"The level of transparency that Iran is required to provide through its Comprehensive Safeguards Agreement enables the judgements of analysts and commentators to be informed by hard facts rather than mere speculation. Through the inspection regime of the IAEA, the world knows far more about Iran's nuclear programme than it would do otherwise."

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B R I E F

Iran's nuclear fuel cycle: a technical outline

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VERTIC

"The objective has been to provide clarity, as far as possible, regarding the technical components of the Iranian fuel cycle."

Overview

The aim of this study is to provide an overview of what is known about Iran's nuclear fuel cycle and how the various parts of it link together, based primarily on reports from the International Atomic Energy Agency (IAEA). In part, this report is also designed to comment on the nature and extent of IAEA safeguards coverage in the country. It should be noted up-front that this is a technical study that does not address political considerations or speculation as to Iran's future nuclear plans. The objective has been to provide clarity, as far as possible, regarding the technical components of the Iranian fuel cycle—and to do so in an impartial manner. The focus is on the past two- to three-year period, as it is for these years that the most detailed information is available and in which the majority of nuclear material in Iran has been produced. It is also in this period, and certainly no further back than 2007, that the nuclear fuel cycle that we see in Iran today began to properly take shape.

The report begins by explaining the principal component parts of a full, generic nuclear fuel cycle, in order that Iran's facilities and processes can be set in their proper technical context. Accordingly, the report will then examine each of the main stages of a nuclear fuel cycle with reference to what is known about nuclear sites and activities in Iran. Starting with uranium mining (for which limited information is available) and on through conversion, enrichment, fuel fabrication and fuel usage in reactors, the report includes information on material form and mass obtained and verified by the IAEA over recent years.[1] The study ends with a concluding section discussing the extent and limitations of current IAEA safeguards coverage in Iran, and by indicating a number of potential next steps for technical research.

Section 1: The nuclear fuel cycle—stages and processes

Before turning to the case of Iran, it is first useful to sketch out the various principal stages and processes of a generic nuclear fuel cycle (only some of which processes Iran currently has). In general—in a full, 'closed', nuclear fuel cycle—nuclear material moves through the following stages:

- Mining
- Milling
- Conversion
- Enrichment
- Fuel fabrication
- Reactors
- Reprocessing

Figure 1 shows these stages represented in graphical form, and each is explained more fully below.

The mining of uranium ore, either through underground excavation or open-cast extraction is the first stage of the process. This ore is then sent to a mill where the uranium is extracted from the ore. Further chemical processing transforms this ore into a concentrate known as yellowcake.

To be useful, yellowcake uranium must be converted into other chemical forms. The next step in the cycle is thus for the material to be shipped to a conversion facility, where a variety of conversion processes can take place. For the purposes of the cycle the most useful process is the conversion of yellowcake into uranium hexafluoride gas, which can then be sent on for enrichment at a facility designed for that process. After enrichment, two streams emerge: a waste stream containing depleted uranium (the 'tails' stream) and a product stream containing uranium enriched to whichever percentage figure was set. This product is sent for fuel fabrication at a fuel fabrication plant.

At a fabrication plant, enriched material is manufactured into reactor fuel, which usually takes the form of ceramic pellets made to the required specifications of the reactor for which the fuel is destined. This fuel is then transferred to a reactor where it is placed in the reactor core. In time, the fuel reaches the stage where the uranium-235 content cannot be further burned-up, at which point it is referred to as spent fuel. This spent fuel is removed from the reactor, whereupon it may be sent into long-term spent fuel storage or it may, if such a plant is available, be sent to a reprocessing facility where—after a cooling period of a few years—the fuel can be separated into three components: uranium, plutonium, and waste containing fission products.

Reprocessed uranium can then be sent to a conversion facility to be turned into UF_6. Meanwhile, plutonium can be combined with natural, depleted or other reprocessed uranium to manufacture 'mixed oxide' (MOX) fuel, or it can be used for military purposes.

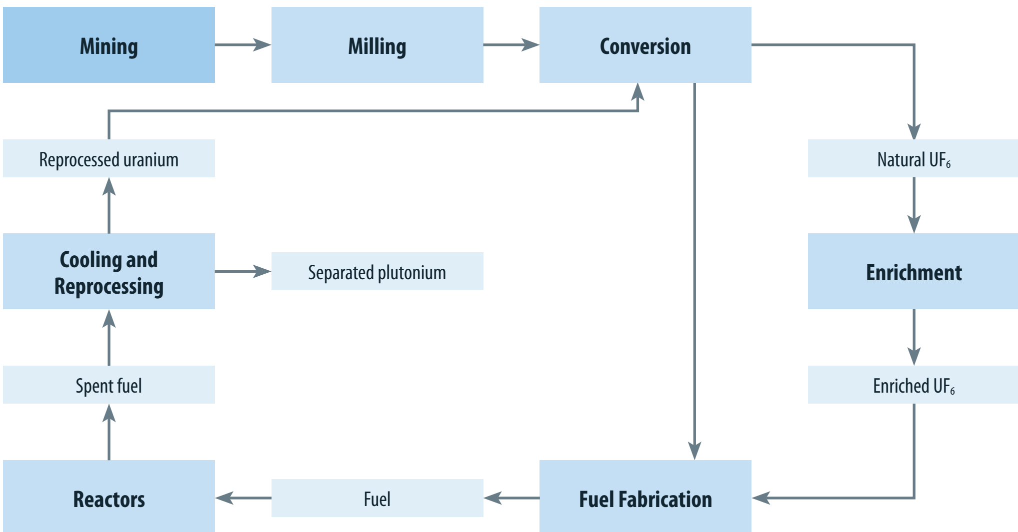
Section 2: Nuclear sites and facilities in Iran

This section of the paper identifies the major elements of the Iranian nuclear fuel cycle, based on the fuel cycle outlined above and shown in Figure 1. Information in this section is drawn primarily from the IAEA's quarterly reports on safeguards implementation in Iran (footnoted). As a result, since it is those facilities that fall under the safeguards regime of the IAEA for which the most detailed information is available, it is these facilities that are covered in greatest depth.

In fact, though, these facilities—principally for the conversion of uranium from one form into another, fuel fabrication using various forms of uranium, and uranium enrichment—are also among the most critical to Iran's nuclear programme. For instance, without a conversion capability, Iran could not turn uranium 'yellowcake' (U_3O_8), into uranium hexafluoride gas for enrichment. Enrichment, for its part, provides Iran with a means of generating fissile material in a form that can be made into enriched uranium reactor fuel in its fuel fabrication plant.

"Enrichment provides Iran with a means of getting fissile material."

Figure 1: A generic civilian nuclear fuel cycle



"Information on Iran's uranium mines and mills is considerably less detailed than information on other parts of the fuel cycle."

2.1 Mining and milling

The mining and milling of uranium fall outside the scope of Iran's 'comprehensive safeguards agreement' (CSA) with the IAEA. Were Iran to be implementing the Agency's so-called Additional Protocol, in addition to its CSA, then material at the mining and milling stage would be covered and verified—as discussed in the concluding section to this paper. Unless or until Iran does so, however, information on its uranium mines and mills is considerably less detailed than information on other parts of the fuel cycle.

Nonetheless, Iran is known to have two uranium mines: Gchine in the south of the country; and Saghand in the centre. Uranium mined at Gchine (an open-pit mine) is sent for processing at the Bandar Abbas Uranium Production Plant, which began operating in 2006. According to the 2011 'Red Book' produced by the IAEA and the Organisation of Economic Cooperation and Development, the Bandar Abbas plant is capable of treating 48 tonnes of uranium ore per day and has a production capacity of 21 tonnes of uranium per year.[2] A second, larger, production facility at Ardakan—with a production capacity of 50 tonnes of uranium per year—is currently under construction. The 2011 Red Book notes that production at this facility was due to begin in 2012, to be supplied with ore from the Saghand mine. In April 2013 Iran announced that mining at Saghand and ore production at Ardakan had begun.[3]

As reported by the International Institute for Strategic Studies, a London-based think-tank, back in the late 1990s Iran stated that its uranium reserves totalled 1,367 tonnes of uranium. Gchine, for its part, is estimated to contain around 40–100 tonnes of uranium, but at the relatively high ore grade of 0.2–0.5 per cent. Saghand is meanwhile thought to hold at least 1,000 tonnes of uranium, but the ore grade, at approximately 0.06 per cent, is lower.[4] IAEA information, correct as of March 2009, states that while Iran's uranium resources have neither been studied completely or precisely, exploration activities by the Atomic Energy Organization of Iran have shown proven reserves of 3,000 tons. Total reserves may be in the range of 20,000–30,000 tons throughout the country, the IAEA estimates.[5] Moreover, in February 2013 Iran announced that it had discovered major new reserves of uranium that would treble the size of its known uranium deposits.[6]

2.2 Uranium conversion

Uranium conversion activities in Iran take place at the Uranium Conversion Facility (UCF), located at Iran's Esfahan nuclear complex in the centre of the country. Several conversion processes take place at the UCF, including the conversion of uranium ore concentrate, via U_3O_8, into uranium hexafluoride (UF_6)—a gaseous form of uranium that can then be enriched in Iran's centrifuge plants to increase the proportion of the fissile isotope U-235 relative to that of the non-fissile U-238[7].

2.2.1 Conversion of uranium ore concentrate into natural UF_6

The conversion of U_3O_8, into natural uranium hexafluoride (UF_6) at the Uranium Conversion Facility began in March 2004. Production of this material was stopped on 10 August 2009, by which time 371 tonnes had been produced (some of which had been transferred to Iran's enrichment plants at the Natanz nuclear site). Iran was intending to restart UF_6 production at the UCF on 23 October 2011 using ore concentrate from the Bandar Abbas Uranium Production Plant.[8] That plan was soon shelved though, as on 4 October 2011 Iran informed the Agency that UF6 production was being postponed. Uranium ore concentrate from Bandar Abbas was to be used at the UCF in the production of natural uranium dioxide (UO_2) instead.[9]

Production of natural (i.e. un-enriched) UF_6 has clearly resumed, as in August 2012 the IAEA noted that, 'according to the latest information available' to it, Iran has produced some 550 tonnes of natural UF_6 at the UCF.[10] Of this total, 91 tonnes has reportedly been transferred to the Fuel Enrichment Plant at Natanz[11] (a plant examined in detail later in this report). By November 2012, 99 tonnes had been sent to Natanz.

2.2.2 Production of isotopically-natural UO_2

As mentioned above, the production of natural UO_2 is also conducted at the Esfahan Uranium Conversion Facility. The exact date this began is unclear, but the IAEA's May 2011 report notes that the process for the production of natural UO_2 at the UCF was underway by 18 May 2011 (when the Agency carried out a Design Inventory Verification inspection, or 'DIV', at the plant) with a view to producing fuel for Iran's IR-40 reactor at Arak, which is not yet commissioned. At that time, however, no UO_2 had yet been produced.[12]

The IAEA's September 2011 report noted that according to an 'updated schedule for the operation of the UCF' provided by Iran on 15 June 2011, the production of natural UO_2 would begin on 23 July 2011.[13] Between 23 July and 18 October 2011 Iran reportedly fed 958.7kg of uranium ore concentrate into the process and produced approximately 185.6kg of natural UO_2.[14] According to Iran, some of this product had been 'fed back into the process', and around 1kg transferred to the Fuel Manufacturing Plant (FMP) at Esfahan 'in order to "conduct research activities and pellet fabrication."'[15]

By August 2012, Iran had produced approximately 3,340kg of natural uranium in the form of UO_2 through the conversion of uranium ore concentrate.[16] The Agency had by then been able to verify that 1,272kg of this material had been sent to the Esfahan Fuel Manufacturing Plant (FMP).[17] According to Iran, as of 3 February 2013 it had produced a total of 9,056kg of natural UO_2, of which 3,823kg had been verified as having been transferred to the FMP.[18]

The origin of the ore concentrate is reportedly both domestic and imported. (In the 1970s Iran imported 600 tons of yellowcake uranium from South Africa.) On 22 April 2012 Iran brought into the Uranium Conversion Facility process area 25 drums containing a total of approximately 6,560kg of domestically-produced uranium ore concentrate and 25 drums holding some 9,180kg of concentrate taken from Iran's stockpile of imported material. The material from all these drums was reportedly mixed together before then being used in the production of natural UO_2.[19]

"The origin of the ore concentrate is reportedly both domestic and imported."

2.2.3 Production of low-enriched UO_2

Another process underway at the Uranium Conversion Facility is the conversion of 3.34 per cent enriched UF_6 into UO_2. This, like the production of natural UO_2, is also a fairly recently-begun process in Iran. The country informed the Agency on 28 July 2011 that it was to start research and development (R&D) work at the Esfahan UCF for the conversion of five per cent U-235 enriched UF_6 into UO_2.[20] By late August 2011 Iran had also begun R&D activities for the conversion of UF_6 into UO_2 using depleted uranium.[21]

On 18 October 2011 Iran told the Agency that 6.8 kg of depleted uranium in the form of UF_6 had been processed and that 113g of UO_2 'that met its specifications' had

"Regarding the enrichment of uranium, Iran has three declared enrichment plants."

been produced. This UO_2 had reportedly been sent to the FMP 'to produce test pellets.'[22] In its November 2011 report, the IAEA also noted that Iran had by then begun using UF_6 enriched to 3.34 per cent to produce UO_2 (noted in later reports as also being R&D activities).[23] This material was to be sent to the Esfahan Fuel Manufacturing Plant as well, in order to produce fuel pellets that would then be sent on to the Tehran Research Reactor (TRR) for testing.[24]

As of 19 February 2012 Iran had produced 24kg of 3.34 per cent enriched UO_2 and transferred 13.6 kg of this to the Fuel Manufacturing Plant.[25] At the Fuel Manufacturing Plant this material was used to produce two fuel assemblies, each consisting of 12 fuel rods, for use in the Teheran Research Reactor.[26] The R&D work that saw the production of this 24 kg of 3.34 per cent enriched UO_2 was reported in May 2012 to have ceased,[27] but as of 10 August 2012 it had apparently resumed, although no additional material had by then been produced.[28]

2.2.4 Conversion of 20 per cent UF_6 into U_3O_8

Iran began converting UF_6 that had been enriched up to 20 per cent U-235 back into U_3O_8 on 17 December 2011. By 19 February 2012 some 8kg of enriched U_3O_8 had been produced and 7.3kg of this had been transferred to the Fuel Manufacturing Plant.[29]

Mid-2012 saw a significant development on this front: a new facility. On 2 May 2012 Iran informed the Agency 'that it had decided to combine into one facility the activities involving the re-conversion of UF_6 enriched up to 20% U-235 into U_3O_8 and the manufacture of fuel assemblies made of fuel plates containing U_3O_8'.[30] At the time, these activities were being conducted at Esfahan's Uranium Conversion Facility and Fuel Manufacturing Plant respectively. The new facility where these activities were to be combined was called the Fuel Plate Fabrication Plant (FPFP). The FPFP is also located at Esfahan (see section 2.4 of this report).

Between 17 December 2011—when conversion of 20 per cent enriched UF_6 into U_3O_8 began (at the UCF)—and 15 May 2012, Iran had reportedly fed into 'the process' 43kg of 20 per cent enriched UF_6 and produced 14kg of 20 per cent enriched uranium in the form of U_3O_8.[31] By 12 August 2012, as reported by the IAEA in its August 2012 report, 71.25kg of up to 20 per cent enriched uranium had been fed in and 31.1kg of similarly-enriched U_3O_8 produced.[32]

Iran suspended the conversion of 20 per cent UF_6 into U_3O_8 at the FPFP in late September 2012, resuming them again in early December. Between 2 December and 11 February 2013 Iranian estimates assert that 28.3kg of 20 per cent UF_6 was fed into the FPFP and 12kg of U_3O_8 was produced. That, the Agency notes in its February 2013 report, would mean that the total amount of UF_6 fed in would stand at 111kg and the total amount of U_3O_8 produced would come to 50kg.[33]

2.3 Uranium enrichment

Regarding the enrichment of uranium to increase the proportion of U-235 contained within it, Iran has three declared enrichment plants. At its Natanz site is the Fuel Enrichment Plant (FEP) and the Pilot Fuel Enrichment Plant (PFEP), while near the city of Qom lies the Fordow Fuel Enrichment Plant (FFEP).

2.3.1 Natanz Fuel Enrichment Plant

The Natanz FEP is a centrifuge enrichment facility used for the production of uranium enriched up to five per cent U-235.

This facility began operating in February 2007. Within the FEP are two areas: Production Hall A and Production Hall B. Design information submitted by Iran to the IAEA states that Production Hall A is planned to hold eight units, with 18 cascades per unit—i.e. 144 cascades altogether. The IAEA reports that no detailed design information has yet been provided for Production Hall B.

In its August 2012 report the IAEA provided a breakdown of the status (as of 21 August 2012) of each of the eight units—designated A21 to A28—of FEP Production Hall A. That list is reproduced below:

Unit A21—No centrifuges installed

Unit A22—No centrifuges installed

Unit A23—No centrifuges installed

Unit A24—18 cascades of 16 IR-1 centrifuges, producing UF_6 enriched up to 5 per cent U-235

Unit A25—18 cascades with empty IR-1 centrifuge casings

Unit A26—6 cascades of 164 IR-1 centrifuges producing UF_6 enriched up to 5 per cent U-235; 12 cascades of 174 IR-1 centrifuges producing UF_6 enriched up to 5 per cent U-235

Unit A27—15 cascades with empty IR-1 centrifuge casings; 1 cascade of 174 IR-1 centrifuges installed; 1 cascade with 93 IR-1 centrifuges installed; 1 cascade empty

Unit A28—18 cascades of 174 IR-1 centrifuges producing UF_6 enriched up to 5 per cent U-235

Source: GOV/2012/37, 30 August 2012, p13, figure 5.

Iran announced in January 2013 that it was to install IR-2m centrifuges in one of the FEP's units. Prior to this, as seen in the above box, those units where machines had been installed all contained 'IR-1' centrifuges—the earliest generation of Iranian centrifuges, based on a design acquired from Pakistan through the A.Q. Khan network. As of 19 February 2013 Iran had fully installed 74 cascades in Production Hall A, with 54 of these being fed with natural UF_6.[34] (During a DIV to the FEP on 11 August 2012 the Agency observed that 'general preparatory work' in Production Hall B had begun.)[35]

In terms of material balances at the FEP, the Agency has verified that as of 21 October 2012 some 85,644kg of natural UF_6 had been fed into cascades at the FEP since the plant became operational in 2007, with a total of 7,451kg of UF_6 enriched up to five per cent U-235 having been produced. In addition, Iran estimates that between 22 October 2012 and 3 February 2013 a total of 9,106kg of natural UF_6 was fed into the FEP and approximately 820kg of UF_6 enriched up to five per cent was produced. Thus, assuming the correctness of Iran's estimates, that would result in a total production of 8,271kg of UF_6 enriched up to five per cent at the FEP since February 2007 when production began.[36]

2.3.2 Natanz Pilot Fuel Enrichment Plant

The Natanz PFEF is the older of the two Natanz plants, having been first brought into operation in October 2003. It is used both for the production of low-enriched uranium (LEU)—albeit to higher enrichment levels than the FEP—and for R&D purposes and is accordingly divided into an area designated for the production of LEU enriched up to 20 per cent and an area designated for R&D. This facility includes both IR-1 centrifuges and more advanced designs, as indicated by their number designations.

For its part, the PFEP production area contains two interconnected cascades (numbered 1 and 6). Cascades 2, 3, 4, and 5 are situated in the R&D area. The August 2012 IAEA report provides a breakdown of the status each cascade as they were on 18 August 2012, reproduced below:

"The Natanz PFEP is the older of the two Natanz plants, having been first brought into operation in October 2003."

“The existence of the enrichment plant at Fordow was revealed in 2009, some time before the plant began operating.”

Cascade 1—164 IR-1 centrifuges connected to Cascade 6 producing UF6 enriched up to 20 per cent U-235

Cascade 2—10-machine cascade of IR-4 centrifuges

Cascade 3—Empty

Cascade 4—123 IR-4 centrifuges installed

Cascade 5—162 IR-2m centrifuges installed

Cascade 6—164 IR-1 centrifuges connected to Cascade 1 producing UF6 enriched up to 20 per cent U-235

Source: GOV/2012/37, 30 August 2012, p14, figure 9.

Within the production area, the Agency has verified that as of 15 September 2012, 1,119.6kg of UF_6 enriched up to five per cent at the FEP had been fed into the PFEP with a total of 129.1kg UF_6 enriched up to 20 per cent U-235 having been produced. Over and above this, Iran has estimated that between 16 September 2012 and 12 February 2013 a total of 145.5kg of UF_6 enriched up to five per cent U-235 at the FEP was fed into the PFEP. Iran estimates that between these dates around 20.8kg of UF_6 enriched up to 20 per cent was produced. Again, assuming the correctness of Iran’s estimates, that would result in a total production of 149.9kg of UF_6 enriched up to 20 per cent up to early February 2013.[37]

Into the R&D area of the PFEP Iran has been ‘intermittently’ feeding natural UF_6 into IR-2m and IR-4 centrifuges, ‘sometimes into single machines and sometimes into cascades of various sizes.’ Iran has reportedly also been intermittently feeding one cascade with depleted UF_6, rather than natural material. Between November 2012 and February 2013 Iran also installed IR-6 and IR-6s kinds of centrifuges in the R&D area, ‘and has been intermittently feeding natural UF_6 into them as single machines.’[38]

Natural and depleted UF_6 is also fed into the R&D area of the PFEP. But no LEU is withdrawn from this area—as ‘product and the tails [are] recombined at the end of the process.’[39]

2.3.3 Fordow Fuel Enrichment Plant

The existence of the enrichment plant at Fordow, the FPFP, was revealed in 2009, some time before the plant began operating. Its discovery prompted concerns, stemming both from the clandestine manner in which it was hitherto being constructed and from repeated subsequent revisions as to its stated purpose.

According to a ‘Design Information Questionnaire’ provided by Iran on 18 January 2012, the FPFP—which, like Natanz, is a gas centrifuge-based facility—is to be used for the production of UF_6 enriched up to five per cent U-235 and up to 20 per cent. Enrichment work at the FPFP began in December 2011. The plant has been designed to hold 16 cascades equally divided between a Unit 1 and a Unit 2, and comprising of nearly 3,000 centrifuges in all.

The Agency has verified that as of 17 November 2012 a total of 769kg of UF_6 enriched up to five per cent U-235 at the FEP had been fed into the Fordow plant since production there began in December 2011. Since then 101.2kg of 20 per cent enriched material had been produced.[40]

In addition, Iran estimates that between 18 November 2012 and 10 February 2013 a total of 210.1kg of five per cent enriched UF_6 was fed from the FEP to Fordow, and that approximately 28.7kg of 20 per cent enriched material was produced. This, added to the verified figure, would make a total production of 129.9kg of 20 per cent enriched UF_6 since production began. Of this, the Agency notes that 125.3kg has been withdrawn from the production process and verified.[41]

2.4 Fuel fabrication

Fuel fabrication in Iran occurs mainly at the Esfahan Fuel Manufacturing Plant. Here, Iran conducts (or has conducted) several kinds of fuel manufacture involving a variety of nuclear materials: natural UO_2; low-enriched UO_2; and, prior to the construction of the Fuel Plate Fabrication Plant, U_3O_8.

On 31 May 2011 Iran informed the Agency 'that a fresh fuel rod of natural UO_2 manufactured at FMP would be shipped to the Tehran Research Reactor for irradiation and post-irradiation analysis.'[42] By 10 August 2011 Iran had yet to install equipment for the fabrication of TRR fuel. On 15 October 2011—according to the IAEA's November 2011 report—an inspection at the TRR confirmed that on 23 August 2011 Iran had commenced the irradiation of a 'prototype fuel rod containing natural UO_2 that had been manufactured at FMP.'[43] This report also revealed that, as of 22 October 2011 Iran had begun to install equipment for the fabrication of fuel for the TRR.[44] On 26 November 2011 the Agency verified one fuel assembly made up of 12 fuel rods containing UO_2 enriched up to 3.34 per cent U-235.[45] On 22 December 2011 it verified a second such assembly, with both of these reportedly transferred to the TRR for irradiation testing.[46]

That inspection on 22 October 2011 also saw the verification of five fuel plates containing natural U_3O_8 that had been produced in the R&D area of the FMP.[47] The next report by the IAEA, released in February 2012, noted that on 14 November and 19 November 2011 the Agency had verified two more fuel plates containing natural U_3O_8 that had also been produced in the FMP's R&D laboratory.[48] These were sent to the TRR for irradiation testing. The Agency reported that on 3 January 2012 it had verified a fuel plate containing U_3O_8 enriched up to 20 per cent U-235, and that on 1 February 2012 it had verified a fuel assembly consisting of 14 fuel plates containing 20 per cent enriched U_3O_8.[49] These plates and assemblies were also transferred to the TRR for tests. (It is unclear whether the five fuel plates verified on 22 October 2011 were also sent to the TRR.)

In addition, on 8 February 2012 Iran told the Agency that it intended to start 'pellet, fuel rod and fuel assembly production' using natural UO_2. The intention of this was to produce fuel for the IR-40 reactor. By 18 February 2012, on which day the Agency carried out a DIV at the FMP, the IAEA observed that the fabrication of pellets for the IR-40 reactor was underway.[50]

Later in the year, on 12 May 2012, the Agency was able to confirm that the manufacture of fuel assemblies using 12 rods of 3.34 per cent enriched UO_2 had been stopped, but that the manufacture of pellets for the IR-40 using natural UO_2 was ongoing.[51] In its May 2012 report the IAEA also noted that the manufacture of 'dummy' assemblies—i.e. assemblies similar to fuel assemblies but containing non-nuclear material—was underway also at the FMP.[52] (By August this situation was unchanged: pellet manufacture for the IR-40 using natural UO_2 was ongoing, as was the manufacture of dummy fuel assemblies for that reactor; the production of fuel assemblies containing nuclear material remained stopped.)[53]

By May 2012, the FPFP was also in play, so the manufacture of fuel plates and assemblies containing U_3O_8 would presumably have by then been halted at the FMP and moved to the new facility. Indeed, on a visit to the FPFP on 15 May 2012 the Agency verified two fuel plates and one fuel assembly containing 19 plates. All of this was subsequently transferred to the TRR, the Agency

"Fuel fabrication in Iran occurs mainly at the Esfahan Fuel Manufacturing Plant."

"Iran is not known to have—nor to be constructing—any undeclared, clandestine reprocessing facilities."

reported.[54] On 20 May 2012 IAEA inspectors verified a second 19-plate assembly prior to the transfer of this also to the TRR.[55]

2.5 Reactors

There are several nuclear reactors in Iran—both operating and under construction. Principally, these are situated at Bushehr, in Tehran and at Arak.

Iran's reactor at Bushehr was constructed with Russian assistance. The plant is a pressurised water-based reactor, a kind of design that uses water heated by the reactor core to heat a secondary water circuit wherein steam is created—the steam in turn driving turbines to produce electricity. At least for now, Russia supplies fuel for the plant, operates it and manages the spent fuel. Commissioning activity at this plant began, according to Iran and as reported by the IAEA, on 31 January 2012. In July 2012 the Agency conducted an inspection at the Bushehr Nuclear Power Plant; the reactor was then operating at 75 per cent of its total nominal capacity.[56] Power output reached full capacity in late August 2012.

The Tehran Research Reactor, housed in the Tehran Nuclear Research Centre in the suburbs of the Iranian capital, is a 5-megawatt-thermal (MWth) pool-type light-water reactor. In June 2012, as reported by the IAEA in August, Iran started using one fuel assembly made of 19 fuel plates containing U_3O_8 enriched up to 20 per cent U-235 'as an integral part of the core' of the TRR.[57] The IAEA reported that in July 2012 it verified the receipt at the TRR of one control fuel assembly containing 14 fuel plates and two fuel rods containing natural UO_2.[58] August 2012 saw Iran begin using a control fuel assembly consisting of 14 fuel plates of U_3O_8 enriched up to 20 per cent in the TRR core.[59] The IAEA's August 2012 report noted that Iran was also using a fuel assembly containing 12 rods of UO_2 enriched up to 3.34 per cent U-235 as one of the TRR's control assemblies.

At Arak, Iran has been constructing an IR-40 heavy water reactor, which remains under construction and under Agency safeguards. The IAEA carried out a DIV at the IR-40 reactor on 1 August 2012, during which visit they observed that 'cooling and moderator circuit piping was being installed.'[60] Iran plans to have this reactor operating by the end of 2013. (Also at Arak is the so-called Heavy Water Production Plant, the HWPP, which the Agency reported in August 2012 as seemingly being in operation. The IAEA visited the facility on 17 August but thereafter was being obliged to rely on satellite imagery to monitor its status.)[61]

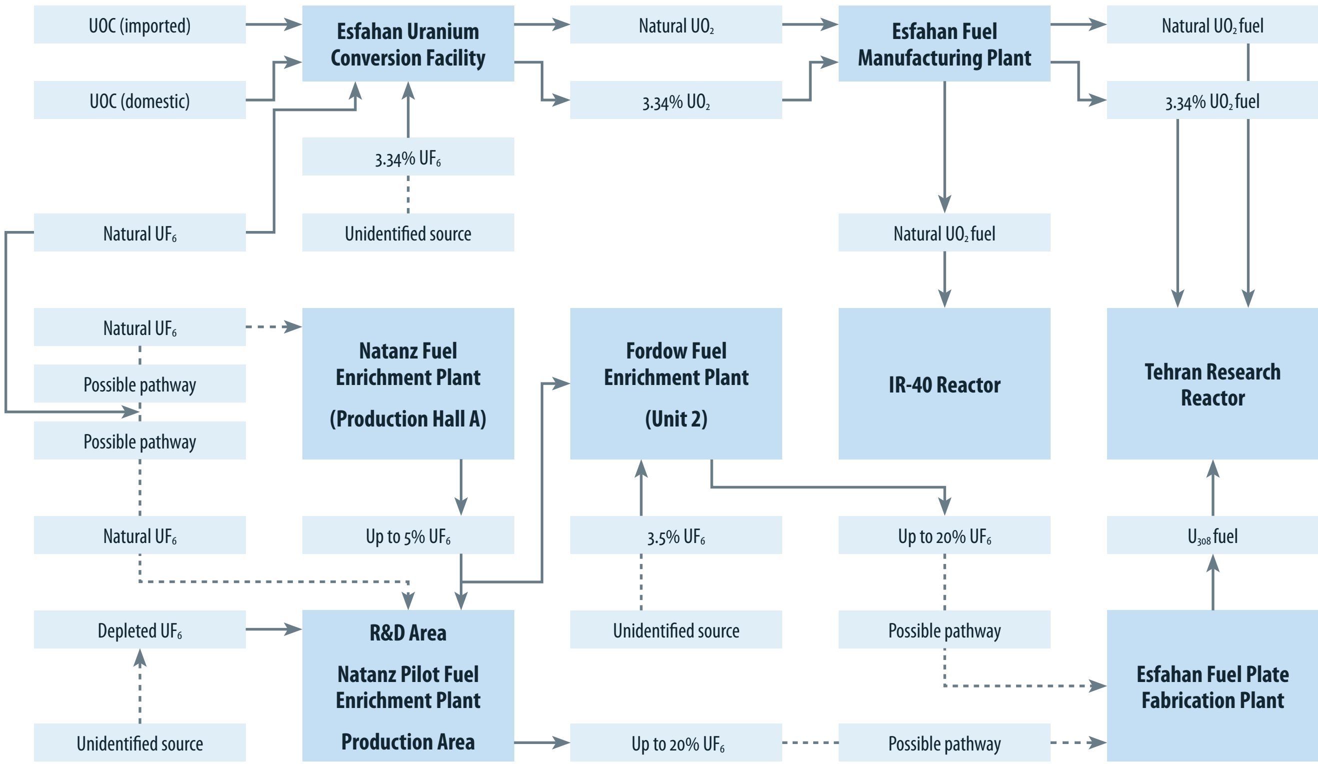
2.6 Reprocessing

Iran stated in 2008 that it does not have any fuel reprocessing facilities, and it maintains this statement. The country is not known to have—nor to be constructing—any undeclared, clandestine reprocessing facilities.

Section 3: Facility linkages and material flows

This section of the paper seeks to describe—as far as possible given what is known from the IAEA reports examined above, and to extrapolate from there—the various material flows that make up the Iranian nuclear fuel cycle. It also seeks to show, as required, how these flows have evolved over time. This section of the report is complemented by Figure 2, below, which seeks to 'map' Iran's main nuclear facilities and the flows between them—a number of which have needed to be estimated based on the likely routes for material of various kinds.

Figure 2: The Iranian nuclear fuel cycle (c. March 2013)



3.1 Nuclear material linkages in Iran

With regard to Iran, the starting point is taken as the entry of uranium ore concentrate into the UCF at Esfahan.

3.1.1 Conversion of UOC into natural UF_6 at UCF, transfer to Natanz

Uranium ore concentrate entering Esfahan comes from two sources: first is the domestically-produced material that arrives from the Bandar Abbas Uranium Production Plant; and second is the material that comes from Iran's stockpile of imported concentrate. At the UCF this material is converted into natural UF_6, some of which is transferred to the two enrichment facilities at Natanz.

3.1.2 Receipt of natural UF_6 at Natanz, enrichment to 5 and 20 per cent U-235

Natural UF_6 is received at both the Natanz FEP (into Production Hall A) and the R&D area of the PFEP. In the FEP this material is enriched up to five per cent U-235 and transferred to the production area of the PFEP. There it is further enriched up to 20 per cent U-235.

In the R&D area of the PFEP meanwhile, depleted UF_6 is also introduced. Here, though, no low-enriched material is withdrawn as—the IAEA reports—the product and tails are recombined at the end of the process.

3.1.3 Enrichment of UF_6 up to 20 per cent U-235 at Fordow

Aside from Natanz, of course, is the Fordow Fuel Enrichment Plant, where enrichment up to 20 per cent is also carried out (within Unit 2 of the facility). As noted above, it is unclear whether there are two flows of low-enriched uranium entering the FFEP (one at 3.5 per cent, one enriched up to five per cent) or whether the 3.5 per cent flow is counted within the amount of material enriched up to five per cent going into the plant.

In any case, within Unit 2 of the FFEP UF_6 is further enriched up to 20 per cent

"IAEA inspections in Iran afford the international community a great insight into Iran's nuclear activities."

U-235. There are, thus, two outlets of UF_6 enriched up to 20 per cent U-235 in Iran: one from the Natanz PFEP and one from the FFEP at Fordow. Where this material goes is the next question.

3.1.4 Movement of UF6 enriched up to 20 per cent beyond the enrichment stage

Prior to the introduction of the Fuel Plate Manufacturing Facility at Esfahan, UF_6 enriched up to 20 per cent was transferred to the UCF and used for the production of U_3O_8 involving uranium enriched up to 20 per cent. This conversion work got underway in December 2011, with the enriched yellowcake product being transferred to the Fuel Manufacturing Plant. At the FMP it was made into fuel plates and assemblies containing U_3O_8 enriched up to 20 per cent. That fuel was then transferred to the Tehran Research Reactor.

Iran's decision to transfer these processes to the FPFP took the UCF out of this particular loop. Since May 2012, UF_6 enriched up to 20 per cent U-235 has been transferred to the FPFP at Esfahan for it to be converted into U_3O_8 and made into fuel. Where the UF6 flows into the FPFP and—before it—into the UCF, flows *from*, however, is unclear. It may come from either the Natanz PFEP or the FFEP at Fordow. On this point the IAEA reports are vague.

3.1.5 Other flows of low-enriched UF_6 beyond the enrichment stage

Although it no longer carries out the conversion of 20 per cent material into U_3O_8, the UCF does convert lesser-enriched UF_6—UF_6 enriched up to 3.34 per cent U-235 into UO_2. Where this material comes from is unclear, although it can perhaps be assumed to arrive from the Natanz FEP, as another exit flow from that facility (i.e. aside from the UF_6 enriched up to five per cent that is transferred from the FEP to the PFEP). The UO_2 produced using the 3.34 per cent enriched UF_6 is transferred across to the Esfahan Fuel Manufacturing Plant where it is manufactured into fuel elements for the TRR.[62]

3.1.6 Use of uranium ore concentrate other than for production of natural UF_6

In addition to being used for the production of natural UF_6, uranium ore concentrate entering the UCF is also used for the production of natural UO_2—which, once produced, is transferred to the Fuel Manufacturing Plant to make fuel for the Tehran Research Reactor, as well as fuel pellets for Iran's still-under-construction IR-40 reactor at Arak.

Section 4: Conclusions

At the outset of the concluding section of this paper it is worth remarking—although an obvious point perhaps—that IAEA inspections in Iran afford the international community a great insight into Iran's nuclear activities. The level of transparency that Iran is required to provide through its Comprehensive Safeguards Agreement enables the judgments of analysts and commentators to be informed by hard facts, rather than have them based on mere speculation. Again, although it may be an obvious point, through the inspection regime of the IAEA the world knows far more about Iran's nuclear programme than it would do otherwise.

As with all those that have gone before, the Agency's most recent report on the implementation of safeguards in Iran—from February 2013—declared that the Agency continues to verify the non-diversion of *declared* nuclear material in the country. But as Iran has only an IAEA Comprehensive

Safeguards Agreement in force and not an Additional Protocol also (coupled to lack of Iranian cooperation in other respects), the Agency is 'unable to provide credible assurance about the absence of *undeclared* nuclear material and activities in Iran'. It is, as a result, unable to draw the conclusion that all nuclear material in Iran is being used in peaceful activities.

4.1 The introduction of the Additional Protocol

The scope of this section, nor this paper, does not stretch to a full in-depth look at the evolution of the IAEA safeguards system. Suffice to say here that all non-nuclear-weapon state parties to the Non-Proliferation Treaty (NPT) are required to conclude a Comprehensive Safeguards Agreement with the Agency covering nuclear material under their control or jurisdiction. Iran, a non-nuclear-weapon state NPT party since 1970, has had one of these agreements in place since 1974.

In the early 1990s, however, it became apparent that the CSA provided the IAEA with insufficient information and tools to be able to determine both the correctness *and completeness* of states' declarations. A state, in other words, could simply not declare material that it wanted to keep hidden—as in the case of Saddam Hussein's Iraq prior to the 1991 Gulf War—with there being little the Agency could do to either deter such violations or uncover them. As a result, in the 1990s the Agency brought in a raft of measures to strengthen the safeguards system, the centrepiece of which was the introduction of the Additional Protocol in 1997.

Non-nuclear-weapon states did not—and do not—have to sign up to the Additional Protocol, which complements a CSA and which requires states to provide far more information on the nuclear activities than under a CSA alone. Where such a protocol is in force, however, the Agency can draw considerably stronger conclusions as to the purely peaceful use of nuclear energy in a country. Under an Additional Protocol, the Agency also has enhanced rights of access into and around nuclear sites and facilities, allowing much greater freedom of movement for inspectors.

Iran signed an Additional Protocol with the Agency in December 2003, implemented the measures contained within it for a number of years (pending ratification of the protocol by the Iranian parliament), but ceased implementation in February 2006 in protest at the IAEA Board of Governors' decision to refer Iran to the UN Security Council. Iran's Additional Protocol has never been ratified, and provisional implementation of it has not resumed.

"Iran's Additional Protocol has never been ratified, and provisional implementation of it has not resumed."

4.2 Safeguards coverage in Iran

Under a CSA, safeguards coverage applies to all nuclear fuel cycle activities upstream and inclusive of uranium conversion. That is to say: conversion, enrichment, fuel fabrication, use of nuclear material in reactors and other civilian applications, spent fuel storage and reprocessing. The model text of the CSA (known as document INFCIRC/153) notes that the 'starting point of safeguards' shall not apply to either mining or ore processing activities. Rather, the starting point, as set out in paragraph 34(c) of INFCIRC/153 is the point at which nuclear material reaches 'a composition and purity suitable for fuel fabrication or for being isotopically enriched' and when such material either 'leaves the plant or the process stage in which it has been produced' or is imported into the state.

By contrast, an Additional Protocol (based on the model text of INFCIRC/540)

"Compared to states who took the nuclear option in the 1950s, or earlier, Iran's nuclear programme is still in its early stages and developing all the time."

widens the scope of safeguards to cover the *entire* nuclear fuel cycle of a state. Under an CSA plus Additional Protocol arrangement a state must provide the IAEA with information about the whole of its fuel cycle activities—from uranium mining through to waste storage—as well as any other location where nuclear material is present.

One specific extension over the CSA, then, is the provision of information on mines. At present a limited amount of information is available on Iranian mining activities, but Iran is not obliged to provide any information. By contrast, under Article 2a(v) of the Additional Protocol, Iran would be required to provide the IAEA with information 'specifying the location, operational status and the estimated production capacity of uranium mines and concentration plants and thorium concentration plants', as well as the annual production of such mines and plants as a whole. The same clause notes that upon request of the Agency, a state must provide the current annual production of an individual mine or concentration plant.

Among other provisions, an Additional Protocol would also oblige Iran to provide information on all buildings on nuclear sites (with the IAEA having the right to short-notice inspections of them), whereas now inspections are limited to what are termed 'strategic points' within certain designated facilities. Under an Additional Protocol Iran would also have to permit the Agency to collect environmental samples at locations other than declared locations, to provide information on the export of designated equipment and non-nuclear material (which implicitly includes their manufacture), and, not least, to provide information on 'nuclear fuel cycle-related research and development activities not involving nuclear material'.

4.3 Possible next steps for technical research

International concern over Iran's nuclear ambitions seems set to persist to an indeterminate future point. Amidst these concerns, this report has sought to provide a better picture of what Iran's nuclear capabilities are at present, and an overview of how the key parts of its nuclear infrastructure link up.

Despite the aforementioned degree of transparency into Iran's programme, provided for by the IAEA's inspection regime, there is much that remains unknown however. And compared to states who took the nuclear option in the 1950s, or earlier, Iran's nuclear programme is still in its early stages and developing all the time. Inevitably, this means that mass flow rates of the various forms of uranium between one facility and another in Iran cannot yet be regarded as continuous smooth processes. Nor do we yet know that individual plants, such as Iran's enrichment facilities, have operated in a steady and continuous manner. This being the case it is not appropriate to use straight-line interpolation between 'snapshot' information points where the IAEA has visited and verified mass measurements.

This combination of uncertainty and a less-than-smooth growth pattern inevitably limits the value of predictions as to Iran's current and future capabilities—even though suitable computer modelling software is available to the authors. As a result, this report is best seen as a descriptive summary of the state of the Iranian nuclear programme today, in early 2013, around five years after the nuclear infrastructure that we know today in Iran began to take shape.

Accordingly, a similar exercise some years from now would present a useful comparison that would demonstrate the rate and extent of growth of country's nuclear programme. More time would also allow processes, such as the development of centrifuge technology and fuel fabrication, to stabilise. In addition, a similar exercise would be useful at any point were Iran to ratify and begin implementation of its Additional Protocol. Should that happen, a curtain would be lifted on large parts of the Iranian fuel cycle—particularly the very front-end, as well as nuclear-related research and development activities—and the extent of overall transparency would be greatly enhanced. That may also have the additional benefit of going a long way toward alleviating concerns over the nature and extent of Iran's nuclear programme if, as Iran claims, the programme is for peaceful purposes only.

Endnotes

1 Note that this study does not include information on research and development (R&D) facilities and activities, nor does it address companies supplying relevant technology or sites suspected of possible weaponisation activities.

2 Uranium 2011 Resources, Production and Demand: Resources, Production and Demand, p265.

3 'Iran announces uranium mining after nuclear talks fail', Reuters, 9 April 2013.

4 'Iran's Nuclear, Chemical and Biological Capabilities: A net assessment', IISS, 2005, pp50-51.

5 See http://www-pub.iaea.org/MTCD/publications/PDF/cnpp2009/countryprofiles/Iran/Iran2008.htm

6 'Iran announces uranium finds and power plant expansion', BBC News, 23 February 2013.

7 In its natural form, uranium contains more than 99 per cent of the isotope 238 and less than one per cent of the isotope 235. Centrifuge enrichment, using cascades of linked centrifuges, each one of which enriches by a tiny percentage, leads to the production of 'product' that can be almost any percentage of 235-U required. The waste product, or 'tails', is depleted UF_6.

8 GOV/2011/54, 2 September 2011, p6 (paragraph 36).

9 GOV/2011/65, 8 November 2011, p7 (paragraph 35).

10 GOV/2012/37, 30 August 2012, p7 (paragraph 33). (Note: This figure is unchanged in the IAEA's February 2013 report.)

11 Ibid.

12 GOV/2011/29, 24 May 2011, p6 (paragraph 31).

13 GOV/2011/54, 2 September 2011, p6 (paragraph 36). (Note: Here there is a discrepancy. Although nothing had been produced, the IAEA's May report clearly states that the process for the production of UO_2 was underway as of 18 May 2011. If, in June, Iran's updated schedule for the operation of the UCF noted that the production of UO_2 would only begin on 23 July, what was the IAEA referring to as happening on 18 May? One assumption might be that the conversion plant was operating on 18 May, with yellowcake being fed in, but that UO_2 product was not to be extracted from the process until 23 July and thereafter.)

14 GOV/2011/65, 8 November 2011, p7 (paragraph 37). (Note: This again calls into question what was happening on 18 May, and the assumption made in footnote 7, as this information from the IAEA seems to suggest that prior to 23 July no uranium ore concentrate whatsoever had been fed in to the UO_2 process line.)

15 Ibid.

16 GOV/2012/37, 30 August 2012, p7 (paragraph 34).

17 Ibid.

18 GOV/2013/6, 21 February 2013, p8 (paragraph 39).

19 GOV/2012/37, 30 August 2012, p7 (paragraph 35).

20 GOV/2011/54, 2 September 2011, p6 (paragraph 37).

21 Ibid., p7 (paragraph 39)

22 GOV/2011/65, 8 November 2011, p7 (paragraph 34).

23 Ibid.

24 Ibid.

25 GOV/2012/9, 24 February 2012, p7 (paragraph 35).

26 Ibid., p8 (paragraph 37).

27 GOV/2012/23, 25 May 2012, p8 (paragraph 35).

28 GOV/2012/37, 30 August 2012, p7 (paragraph 34).

29 GOV/2012/9, 24 February 2012, p7 (paragraph 34).

30 GOV/2012/23, 25 May 2012, p35 (paragraph 38).

31 Ibid. (Note: The language used here by the IAEA is somewhat unclear, but 'the process' can presumably be taken to mean the conversion of UF_6 into U_3O_8 wherever it has been taking place. Accordingly, the 71.25kg and 31.1kg figures presumably refer cumulatively to the feed and product of conversion activities undertaken at the UCF (before the FPFP came into being) and at the FPFP once that facility was up and running.)

32 GOV/2012/37, 30 August 2012, p8 (paragraph 37).

33 GOV/2013/6, 21 February 2013, p8 (paragraph 45).

34 GOV/2013/6, 21 February 2013, p4 (paragraph 12).

35 GOV/2012/37, 30 August 2012, p4 (paragraph 14).

36 GOV/2013/6, 21 February 2013, p4 (paragraph 15).

37 GOV/2013/6, 21 February 2013, p4 (paragraph 19).

38 GOV/2013/6, 21 February 2013, p4 (paragraph 20).

39 GOV/2012/37, 30 August 2012, p5 (paragraph 21).

40 GOV/2013/6, 21 February 2013, p4 (paragraph 26).

41 Ibid. (paragraph 27).

42 GOV/2011/54, 2 September 2011, p7 (paragraph 40).

43 GOV/2011/65, 8 November 2011, p7 (paragraph 36).

44 Ibid., p7 (paragraph 37).

45 GOV/2012/9, 24 February 2012, p8 (paragraph 37).

46 Ibid.

47 GOV/2011/65, 8 November 2011, p7 (paragraph 37).

48 GOV/2012/9, 24 February 2012, p8 (paragraph 37).

49 Ibid.

50 Ibid., p8 (paragraph 38).

51 GOV/2012/23, 25 May 2012, p8 (paragraph 37).

52 Ibid.

53 GOV/2012/37, 30 August 2012, p7 (paragraph 36).

54 GOV/2012/23, 25 May 2012, p8 (paragraph 38).

55 Ibid.

56 GOV/2012/37, 30 August 2012, p11 (paragraph 51).

57 Ibid., p10 (paragraph 50).

58 Ibid.

59 Ibid.

60 Ibid., p6 (paragraph 30).

61 Ibid., p7 (paragraph 31).

62 According to the IAEA's most recent safeguards report on Iran (GOV/2013/6, 21 February 2013), Iran has up to now transferred five fuel assemblies containing 20 per cent enriched U-235 and two fuel assemblies containing 3.34 per cent enriched material to the Tehran Research Reactor.

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About this paper

In this brief, David Cliff and David Keir present a technical outline of the Iranian nuclear fuel cycle, drawing primarily on the quarterly reporting of the International Atomic Energy Agency (IAEA). The aim is to provide an overview of what is known about Iran's fuel cycle and how the various parts of it link together, while also commenting on the nature and extent of IAEA safeguards coverage in the country.

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