energy Authority (UKAEA) on reactor systems, high temperature reactor fuel, moderator core coolant flows and aspects of other nuclear topics and devices.

For Large & Associates he has presented evidence to the UK parliament select committees on Environment and Energy, given evidence at the Court of Human Rights in Strasbourg on the dose exposure to HM services personnel exposed during the Christmas Island nuclear tests, and been involved in investigating nuclear weapons programs in South Africa, Taiwan and, most recently, Korea. John Large was personally responsible for selecting and heading up the team of specialists, engineers and scientists that undertook the nuclear and radiological assessments of the reactors and weapons systems on board the sunken submarine *Kursk* throughout the world-first salvage operation of 2001, being awarded a commemorative medal for his contribution from the authorities of the Russian Federation.

Notes

[1] Nuclear weapons were developed by the United States in the 1940s, first being used in anger against the Japanese at Hiroshima and Nagasaki in August 1945. The Soviet Union commenced its nuclear bomb program shortly after the cessation of World War II hostilities, detonating its first atomic bomb in August 1949. Britain followed with its first atomic test in 1952 (then France in 1960 and China in 1964). Proliferation of nuclear weaponry spread to India with its "peaceful" nuclear explosion of 1974, Pakistan in 1998 and, most recently, North Korea in 2006. South Africa was believed to be nuclear capable and may have conducted a nuclear weapons test jointly with Israel in the late 1970s, but it dismantled its nuclear warheads in 1990.

[2] For an explanation of the specialized jargon refer to Appendix 2: Nomenclature.

[3] Because of its long radioactive half-life (24,300 years), plutonium remains a hazard for something like half a million years. Unlike chemical or biological hazards, plutonium is essentially impossible to destroy (except by irradiation in a fast-breeder reactor). The chief hazard from plutonium derives from the alpha particles emitted during its slow but steady radioactive decay. The combined physical properties of alpha particles (large mass and diameter, double positive charge) emitted by plutonium cause large amounts of energy to be transmitted from the alpha particles to living tissues when the particles travel through human or animal bodies, and until the particles are absorbed. Typically over 100,000 ionizations of atoms and molecules might be caused by one alpha particle. Each such ionization absorbs about 35 electron volts (eV) of energy from the alpha particle and results in electrons being released from some molecules in the living tissues and leaving behind positively charged atoms (radicals). This process causes changes in the chemical structure in the area of the ionizations. Cells within about 10 microns of a plutonium-dioxide particle will be killed by this ionizing radiation, whilst cells from 10 microns to 50 microns away are

likely to have their genetic materials changed. Such changed cells are potential cancer cells. Cells that are not killed by the radiation may have various end results depending on how well or poorly the DNA is repaired and what sort of cell has been affected. The cells may become cancerous, weaken the body against infection (e.g., in the lymph nodes) or, in reproductive organs, cause birth defects. The alpha particles emitted by plutonium atoms which have lodged in bone (especially in the areas of the periosteum, endosteum and trabeculae) attack the radio-sensitive haematopoietic tissue in the bone marrow, leading to a reduction in the number of red blood corpuscles and serious effects on the body.

4 Large J.H., *Transportation of Nuclear Weapons through Urban Areas In the United Kingdom*, National Steering Committee of Nuclear Free Local Authorities, Manchester, United Kingdom, January 1990.

5 All of these uranium enrichment techniques rely on the physical fact that the velocities of molecules of different mass differ, and that the minuscule difference between U-235 and U-238 gives the U-235 a slightly higher velocity, kinetic energy and, hence, pressure. This is used to differentiate and separate molecules either by diffusing these through a membrane (diffusion), skimming the outer layer of a rapidly rotating mix (centrifuge and vortex—but the latter has now generally fallen into commercial disuse because of the very high energy consumption involved), or by targeting the higher velocity molecules of a distended jet. Since the enrichment gain produced by a single separation is very slight, a very large number of separations (hundreds and thousands with, as a result, enrichment plants covering the area taken up by a dozen or so football pitches) are necessary for substantial enrichment. This requires the separator stages to be cascaded with, at each separator, about one half of the feed gas passing through (now slightly enriched) to the next higher stage for a repetition of the cycle. The gas that does not pass through (slightly depleted) is returned to the previous lower stage for repetition. At each cascade of stages, compressors and heat exchangers are stationed to maintain the temperature and pressure conditions required, both being energy intensive processes.

6 During the staging a small proportion of the feedstock undergoes hydrolysis to form a solid uranyl fluoride compound, which depletes the enrichment. Similarly, some of the uranium hexafluoride converts to uranium pentafluoride (by loss of an atom of fluorine), again depleting the enrichment particularly in the higher level stages. Also, a small amount of adsorption involving the deposit of uranium hexafluoride on the surfaces of the vessels and interconnecting piping occurs, which although small per unit represent, overall, a significant loss since the thousands of stages making up the plant comprise many square kilometers of exposed surfaces.

7 There are two means of expediting uranium enrichment, these are *stretching* and *recycling*, both of which break down the normally continuous process into batches. In *stretching* the cascade flow is "blocked" by lowering the differential pressure over the stage, this increases the enrichment level of each stage but reduces the flow rate, thus lengthening the overall processing cycle time to obtain very small amounts of enriched product. In *recycling*, the outputs of several cascades are reintroduced as feed to a single cascade, again this is time consuming and can lead to criticality problems.

8 Not necessarily a perfect sphere, with modern warhead designs incorporating a non-spherical oblate fissile pit.

9 In a uranium fuelled reactor some neutrons (as many as 30 to 40% of those produced by fissioning U-235) are captured in U-238 and produce U-239. In a reactor containing a large amount of fertile material – that is, a natural or slightly enriched uranium fuelled reactor – the creation of the new fissile material Pu-239 offsets the burn-up of the original fuel. This interplay between the uranium isotopes and the fissioning of the plutonium produces an exponential relationship in the decay and growth of U-235 and Pu-239 respectively in the reactor core over time. Essentially, the Pu-239 reaches a saturation content whilst the U-235 continues to decrease until it reaches a level at which the reactor requires refueling to maintain criticality. The number of fissions occurring in the reactor can be measured indirectly by the heat output of the reactor, appropriately modified for the position of the fuel in the reactor core, so plutonium production is given by a conversion ratio, such as:

$$\text{Pu grams/U tons} = a\text{Ee-}b\text{E}$$

where a and b are constants and E is the fuel irradiation or burn-up in MWday/ton.

So long as fissile and fertile materials (U-235 and U-238) are available in the core, any reactor will produce a proportion of plutonium integrated within the fuel matrix. Since Pu-239 is a fissile material it,

once established, will also be subject to fissioning, so under the right conditions the Pu-239 also transmutes to Pu-240 which will subsequently be available to fission to Pu-241 and Pu-242. Essentially, the aggregate increase of Pu-239 reaches a saturation point as the fission rate of the Pu-239 increases, this is accompanied by a greater content of the other plutonium isotopes, whilst the U-235 decreases down to a level at which the reactor requires refueling to maintain criticality. Since the higher plutonium isotopes (240–242) are undesirable for weapons grade plutonium (because these absorb neutrons, give rise to pre-detonation and/or – and give rise to decay products that – are strong gamma emitters) the subsequent fissioning of Pu-239 has to be inhibited by either removing the plutonium yielding fuel (or reactor blanket elements) from the reactor at a very low burn-up and/or by limiting the neutron absorption window of the Pu-239 by temperature control of the moderator. Reactor features that aid weapons grade plutonium production include facilities to remove short-burn irradiated fuel whilst the reactor is on load (referred to as *on-load refueling*); where the reactor core is wrapped in a blanket of U-238 fertile charge; and/or where the fuel is of natural or low U-235 enrichment and in which the graphite moderation in which the temperature is relatively low. Ideal fuel irradiation rates for plutonium production are very low, at about 200–250 MWd/t and to limit the shift of the thermal neutron spectrum of Pu-239 the outer moderator region temperature is maintained between 150 and 300^{o}C, although for graphite moderated reactors this gives rise to the storage of large amounts of (Wigner) energy in the graphite moderator core.

[10] The plutonium used in nuclear warheads is not 100% Pu-239 but includes other isotopes of plutonium, including Pu-240 and Pu-241. The plutonium is also alloyed with traces of other metals – usually gallium to facilitate machining – and includes traces of other impurities (chiefly uranium) which were not removed during reprocessing of the irradiated fuel. Pu-240 is more radioactive than Pu-239 and has a higher critical mass, being fissionable by fast neutrons like all other plutonium isotopes. Pu-238 is an undesirable inclusion due to its high heat generation rate.

[11] For the first of these objectives, the ideal period for plutonium breeding in a relatively low power reactor core is between four to eight months, or less. It would be very disruptive to have to close down the reactor for dismantling at this frequency so, for this reason, the large, high-powered light water reactors (PWRs and Boiling Water Reactors—BWRs) are not well suited to plutonium production since these types of reactor require 6 to 8 weeks for close-down and partial dismantling of the reactor at each refueling outage.

[12] Commercial or civil reprocessing plants are very large installations, such as the Magnox plant and the Thermal Oxide Reprocessing Plant (THORP) operated by British Nuclear Fuels (BNFL) at Sellafield, UK. However, such plants are not dependent upon scale for success and quite efficient chemical separation can be achieved by small-sized plants. The range of scale of reprocessing plants can be gauged by comparison of BNFL's Sellafield Magnox plant at 1,500 spent fuel tons/year and THORP at 1,200t/y compared, for example, to the 30t/y plant at Trombay in India and the pilot plant at Ezeiza in Argentina at 5t/y.

[13] It is quite feasible for an *implosion* type warhead to detonate successfully with a *reactor-grade* plutonium pit. The geometry of the US Trinity weapon detonated in the test of 1945 meant that it was capable of detonating with a fissile pit fabricated in reactor-grade *delta*-phase plutonium. Also, Hans Blix, the former Director-General of the IAEA has stated "On the basis of advice provided to it by its member states and by the Standing Advisory Group on Safeguards Implementation (SAGSI), the Agency considers high burn-up 'reactor grade' plutonium and in general plutonium of any isotopic composition with the exception of plutonium containing more than 80 percent Pu-238 to be capable of use in a nuclear explosive device. There is no debate on this matter in the Agency's Department of Safeguards.", see Letter from Hans Blix, Director-General of the IAEA, to Paul Leventhal, NCI, November 1, 1990

[14] Metal finishing of plutonium involves a number of processes, including precipitating plutonium peroxide and conversion to plutonium tetrafluoride by anhydrous hydrogen fluoride, calcium and iodine added for reduction to metal buttons which are pickled in a dilute nitric acid to remove slag. These are cast into gallium alloyed ingots by gravity or pre-machining shapes (hemispheres) in rapidly rotating moulds, thereafter the final pit components (two hemispheres) are precisely machined by cutting, bead blasting and/or electrolytic reduction to the final components which are surface plated to inhibit oxidation. The metal uranium components of a nuclear warhead are formed and finished using similar processes.

[15] Properly referred to as The Treaty on the Non-Proliferation of Nuclear Weapons 1968.

[16] In reactors that are designed for power generation and plutonium breeding, the core may be divided into two regions, an inner fuelled power section and an outer blanket which contains the fertile material—some research reactors utilizing enriched uranium fuel cores are configured in this way. Neutrons produced by fission diffuse into the blanket and are captured by the fertile U-238 to produce Pu-239 which can be extracted or further fissioned in-situ if required. Neutron capture in the moderator and structural core materials, as well as leakage from the core, has to be reduced to a minimum to maintain a high breeding ratio. Graphite- and heavy water-moderated cores have a low capture cross section, so neutron absorption is low, whereas water (light) moderation (as in a PWR) has a high capture cross section, reducing the breeding ratio which, with the difficulties of arranging on-load refueling for PWRs, further detracts from the use of PWR and BWR designs for the dual capable role.

[17] It seems that the original Urenco P-1/P-2 centrifuge designs were copied in the 1970s by Pakistan for its enrichment program.

[18] Kampani, G., *Proliferation Unbound: Nuclear Tales from Pakistan*, Center for Nonproliferation Studies, February 2004.

[19] Simpson, J, et al., *Iran's Nuclear Program: Realities and Repercussions*, Emirates Center for Strategic Studies and Research (ECSSR), 2006.

[20] Kraftwerk assessed the possible recovery and completion of the Bushehr NPPs in 1984 but any intention to resume work was thrown back in March 1984 with the first of a series of air strikes on the plants by Iraq.

[21] The French-sourced low enriched uranium was supplied under EURODIF (the European Gaseous Diffusion Uranium Enrichment Consortium).

[22] Based on Appendix 1 but with additional information included from *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, Report by the Director General, IAEA, Gov/2004/83, November 2004.

[23] This HEU (93%) fuelled, pool-type light water research reactor was supplied by the United States in 1967/8 but has been subsequently modified by the Argentina Applied Research Institute to operate on 20% U-235 enriched fuel for which Argentina provided 115.8 kg of uranium fuel in 1987.

[24] An agreement specifying the fuel supply and commissioning date for the Bushehr NPP was signed on or about September 26, 2006. Essentially, unirradiated fuel supply to Iran commences in March 2007, plant commissioning is to commence in September 2007 and first electricity output generation (somewhat ambitiously) in November 2007.

[25] When in operation and with account of **short-to-interim half-life** radionuclides, the reactor core inventory of the Bushehr NPP at about 3 years full operation would be expected to be about 200.10^{18} Bq or 200 Million TBq.

[26] Ghannadi-Maragheh, M., *Iranian Nuclear Fuel Cycle Experience*, World Nuclear Association Annual Symposium, 2003.

[27] Saghand is reckoned to access total reserves of 1,600,000 tons of uranium ore with about 225 parts per million (ppm) uranium. The scheduled production target is 120,000 t/y ore with the uranium extracted by acid leach and pulping. It is believed that these deposits are now accessed by underground mining although the rate of extraction is unknown.

[28] IAEA GOV/2003/9, November 2003

[29] It is not at all established that Iran has achieved a cascade of more than 19 units at the Pilot Enrichment Plant at Natanz, although the pilot plant has the capacity to operate 164 unit cascades for a total of about 1000 units. The projected larger Fuel Enrichment Plant at Natanz will have a capacity of 30,000 to 50,000 units, although the plan now seems to be limited to installing groups of cascades made up of 3,000 units—a single 3,000 unit cascade configured to enrich to HEU might produce about 20 kg per annum or enough to provide the fissile components for one gun-type nuclear warhead. The Iranian companies involved in the procurement of the centrifuges and associated equipment have been the Pars Trash Company and Farayand Technique, both under the direction of the Defense Industries Organization.

[30] The heavy water is used as a moderator in a natural uranium fuelled reactor. The purpose of the moderator is to moderate or slow the neutrons to improve the fissioning rate. This can be achieved with light (normal) water but at the sacrifice of the protium element of the water absorbing neutrons so, for a

light water moderated reactor (such as a PWR), there is a need to further U-235 fissile isotope enrich the uranium fuel to compensate for this unwanted absorption (by 2 to 5% U-235 over the 0,7% U-235 present in natural uranium). Heavy water or deuterium, though requiring more collisions and hence a larger volume of moderator, slows neutrons with a much lower risk of capture. Minimal capture means that natural uranium can fuel a reactor moderated with deuterium in the form of heavy water.

[31] A heavy water reactor which, according to the Iranian authorities, is to be used to meet its radioisotope production requirements. Such a reactor should have a neutron flux of 10^{13} to 10^{14} n/cm^2/s, based on a power of the order of 30–40 MW_t when using natural UO_2 fuel clad in zirconium produced at Esfahan.

The Arak deuterium plant output and commissioning of the IR-40 reactor are linked. For start up the ARAK IR-40 reactor will require an initial deuterium charge of about 80 to 90 tons, and thereafter an annual replenishment rate of up to 8 tons per year of D_2O. Thus the scheduled IR-40 commissioning date of around 2010 – 2012 depends upon the heavy water plant maintaining consistently high output capacity.

[32] Compares to the 33 to 55 GWd/tU burn-up being achieved in light water reactors such as the PWR which uses low enriched (up to 3.5% U-235) fuel.

[33] The possibility that Iran will use the IR-40 reactor and develop a plutonium separation process at Arak is entirely speculative and assumes that Iran is currently and will continue to pursue a plutonium-cored nuclear warhead development program.

[34] The definitions of low- and intermediate-level radioactive waste adopted in Iran is not known, although the usual specific activity definition for low-level (LLW) is taken as 12 GBq/m^3 for βγ containing waste and 4 GBq/m^3 for α wastes.

[35] Ghannadi-Maragheh, M., op. cit., *Iranian Nuclear Fuel Cycle Experience.*

[36] Ibid.

[37] IAEA, *Improvements of Radioactive Waste Management at WWER Nuclear Power Plant***,** IAEA-TECDOC-1492, April 2006.

[38] The discharge limits are set by the Iran Nuclear Regulatory Authority (INRA)

[39] The total annual radioactive waste production rate for the Bushehr nuclear power plant will be about 750m^3, comprising 363m^3 (of which ~12m^3 is intermediate-level) wet solid wastes, 380m^3 raw dry solid waste (mostly LLW) For this Bushehr will have a very limited waste storage capacity for both liquid (5 tanks of 70m^3) and solid (3 silos of 35.5m^3) wastes, Once the waste radioactivity levels have been allowed to decay (where appropriate) and/or that the mostly LLW wastes have been compacted in volume then most of this is to be consigned to a temporary storage area in 200 liter capacity drums on the NPP site.

[40] Since the heavy water moderated reactor under construction at Arak will be fuelled with natural (unenriched) uranium fuel it will not require any output from the Natanz enrichment plant.

[41] This involved installing a Russian PWR in the NPP buildings of the most complete Kraftwerk nuclear island structures – the Russian variant of the PWR is referred to as a *water-cooled, water-moderated energy reactor* (WWER).

[42] Upon further IAEA investigation, Iran acknowledged that between 1998 and 2002 it had carried out some testing of centrifuges at the Kalaye Electric Company using a batch of UF_6 imported in 1991.

[43] Whereas the international concern, first provoked by the United States in about 2000, is that this will lead Iran to HEU and capability in gun-type nuclear weapon assemblies. Advocates to this line of reasoning argue that there can be no economic justification for Iran, which has yet to commission and operate a civil nuclear reactor, to provide a fuel enrichment facility for civil fuel alone, nor would it be justified in advance of Iran developing a series of nuclear power electricity generating plants over the next three decades, or for it to become the nuclear fuel supplier for the region should nuclear power be developed on a wider scale.

[44] IAEA, GOV/2006/14, February 2006.

[45] The Additional Protocol is voluntary and is designed to strengthen and expand existing IAEA safeguards for verifying that non-nuclear-weapon state parties to the NPT only use nuclear materials and facilities for peaceful purposes. The Additional Protocol expands the IAEA's ability to check for clandestine nuclear facilities by providing the agency with authority to visit any facility – declared or not – to investigate questions about or inconsistencies in a state's nuclear declarations, including access to individuals,

documentation relating to procurement, dual use equipment, certain military-owned workshops and research and development as the Agency may request in support of its ongoing investigations. Iran signed the Additional Protocol in 2003 but has never fully ratified it. Until June 2004 the IAEA reported that Iran continued to act as though the protocol was fully in force but by February 2006 the IAEA deemed it necessary for Iran (see IAEA GOV/2006/14) to promptly ratify and implement the Additional Protocol—which it never has.

46 *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, Resolution by the Governors, IAEA, Gov/2005/77, September, 2005.

47 The Arak heavy water plant was commissioned in mid-2006 and it is expected to produce sufficient quantities of heavy water moderator for the IR-40 plutonium production capable reactor now under construction and scheduled for commissioning in 20010–12, also at Arak.

48 Between 1988 and 1993 Iran carried out plutonium separation trials using depleted UO_2 targets at the TNRC and these were not reported to the IAEA until 2003. According to Iran, a total of about 7 kg of UO_2 was irradiated, 3 kg of which was processed to separate plutonium. The small amount of separated plutonium was stored in a laboratory at Jabr Ibn Hayan Multipurpose Laboratories (JHL), while the remaining 4 kg of unprocessed irradiated UO_2 targets was placed in containers and stored at the TNRC site, and the wastes disposed of at the Qom salt marsh. The IAEA claimed that about 100 milligrams of plutonium was extracted and isolated. However, in its somewhat belated first reporting Iran indicated a much lower quantity (in micrograms), but subsequently confirmed the 100 mg quantity to be about correct.

49 According to the IAEA, Iran extracted the alpha rich polonium-210 isotope from irradiated bismuth targets between 1989 and 1993 which, Iran claims, was for the development of thermoelectric batteries although the IAEA's concern is with the other potential use of polonium when reacted with beryllium as a neutron initiator for the first stage nuclear detonation sequence.

50 *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, Report by the Director General, IAEA, Gov/2006/27, April 2006.

51 *See* note 48.

52 It has never been openly established from where Iran procured the centrifuge components and, now, it is very much doubted that Iran undertook its own centrifuge component manufacture as then reasoned by the IAEA in the March 13, 2004 *Statement on the Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*. Now it has been acknowledged that suspicion must be directed towards the Malaysian Scomi Precision Engineering SDN Berhad, which supplied about 15% of the centrifuge components for the Libyan nuclear program. The Libyan enrichment activity was brought to a close in 2004 by international agreement and since that time Iran may have experienced difficulties sourcing certain centrifuge components.

53 Resolution 1737 (2006), UN Security Council 5612th Meeting (AM), December 23, 2006.

54 *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, IAEA, Gov/2006/27, op. cit.

55 Ibid.

56 There are a number of difficulties in estimating Iran's target for enrichment throughput and the total number of individual centrifuge units needed to achieve this, and there is considerable ambiguity about the year at which Iran believes it could have the Natanz enrichment plant at a level of useful throughput. When enrichment activities recommenced in January 2006, the general consensus was that Iran possessed some 700 centrifuge units and that by the close of 2007 there would be about 1,600 centrifuge units operating in the requisite-sized cascades – see Albright, D. and Hinderstein, C., *Iran, Player or Rogue*, Bulletin of Atomic Scientists, V59, No 5 – but intelligence gleaned from the IAEA reports suggests that HEU enrichment might be much further down the road, perhaps not until 2009 or in sufficient quantities for a nuclear weapons arsenal until 2011 to 2016 – see respectively Albright, D. and Hinderstein, C., *The Clock is Ticking*, Institute for Science and International Security, March 2006; and Cirincione, J., *No Military Options*, Carnegie Issue Brief, January 2006.

57 The *National Security Strategy of the United States of America* (September 2002), identifies the options of preventative and proactive actions to counter nuclear proliferation, and states that the United States may have to become involved in periodic wars in pursuing such a strategy.

[58] The *National Security Strategy of the United States of America* (2006) specifically cites Iran as harboring terrorists at home and sponsoring terrorist activity abroad, and states that Iran has violated the NPT with its nuclear weapons program.

[59] Although details of the Russian Federation modifications to the original Kraftwerk-Siemens building and containment design of the 1970s are not available, the reactor island building containments and layouts are pre-9/11, 2001, and thus it is unlikely that the finished NPP will possess a full and robust resilience against terrorist or armed insurgency attack, or military strike. Following the aerial attacks of 9/11, new nuclear plants claim to be resilient against aircraft crash by both robustness of the containment structures and the intentional placing of 'sacrificial' buildings in front of key nuclear safety buildings, although there is little evidence of the pre-9/11 Kraftwerk layouts being changed in this respect, see Large, J. H., *Demarche De Dimensionnement Des Ouvrages Epr Vis-À-Vis Du Risque Lie Aux Chutes D'avions Civils* (Assessment of the Operational Risks and Hazards of the EPR When Subject to Aircraft Crash), May 2006. Also, The Kraftwerk-Siemens design for Bushehr derives from the PWR NPP at Biblis in Germany for which the main reactor containment, fuel pond and turbine hall buildings remain. The Russian Federation reactor, a modified WWER-1000 PWR, and its somewhat more complex primary circuit will have been literally shoe-horned into the existing buildings, although some extension of the reactor containment may have been undertaken to accommodate the 4 WER-1000 steam generators compared to the 2 generators of the original Biblis design

[60] Israel launched a military strike against the French-supplied 70 MW reactor at Osirak, about 18 miles south of Baghdad in early June 1981. Israel claimed that its reason for doing this was that the rector would have been capable of producing fissile material for a nuclear weapons program with the Israeli government declaring "Under no circumstances will we allow an enemy to develop weapons of mass destruction against our people." The reactor was not fuelled at the time of the attack and no radioactive release was detected.

[61] When in operation, and with account of short-to-interim half-life radionuclides, the reactor core inventory of the Bushehr NPP at about 3 to 4 years full operation would be expected to be about 200.10^{18} Bq or 200 Million TBq, not that in the first 3 to 4 years the radiological consequences of short-term radionuclides, such as radio-iodine, should be discounted.

[62] *An Assessment of the Radiological Consequences of Releases from Degraded Core Accidents for the Sizewell PWR*, NRPB-R137, National Radiological Protection Board (UK), July 1982—this assessment considers an accident scenario that is reckoned to have a chance of 4.10^{-10} per year of reactor operation.

[63] These *expected* (E) fatalities have been corrected upwards in account of the risk factors introduced by the succession of the International Commission on Radiation Protection's recommendations in Publication 60 (ICRP60). The R137 analysis examines the probabilistic range from ~12 to 26,280 fatalities (3 to 6,570 uncorrected) and 11,000 to 33,000 (uncorrected) fatalities in the longer term. The analysis applies to the mostly rural and relatively sparsely populated area on the south-east coast of England. The numbers of people requiring evacuation ranged from 480 (3,100 expected) to 420,000. The range of probabilities is determined by the atmospheric stability in the aftermath of the release which determines the dispersion and intensity of the overhead plume and ground deposition of radioactive contaminants.

For a more recent analysis of the radiological impact of reactor accidents and incidents so Large H J, *Assessments of the Radiological Consequences of Releases from Existing and Proposed EPR/PWR Nuclear Power Plants in France*, Greenpeace France, February 2007.

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