CHAPTER 2

Securing the front end of Iran's fuel cycle

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Introduction

On 14 July 2015, Iran agreed to a Joint Comprehensive Plan of Action (JCPOA) with the permanent members of the United Nations Security Council, the European Union and Germany. In return for sanctions relief, the country pledged to downsize its nuclear ambitions and put large swathes of its nuclear fuel cycle under international monitoring. This agreement promises to put a long-running nuclear standoff between Iran and most of rest of the international community to rest.

As a consequence, Iran may find itself normalising its relations with much of the rest of the world, and it may see its economy recovering as trade starts to flow. However, that future hangs by a single hair of a horse's tail. Should Iran be suspected of straying from the deal at any stage, it may find sanctions reapplied, confounding most hopes of normal trading relations. At that stage, Iran could be pushed into seriously considering acquiring nuclear weapons. This possibility alone would stoke fears over Iran's nuclear ambitions, in turn elevating the possibility of armed conflict.

Against that backdrop, all parties to the JCPOA have a strong incentive to make the agreement successful. However, given recent history, parties also have reasons to distrust each other (see Chapter 1 by Mark Hibbs). The complicated deal, with its many reversible provisions, should be understood from that perspective. Its unique verification and monitoring provisions are a reflection of the distrust of the West, and the willingness of Iran to assuage those concerns, at least partially.

The International Atomic Energy Agency (IAEA) will play a central role in JCPOA implementation, despite not being a party to the negotiations themselves. The majority of the restrictions in the agreement will be verified through the application of established IAEA mechanisms, in particular through Iran's Comprehensive Safeguards Agreement (CSA) and the Additional Protocol.

However, the JCPOA will also increase the level of detail in IAEA accountancy in the industrial processes of mining, milling and conversion of uranium ore; which is sometimes referred to as the 'front end' of the nuclear fuel cycle. Accounting for Iran's source material aims to cut off the country's ability to develop and use clandestine enrichment and reprocessing facilities. These activities constitute the two possible routes for any country to build a domestic capacity for producing weapons-usable material). While it would be possible for the country to build such plants, they cannot operate without nuclear material. Iran cannot use materials that are accounted for by IAEA safeguards in such facilities. It would need to find them elsewhere, either through diverting its domestic supplies or through clandestine import.

This chapter will describe the front end of Iran's nuclear programme. It will outline existing verification measures applicable to it, and explore additional safeguards steps. It will conclude by offering a reflection on how well existing and proposed steps may constrain the country's ability to operate a clandestine fuel cycle.

The JCPOA

Iran's nuclear programme has grown substantially over the last decade. In 2004, it maintained modest small-scale capabilities. The debate then focused on persuading Iran to give up its enrichment programme in its entirety.[1] These efforts proved to be in vain. Ten years later, the country had put into place two working gas centrifuge enrichment facilities, and appreciably expanded the front end of its nuclear fuel cycle. However, despite this growth its assets remain meagre compared to many other countries with nuclear industries.

The country's fuel cycle is under-dimensioned for the purpose of supporting its civilian nuclear industry. However, it is adequately sized for a small weapons programme.[2] Information on Iran's activities—including facts verified by the IAEA and details alleged by some of the organisation's member states—remains concerning. Today, the country has developed a 'uranium route' that could be exploited for a nuclear explosive programme, complete with mines, conversion capabilities as well as the ability to enrich moderate amounts of uranium to weapons-grade level. The country's capacity to fabricate weapons components is less clear—and information pointing to such abilities remains largely unverified. On balance, however, Iran appears to have a basic capability to assemble fissionable material into compressible hemispheres. Moreover, the country is alleged to have conducted tests on high explosives and lens systems, and is confirmed to have tinkered with neutron initiator components.[3] All these processes are prerequisites for building a nuclear weapon, and all this information points to a potential military use of fissionable material—possibly by having used undeclared stocks (or intending to use them in the future). Therefore, the IAEA is obliged to follow up on the information, despite it being mostly unconfirmed.

The JCPOA aims to cut off all pathways through which Iran can acquire weapons. It focuses on monitoring the production and stockpiling of fissionable material rather than conclusively establishing what transpired in the programme's past. The agreement's emphasis on the future is its main strength, but also its principal weakness. It is not possible to produce nuclear explosive devices without access to fissile material, so the focus on achieving a comprehensive account of Iran's material balances is, from that perspective, a wise strategy. However, a lack of a firm understanding of what transpired in the past will make it harder to reach a broader conclusion that all nuclear material in a state has remained in peaceful activities, that is, that the state declaration is both complete and correct.

The agreement will effectively shut off Iran's ability to produce weapons-grade plutonium. The document calls for a redesign and rebuild of Iran's existing reactor—located near Arak—and sets out that it should use 3.76 per cent enriched fuel. An international partnership will certify the new design, and all spent fuel will be shipped out of the country, preventing domestic reprocessing. Moreover, Iran will cease production of heavy water and export whatever stocks it may hold in excess.[4]

The agreement focuses on Iran's burgeoning enrichment capabilities, which is not surprising given that enrichment constitutes the country's most established (as well as its fastest) pathway to a nuclear explosive device. The JCPOA limits Iran's ability to produce weapons by establishing a hard ceiling on Iran's enrichment capability for the period 2015–2023, after which the country is free to expand at a 'reasonable pace.'[5] So what is that ceiling? Until 2025, Iran is limited to using 5,060 early-generation gas centrifuges at one main facility—located near Natanz—while also keeping its stockpile of enriched hexafluoride gas to below 300 kilograms (enriched to 3.67 per cent in the isotope uranium-235).[6]

The assumed objective for Western negotiators has been to keep the time needed for Iran to produce enough fissionable material for one nuclear weapon—sometimes referred to as the 'break-out' time—to less than one year. The hard ceiling appears to meet this objective while allowing Iran to continue some of its nuclear activities. However, considerable uncertainties remain. For instance, the actual capability of the installed centrifuge design is not known.[7] Other uncertainties also remain: for instance, the tails settings (that is, the uranium depletion ratio in the waste-product) could have a deciding influence on the enriched uranium production rate, and consequently the breakout time.

Accounting for Iran's fissionable material, and putting its facilities under surveillance, should dramatically reduce—or eliminate completely—the appeal of using safeguarded material for weapons purposes. To avoid detection, Iran would need to use undeclared stocks of fissile material in undeclared facilities. Some JCPOA provisions aim to address this risk: remaining centrifuge components, for instance, are required to be placed in containment, and under surveillance. The agreement puts into place a challenge inspection regime, which allows the IAEA to visit any site in the country, albeit after a 24-day delay. Moreover, the application of the Additional Protocol should enable the agency to draw a broader conclusion that all materials that should have been disclosed have in fact been declared as required. Finally, and perhaps most importantly, enhanced monitoring measures on the front end should make it more time-consuming, and overall more costly, for Iran to acquire the necessary feed material.

The front end of Iran's nuclear programme

The most important task facing a country seeking nuclear weapons is getting hold of enough fissionable material.[8] Uranium exploration is a costly and resource-intensive industrial process. To date, two elements have been used in nuclear weapons: element 92 (uranium) and element 94 (plutonium). Three principal isotopes are useful in a weapons design: uranium-233, uranium-235, and plutonium-239.[9] Natural uranium contains about 0.7 per cent uranium-235 and 99.3 per cent uranium-238, in addition to traces of other isotopes. Uranium containing more than 20 per cent of uranium-235 is considered weapons-usable.[10]

Uranium route

Uranium ore needs to undergo extensive refinement before it can be used to fuel a weapon. For instance, and as will be noted below, Iran has declared that it may be able to produce ore containing roughly 250 kilograms of uranium per day. Of that, 1.75 kilograms would be in the isotope 235. The metal would need to contain about 50 kilogrammes in the isotope 235 to be directly usable in a nuclear explosive device. The ratio of fissile isotopes in the metal would, in other words, need to be improved by several orders of magnitude; and this is accomplished through the industrial process referred to as enrichment.

Uranium—plutonium route

Uranium can also be transmuted into plutonium, which is more directly usable in nuclear explosives. Bombarding uranium metal with neutrons creates plutonium-239, and this transmutation is a natural process occurring in nuclear reactors. From time to time, the uranium-238 will capture a neutron and increase its weight, transmuting into plutonium-239. However, if the fuel is left in the reactor too long, it risks becoming less appealing to a weapons manufacturer. From time-to-time, plutonium-239 captures another neutron, transmuting further into plutonium-240, which, although theoretically usable, is an undesirable isotope from a weapons design perspective.

When producing high-quality material for weapons, it is for these reasons preferable to use natural uranium fuel (which has a high uranium-238 content) as this maximises the production of plutonium in the isotope 239. Moreover, the amount of material undergoing fission in the reactor would need to be kept low, to minimise the production of the isotope 240. Iran's heavy-water reactor near Arak would have been perfectly suitable for this type of production. That is why the JCPOA stipulates that the Arak facility is to be converted to a type using slightly enriched fuel. Since this is scheduled to happen within the next few years, this paper will not examine potential diversion paths to the Arak plant.

Uranium imports

To date, Iran is likely to have relied on nuclear material imported from abroad to supply its nuclear fuel cycle. The country is known to have imported around 600 metric tonnes of yellowcake—a uranium concentrate powder—from South Africa in the 1970s. Over the years, this moderate stockpile may have been significantly depleted.[11] At the same time, Iran's effort to develop its indigenous sources of uranium has been slow. The lack of stocks would have forced the country to seek additional supply on international markets.

There has been no absence of speculation in the press about Iranian forays into bulk yellowcake acquisitions. Reports in 2013 about a potential uranium deal with Zimbabwe led to strong denials from the government of President Robert Mugabe.[12] According to the OECD/IAEA 'Red Book', Zimbabwe's uranium reserves are small, undeveloped, and expensive to extract; Chinese companies carry out most exploration in that region of Africa.[13] Press accounts have, moreover, claimed that Iran may seek to import uranium from the Rössing mine in Namibia, in which it holds a small financial stake. The mine has been in operation since July 1976, and has since excavated over 104,000 tonnes of uranium.[14] However, the site's operator has denied any supply deal with Iran.[15] Finally, reporting by Associated Press in 2009 alleged that Iran had tried to acquire 1,350 metric tonnes of yellowcake from Kazakhstan, the world's largest producer of yellowcake. The Kazakh government denied this report, but it is clear that it took the press account seriously, as it shortly thereafter launched an in-depth review of its uranium extraction regulations.[16]

Iranian dignitaries have also been known to visit uranium-producing countries such as Niger and Malawi.[17] While all reports of potential purchases have been denied, the prospect of an Iranian import of source material seems to be high on many suppliers' minds. Moreover, if Iran has indeed been shopping on international markets, it would appear that other international actors have forestalled its attempts.

Domestic uranium mining and milling

If the import route appears closed to Iran, it will make sense for it to try to exploit whatever domestic resources it may have available. Indeed, over the past five years, Iran has invested heavily in uranium exploration in an attempt to uncover further resources. It operates two mines, but one—Gachin—may already be heavily exploited, and is likely to be depleted at some point over the coming decade. The other—Saghand—has been under development for years and the status of operations at the site is unclear.

Gachin is a salt plug where uranium is recovered by open-pit mining. The ore grade is low—by Iran's admission some 800 parts per million (ppm) and declining.[18] The country estimates that about 100 tonnes of uranium can be recovered from the site, and the majority of that should have been extracted by now. The ore is taken from the mine to a facility called the Bandar Abbas uranium plant (BUP), which is capable of processing about 70 tonnes of uranium ore—containing about 50 kilograms of uranium—per day. This plant has been in operation since 2006.[19] Satellite imagery would suggest, however, that mining activities started in earnest in early 2010.

Saghand operates both open-pit and underground mining. The latter contains two main shafts—one main and one for ventilation—and adits and stopes are being continuously developed.[20] The ore grade in this mine is 500 ppm, and the country estimates to recover 900 tonnes of uranium from the site. Iran has built a much larger facility, the Ardakan production centre, to handle ore from this mine. It is capable of processing about 400 tonnes of ore per day, containing between 200 and 220 kilograms of uranium. The plant reportedly went into operation in 2013.[21]

Iran's total stockpile of uranium yellowcake, domestically and internationally sourced, can, therefore, be estimated to be somewhere between 600 and 700 tonnes—and much of that appears to have been converted into uranium hexafluoride (see below).[22] It may double that stockpile in the coming decade if their mining operations go to plan. After that, it would need to exploit new fields. Iran's reliance on domestic supply helps explain the emphasis in the JCPOA on establishing some degree of accountancy on the front end of the nuclear fuel cycle. But as will be discussed below, how to do that is not entirely clear.

Uranium conversion

Before enrichment and reactor operations can commence, the yellowcake would need to be further processed. Iran is doing this work at a uranium conversion facility at the Esfahan Nuclear Technology Centre (ENTC). The facility processes the yellowcake into natural uranium hexafluoride—a feedstock for subsequent enrichment—as well as uranium dioxide. It has an annual capacity of about 200 metric tonnes of uranium hexafluoride gas per year. The facility is also scheduled to produce uranium tetrafluoride as well as uranium metal ingots from natural and depleted uranium tetrafluoride. Since the plant started to operate, it has produced 550 metric tonnes of natural uranium hexafluoride, of which 185 tonnes have been shipped for subsequent enrichment.[23]

Verifying the front end of Iran's nuclear programme

Article 33 of Iran's safeguards agreement makes clear that accountancy does not apply to material in mining or ore processing activities.[24] Article 34 of the agreement defines the starting point of safeguards. Iran must report imports and exports of yellowcake for nuclear purposes to the agency.[25] The declaration must contain information on the quantity and composition of the material, and an export declaration must also declare the destination of the shipment. The import and export statement enables the agency to match the quantity with a corresponding declaration submitted by another member state.[26]

Accountancy, however, starts when material with a composition and purity suitable for fuel fabrication or for isotopic enrichment either leaves the plant or the process stage in which it has been produced.[27] Until 2003, this requirement was interpreted so that only final products of the conversion process were subject to safeguards.[28] However, for the last decade, the agency has applied safeguards at the 'first practical point' before the material *within* the conversion process achieves the required purity. In some of these cases, the agency notes, this point might be the yellowcake input at the beginning of the conversion process.[29] Normally, drums of yellowcake transported to and stored in the receipt area of the conversion plant would not be under any specific material accountancy. However, a drum would need to be weighed and assayed once removed from its storage and transferred to the hopper, from where it then enters the dissolution process.

Under the Additional Protocol, activities in a conversion plant would, in some cases, also be subject to so-called complementary access[30] by the IAEA to parts of the site, and in all cases should the facility hold a uranium weight exceeding ten metric tonnes.[31] Permitted activities include visual observation, examination of records relevant to the quantities, origin and disposition of nuclear material, environmental sampling, non-destructive measurements and sampling. Such activities are carried out with very short notice.[32]

The Additional Protocol covers most of the front end of the fuel cycle. Under it, Iran must report the location and operational status of all domestic mines, alongside their current annual and estimated future production figures.[33] As noted above, storage of yellowcake with a *uranium* weight exceeding ten metric tonnes must be reported in all circumstances.[34] However, detailed material accountancy still does not apply to uranium ore, ore concentrates or residue.[35]

Moreover, the agency has the right to get complementary access to mines on giving 24-hour notice.[36] On average, Iran should expect at least one request per mine per year. These inspections usually start with a pre-activity briefing, followed by a host presentation on the present status of the mine. Inspection activities include a facility walk-through and a visual examination of site infrastructure. The agency will take both environmental samples and conduct a non-destructive assay of selected items. The site operator should prepare to give inspectors product samples, as well as allow sampling of in-process material. Finally, inspectors will examine production records, get information on current operations, and may also examine the site's reagent consumption.[37]

The JCPOA goes beyond this. The reference to *containment* in the agreement suggests that the IAEA is required to establish continuity of knowledge on items on the front end of the fuel cycle, such as drums of yellowcake.[38] The reference to *surveillance* suggests that agreed facilities, containers or equipment should be subject to inspector observation, or through monitoring by various pieces of instrumentation, such as cameras.[39]

Specifically, the JCPOA states that the agency should monitor 'that *all* uranium ore concentrate produced in Iran or obtained from any other source, is transferred to the uranium conversion facility at Esfahan (emphasis added)'.[40] The agreement makes clear that all output from Iran's mines are required to be transferred to one location, and nowhere else, and this also applies to imported material. The emphasis on completeness indicates that stronger safeguards measures may be required than is usual in other safeguarded states.

Under the JCPOA, Iran also needs to supply 'all necessary information' needed to 'verify the production of the uranium ore concentrate and the inventory of uranium ore concentrate.'[41] In other words, as Iran's total stock of uranium ore concentrate is subject to verification, it would in all likelihood be subject to accountancy. The JCPOA does not appear to limit itself to simply enabling the agency to form a rough picture of the size and composition of Iran's front end. Instead, the provisions seem to call for detailed accountancy of Iran's yellowcake at a point well before it fulfils the requirements of Article 34 of the country's safeguards agreement.

While Iran would be treated as a special case, with accounting procedures applied on the so-called pre-34 (c) material, it would not be the only country applying safeguards on uranium ore concentrates (UOC). A recent agency policy paper says that: 'some concentration plants have produced UOC of such composition and purity that it meets the relevant purity requirements of industry standards for uranium dioxide fuel fabrication'[42] In other words, the concentrate contains so few impurities that it does not have to go through uranium conversion. In those cases, comprehensive safeguards—including material accountancy—apply on uranium ore concentrate.

Cindy Vestergaard argues, in her book *Governing Uranium*, that 'the international safeguards system is thus shifting upstream, capturing more materials at the front end of the nuclear fuel cycle.' She cautions, however, that the policy 'has yet to be fully implemented, and its success in addressing gaps in the control of natural uranium will be determined in the years to come.'[43]

Implementing front end transparency measures under the JCPOA

Iran would need to take some practical steps to fully implement the JCPOA. The exact arrangements will be kept confidential, as is the case under IAEA safeguards. However, it is possible that the following steps may be considered by the IAEA and Iran.

First, Iran would need to designate areas where yellowcake is stored. These areas are likely to be one—or perhaps several—buildings containing 200-litre drums filled with uranium concentrate. At a site visit, inspectors would confirm that all produce of the plant is stored at that location. While this may sound like a time-consuming task, it is worth recalling that Iran's mines are relatively small compared to major ore producers. Depending on how well the drums are filled, and the density of the concentrate itself, the content of each drum is expected to weigh between 500 to 650 kilograms.[44] In other words, Iran's annual output of ore—from both mines—would fit into no more than 200 drums filled to 500 kilograms.[45]

Canada, a major uranium mining country, requires that all license holders of so-called Group 2 material maintain an 'Inventory Change Document' and an 'Obligated Material Inventory Summary' for uranium ore and uranium ore concentrates.[46] The license holder needs to report inventory changes to the regulator on the business day following the transaction. The holder needs to submit an inventory summary annually on 31 January, or at any time at the regulator's request.[47] Canada has started to implement an electronic reporting system, which facilitates near-real-time reporting of balances to the IAEA.[48] Iran could usefully implement a similar system for its extractive sites.

In addition, each drum of concentrate should be individually coded and sealed. Modern bar code tagging should be applied. A wide variety of seals can be used, and their suitability depends on other installed surveillance options. If the warehouse itself is placed under camera surveillance, simple wire-loop seals can be considered. Otherwise, more reliable equipment can be applied, such as fibre-optic seals.

If the mill ships a barrel of ore concentrate to Esfahan, it would need to submit an inventory change document to the regulator, who would forward it to the IAEA. Once the conversion facility receives the drum, it would need to fill in a corresponding receipt. At that time, the coding should be checked to confirm that it matches the record at the mill (and if there is a barcode, this can be done electronically). The integrity of the seal should also be checked to make sure that no concentrate has been removed or added. Finally, the drum is placed in monitored storage at a warehouse in Esfahan. The IAEA will have near real-time data on these transactions if Iran puts in place a computer based system similar to that deployed by the Canadian nuclear regulator.

What are the diversion risks associated with a scheme like the one outlined above? One significant quantity of natural uranium is ten metric tonnes. In order to divert this much material, Iran would need to divert at least 20 barrels—or one tenth of its annual output. A diversion this scale is, for comparison, on the order of 100 magnitudes greater than the acceptable uncertainty in Australia's (another major uranium producer) accountancy system for uranium ore concentrate.[49] Detection within one year, the agency's typical timeliness detection goal, is virtually assured.

As noted above, the JCPOA requires that '*all* uranium ore concentrate produced in Iran . . . is transferred to the uranium conversion facility (UCF) in Esfahan [. . .]'.[50] Any other form of transfer would be breaking the terms of the arrangement. The above outlined verification protocol would enable the agency to detect any unauthorised transfer very quickly.

Verifying uranium ore concentrate inventories

Under the JCPOA, Iran should provide the agency with *'all necessary information* such that the IAEA will be able to verify the production of the uranium ore concentrate and the inventory of uranium ore concentrate produced in Iran or obtained from any other source for 25 years.'[51] It is not clear how much information Iran is required to give out.

The total inventory of the stockpile of uranium ore concentrate should naturally be reported, and so should its level of concentration. However, it is not clear how frequently Iran should submit this information. As noted above, it is possible to implement a regime that enables near-real time reporting on inventory levels. It is left to Iran and the agency to agree on the desired level of monitoring.

Iran should be able to furnish verifiable data on the quantity and composition of the yellowcake in each drum. The data could then be verified through, for instance, weighing and non-destructive assaying. While operator supplied scales could be used, it is preferable for the IAEA to use authenticated equipment, such as the 'load cell based weighing system'.[52]

Further checks can be introduced on the yellowcake. Destructive assay techniques, such as 'inductively coupled plasma mass spectrometry' (ICP-MS) in particular, can determine most elements down to parts per billion.[53] Deploying such equipment to the uranium mills, or regularly bringing samples to a qualified laboratory, will enable the agency to get a very comprehensive picture of the impurity content of any batch of uranium ore concentrate. However, it goes beyond that. A sampling regime involving ICP-MS could potentially allow for the content of any individual drum of yellowcake to be matched to a specific mine.[54]

All proposed measures above focus on the finished uranium ore concentrate product. But another possible diversion scenario would involve Iran misleading inspectors about the amount of ore *going into* the mill (or the uranium weight in the ore itself), and consequently underreporting the amount of produced concentrate. However, keeping the mill under continuous surveillance by, for instance, deploying some next generation surveillance system (NGSS) cameras to the mill, could minimise the risk that this scenario occurs. The NGSS collects visual evidence through a networked set of cameras. Images are sent back to a 'consolidator unit' (a databank), which—if Iran agrees—can transmit the data back to Vienna. Public key encryption protects the data.[55]

Ore could also be shipped to a clandestine mill. This would be harder to detect. However, the JCPOA allows for short-notice inspections of suspected undeclared mills. Moreover, space surveillance and other national technical means are likely to provide strong indicators of where clandestine milling may occur.[56]

Even if domestic production of uranium ore concentrate is subject to robust safeguards, the possibility remains that Iran may clandestinely import material. At the moment, exports to Iran are restricted through a set of UN Security Council resolutions.[57] These resolutions will be lifted as the JCPOA goes through implementation. The onus will remain on exporting states to ensure that their exports are reported to the agency in accordance with the export rules in their safeguards agreements.

Monitoring the conversion to uranium hexafluoride

Eventually, the yellowcake will need to be shipped to the conversion plant at the ENTC. At some point in this process, detailed nuclear material accountancy measures will start to apply. Nuclear material leaving the plant is likely to have reached 'a composition and purity suitable for fuel fabrication or for being isotopically enriched.'[58] In Iran's case, the main product of concern is natural uranium hexafluoride, which can be used in subsequent enrichment processes. Uranium hexafluoride is versatile, at atmospheric pressure it remains solid until it is heated to about 50 degrees Celsius, at which point it sublimes into gas. This allows it to be used in centrifuges. The compound is usually stored in standard steel drums—designated 48T through G—that have a fill limit of 9.3 to 12.1 metric tonnes of uranium respectively.[59] Overfilling the drums can lead to severe accidents, possibly rupturing the tank when the material sublimes. The enriched material has to be stored in smaller drums.

The IAEA will always account for the final products of the conversion process (that is uranium hexafluoride, uranium tetrachloride, metallic uranium or uranium dioxide). Until 2003, the feed itself was not subject to any safeguards procedures.[60] Inspectors arriving at a plant would weigh and assay the product, but not do any corresponding verification in the feed areas of the plant. A plant operator could theoretically keep two books. The one examined by the inspectorate could understate receipts of yellowcake—opening up the possibility of clandestine production.

For the last decade, however, material accountancy at conversion plants has begun at the 'first practicable point' in the conversion process, in some cases where the uranium concentrate itself is inputted.[61] In most states, the drums of yellowcake themselves are not subject to any safeguards procedure. Accountancy starts when the drums arrive at the conversion plant. As noted above, there is an emerging exception to this rule. The IAEA has recently been considering moving the starting point of safeguards further to the front of the nuclear fuel cycle.

Uranium conversion is the stage where the nuclear material becomes more tangible and identifiable. This allows for the material to be identified, counted, and where appropriate, sealed. The main difficulty with verification in conversion plants, as in mines, is that the quantities may be large, although this may not be a major factor in Iran at the moment. The material not being especially toxic at this stage, and as criticality risks are non-existing or low, material is easy to remove at any stage.[62]

As noted above, the Iran's conversion facility has a stock of about 365 metric tonnes of natural uranium hexafluoride. The JCPOA states that Iran can hold a total enriched uranium stockpile of no more than 300 kilograms of up to 3.67 per cent enriched uranium hexafluoride.[63] The remainder should be down-blended to natural uranium or sold on international markets.[64] The hard ceiling means that approximately two metric tonnes of natural uranium hexafluoride—less than half a per cent of Iran's available stock—can be used for enrichment purposes, and the rest would need to be held back in storage.

The 48Y-type cylinder—a standardised container used to store uranium hexafluoride—has a maximum fill limit of 12,500 kilogrammes.[65] Iran's presently unshipped stockpile is, therefore, likely to be stored presumably on site in more than 30 cylinders. Another 15 cylinders of down blended material are likely to be added to this stock in the coming year. Given the hard inventory ceiling, this stockpile is unlikely to change much over the coming years, and so should be relatively easy to verify.

In 2012, the IAEA approved the 'Laser Item Identification System' (L2IS) for safeguards use.[66] The system is designed for keeping track of the movement of cylinders in enrichment plants, but could equally be used in conversion facilities. The system has two units. A portable unit allows the inspectors to 'fingerprint' all cylinders that the operator intends to use over a period of time. It does so by reading the microstructure of each drum's surface. A stationary unit—placed at strategic entry and exit corridors—then scans cylinders as they pass through, comparing the laser-image with the template. The system is hence capable of tracking individual cylinders through their use. Given that Iran's inventory is stored in relatively few cylinders, it should be relatively straightforward to fingerprint all of them.

Conclusion

The JCPOA is a complicated agreement—see Mark Hibbs' chapter in this book—containing many interlocking components. The present chapter has looked at how the agency can introduce stricter monitoring on the front end of Iran's nuclear fuel cycle. Introducing such controls, on a scale envisioned by this chapter, would place Iran's uranium extractive industries under state-of-the-art monitoring. It cannot provide foolproof assurances against clandestine uranium import or extraction, but would radically increase detection probabilities, and would make any attempted diversion of source material more expensive.

In the longer term, more countries are likely to bring their extractive industries under a stronger monitoring framework, and Canada's experience as a major uranium producer serves, from this perspective, as an illustrative example. JCPOA implementation in Iran is, therefore, an opportunity to learn how to conduct front end monitoring in a more effective and, in the long run, more economical way.

For Iran and its JCPOA partners, enhanced front end monitoring is only one aspect of a broader verification package. Nevertheless, establishing a firmer grip on the production and import of source material will make the verification task down-stream in the nuclear fuel cycle far easier. It will also make it easier for the agency to some day reach a broader conclusion that all nuclear material in Iran has been declared as required.

Endnotes

1 See for instance, Kerr, Paul. 'Iran Agrees to Temporarily Suspend Uranium-Enrichment Program.' Arms Control Today. December 1, 2004. Accessed September 25, 2015. www.armscontrol.org/act/2004_12/Iran.

2 This has been discussed in both literature and government statements. See, for instance, Hecker, Siegfried, and Perry, William. 'Iran's Path to Nuclear Peace.' The New York Times. January 9, 2014. Accessed September 25, 2015. www.nytimes.com/2014/01/10/opinion/irans-path-to-nuclear-peace.html?_r=0. And DeSutter. Paula. 'Iranian WMD and Support of Terrorism.' US Department of State. December 17, 2003. Accessed October 16, 2015. 2001-2009.state.gov/t/vci/rls/rm/24494.htm.

3 This information was brought to the public domain by the IAEA in 2011; see 'Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions in the Islamic Republic of Iran (GOV/2011/65).' International Atomic Energy Agency. November 11, 2011. Accessed September 23, 2015.

4 JCPOA, operative paragraphs 7, 8 and 10.

5 JCPOA, operative paragraph 1.

6 JCPOA, operative paragraphs 2 and 7. Iran's workhorse centrifuge is the IR-1. In the past, these machines have been capable of producing between 0.59 and 0.79 kg/SWU per year. See Persbo, Andreas. 'Progress at Natanz (reposted).' February 27, 2009. Accessed September 28, 2015. www.armscontrolverification.org/2009/02/progress-at-natanz-reposted.html?q=SWU. The agreement also puts limitations on Iran's research and development work. Until 2025, it can only test the already existing series of machines, domestic designations IR-4, 5, 6 and 8, see operative paragraph 3. The enrichment ceiling corresponds to the fuel requirements of Iran's redesigned heavy water reactor.

7 Heinonen, Olli, and Henderson, Simon. 'How to Make Sure Iran's One-Year Nuclear Breakout Time Does Not Shrink.' Policy Watch #2436. June 17, 2015. Accessed September 25, 2015. www.washingtoninstitute.org/policy-analysis/view/how-to-make-sure-irans-one-year-nuclear-breakout-time-does-not-shrink.

8 Fissionable material is a nuclide that is capable of undergoing fission after capturing either high-energy (fast) neutrons or low-energy thermal (slow) neutrons. See 'Fissionable Material.' NRC: Glossary. July 1, 2015. Accessed October 16, 2015. www.nrc.gov/reading-rm/basic-ref/glossary/fissionable-material.html.

9 Fissile material is a nuclide that is capable of undergoing fission after capturing low-energy thermal (slow) neutrons. See 'Fissile Material.' NRC: Glossary. July 23, 2015. Accessed October 16, 2015. www.nrc.gov/reading-rm/basic-ref/glossary/fissile-material.html.

10 The distinction is arbitrary. It is indeed possible to construct a nuclear explosive device using uranium enriched to below 20 per cent in the isotope 235, but it would be very unpractical. The critical mass—the minimum amount of fissile material needed to maintain a nuclear chain reaction—decreases with increasing levels of enrichment. Near infinite amounts of uranium would be required for a device using uranium enriched to less than 5 per cent in the isotope 235. See Forsberg, C.W. and Hopper, C.M. 'Definition of Weapons-Usable Uranium-233.' web.ornl.gov. March 1998. Accessed September 28, 2015. web.ornl.gov/info/reports/1998/3445606060721.pdf.

11 Albright, D, Shire, J, and Brannan, P. 'Is Iran Running out of Yellowcake?' ISIS Reports. February 11, 2009. Accessed August 28, 2015. isis-online.org/uploads/isis-reports/documents/Iran_Yellowcake_11Feb2009.pdf.

12 'Alleged Iranian Uranium Deal With Zimbabwe May Revive Sanctions Debate | GSN | NTI.' NTI: Nuclear Threat Initiative. August 21, 2013. Accessed October 23, 2015. www.nti.org/gsn/article/alleged-iranian-uranium-deal-zimbabwe-may-revive-sanctions-debate/.

13 See *Uranium 2014 Resources, Production and Demand*. Paris: OECD/IAEA, 2014, pp. 20, 33 and 200.

14 See *Uranium 2014 Resources, Production and Demand*. Paris: OECD/IAEA, 2014, p. 324.

15 Iran owns 15 per cent of the Rössing mine. It seems likely that Iran's 1970s import came from here, but the present owner has not explicitly commented on that. See Maletsky, Christof. 'Iran Did Not Buy Uranium from Rössing, Says Govt.' The Namibian, February 1, 2005. Accessed September 28, 2015.

16 Vestergaard, Cindy. Governing Uranium Globally. Copenhagen: DIIS, 2015, pp. 95

17 See 'Iran's Ahmadinejad Visits Uranium-producing Niger.' Reuters. April 15, 2013. Accessed October 26, 2015. http://www.reuters.com/article/2013/04/15/us-iran-niger-idUSBRE93E0RL20130415; and 'Malawi Gets $50m Iran Aid for Mining.' Malawi Nyasa Times. July 29, 2011. Accessed October 26, 2015. www.nyasatimes.com/2011/07/29/malawi-gets-50m-iran-aid-for-mining/.

18 A grade below 1,000 parts per million is characterised as 'low grade'. See 'World Nuclear Association.' Uranium Supplies: Supply of Uranium. September 1, 2015. Accessed September 28, 2015. www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Supply-of-Uranium/.

19 See *Uranium 2014 Resources, Production and Demand*. Paris: OECD/IAEA, 2014, p. 269. If the mill has been going at full capacity since it opened, Iran would have extracted approximately 164 tonnes by now. In other words, far more metal than the mine is supposed to hold.

20 See *Uranium 2014 Resources, Production and Demand*. Paris: OECD/IAEA, 2014, p. 267. An adit is a horizontal passage leading into a mine for the purposes of access or drainage, and a stope is a step-like working in a mine.

21 'Iran Unveils Uranium Activities at Saghand and Ardakan.' BBC News. April 9, 2013. Accessed August 28, 2015. www.bbc.co.uk/news/world-middle-east-22076784. At full extraction rate, the site will be depleted sometime in 2025.

22 This estimate is based on the import of 600 metric tonnes, in addition to mining activity at Gachin starting from about February 2010, and at declared capacity.

23 To produce this, Iran would have used about 60 metric tonnes of fluorine and another 125 metric tonnes of hydrogen fluoride in addition to about 380 metric tonnes of yellowcake.

24 See 'The Text of the Agreement Between Iran and the Agency for the Application of Safeguards in Connection with the Treaty on the Non-proliferation of Nuclear Weapons (INFCIRC/214).' December 13, 1974. Accessed November 2, 2015. www.iaea.org/publications/documents/infcircs/text-agreement-between-iran-and-agency-application-safeguards.

25 INFCIRC/214, article 34 (a) and (b)

26 These are not verified, so it is in theory possible for two colluding countries to understate an export and import declaration, hence giving the impression that *less* material has been transferred. The unreported yellowcake can then be diverted to an undeclared facility.

27 INFCIRC/214, article 34 (c)

28 See paragraph 8 in 'Safeguards Measures Applicable in Conversion Plants Processing Natural Uranium (Policy Paper 18).' *Safeguards Policy Series* SMR 2.18. Vienna: International Atomic Energy Agency, 2003. These materials include uranium hexafluoride or uranium tetrachloride for subsequent enrichment, and metallic uranium or uranium dioxide for fabrication into fuel.

29 Policy Paper 18, paragraph 10.

30 Complementary access—a type of inspection—is provided by the state to IAEA inspectors in accordance with the provisions of an additional protocol.

31 Compare INFCIRC/540, article 2.a.(i) and (ii) and article 2.a.(vi) (a).

32 Policy Paper 18, paragraph 19.

33 INFCIRC/540, article 2.a (v).

34 INFCIRC/540, article 2.a. (vi).

35 INFCIRC/153, paragraphs 33 and 112.

36 INFCIRC/540, articles 4-9.

37 East, Michael. 'Safeguards Reporting and Verification for Uranium Mines.' Lecture, IAEA Training Meeting on Effective Regulatory and Environmental Management of Uranium Production, Darwin, Australia, August 13, 2012.

38 Containment is defined as: 'structural features of a facility, containers or equipment which are used to establish the physical integrity of an area or items (including safeguards equipment or data) and to maintain the continuity of knowledge of the area or items by preventing undetected access to, or movement of, nuclear or other material, or interference with the items. Examples are the walls of a storage room or of a storage pool, transport flasks and storage containers. The continuing integrity of the containment itself is usually assured by seals or surveillance measures (especially for containment penetrations such as doors, vessel lids and water surfaces) and by periodic examination of the containment during inspection.' See *IAEA Safeguards Glossary*. 2001 ed. Vienna: International Atomic Energy Agency, 2002, section 8.1 at p. 66.

39 Surveillance is described as: 'the collection of information through inspector and/or instrumental observation aimed at detecting movements of nuclear material or other items, and any interference

with containment or tampering with IAEA equipment, samples and data. Surveillance may also be used for observing various operations or obtaining relevant operational data. IAEA inspectors may carry out surveillance assignments continuously or periodically at strategic points.' See *IAEA Safeguards Glossary*. 2001 ed. Vienna: International Atomic Energy Agency, 2002, section 8.2 at p. 66.

40 JCPOA, paragraph 68.

41 JCPOA, paragraph 69.

42 *Determination of Uranium Bearing Materials Meeting the Conditions of Paragraph 34(c) of INFCIRC/153 (Corrected) (Policy Paper 21)*. Vienna, Austria: International Atomic Energy Agency, 2013, paragraph 13.

43 Vestergaard, Cindy. Governing Uranium Globally. Copenhagen: DIIS, 2015, p. 48.

44 One typical 200-litre drum holds 218,276 cubic centimetres when filled to the brim; and yellowcake has a density of 2.5 to 3.0 grams per cubic centimetre. See *Production of Yellow Cake and Uranium Fluorides: Proceedings of an Advisory Group Meeting Organized by the International Atomic Energy Agency and Held in Paris, 5–8 June, 1979*. Vienna: International Atomic Energy Agency, 1980.

45 18,250 kg (50 kg × 365 days) or about 37 drums would come from Bandar Abbas and 80,300 kg (220 kg × 365 days) or about 160 drums would come from Saghand. Uranium ore concentrate is rarely 100 per cent pure, so about 15 per cent of the weight would be various other soluble and insoluble material. See page 9 in Marzo, Marco Antonio Saraiva, Lilia Crissiuma Palhares, Fabio Cordeiro Diaz, Marcos Sodré Grund, Ana Claudia Raffo-Caiado, John M. Begovich, Juan J. Ferrada, and Jennifer Ladd-Lively. *Model of a Generic Natural Uranium Conversion Plant—Suggested Measures to Strengthen International Safeguards (ORNL/TM-2008/195)*. Oak Ridge, TN: Oak Ridge National Laboratory, 2009.

46 The regulator defines Group 2 material as 'natural uranium and natural thorium (including ores and ore concentrates) that has not reached the stage in the nuclear fuel cycle when composition and purity is suitable for fuel fabrication or isotopic enrichment.' It states that, in general, 'this material is possessed by mines, mills, concentration plants, and refineries under licence from CNSC.' See section 4.2.2 and 6 in 'Accounting and Reporting of Nuclear Material (RD-336).' Canadian Nuclear Safety Commission. 2011. Accessed November 6, 2015. nuclearsafety.gc.ca/pubs_catalogue/uploads/RD-336_Final_Accounting_and_Reporting_of_Nuclear_Material_e.pdf.

47 RD-336, section 7.

48 Sample, Jennifer. 'Establishing and Advancing Electronic Nuclear Material Accounting Capabilities A Canadian Perspective.' Lecture, IAEA Symposium on International Safeguards: Linking Strategy, Implementation and People, International Atomic Energy Agency, Vienna, October 22, 2014.

49 See Governing Uranium, p. 93.

50 JCPOA, paragraph 68

51 JCPOA, paragraph 69

52 Safeguards techniques and equipment. 2011 edition. Vienna: International Atomic Energy Agency, 2011, p. 38.

53 Safeguards techniques and equipment. 2011 edition. Vienna: International Atomic Energy Agency, 2011, p. 105

54 See, for instance, Keegan, Elizabeth, Michael J. Kristo, Michael Colella, Martin Robel, Ross Williams, Rachel Lindvall, Gary Eppich, Sarah Roberts, Lars Borg, Amy Gaffney, Jonathan Plaue, Henri Wong, Joel Davis, Elaine Loi, Mark Reinhard, and Ian Hutcheon. 'Nuclear Forensic Analysis of an Unknown Uranium Ore Concentrate Sample Seized in a Criminal Investigation in Australia.' *Forensic Science International*: 111-21.

55 Safeguards techniques and equipment. 2011 edition. Vienna: International Atomic Energy Agency, 2011, p. 67

56 After all, the ore would need to be transported. This would lead to vehicular traffic, which is easily picked up by space-based monitoring assets.

57 See, in particular, 'Resolution 1737 (2006) adopted by the Security Council at its 5612th Meeting, on 23 December 2006.' December 23, 2006. Accessed November 20, 2015. www.iaea.org/sites/default/files/unsc_res1737-2006.pdf. See also 'Resolution 1929 (2010) adopted by the Security Council at its 6335th Meeting, on 9 June 2010.' June 9, 2010. Accessed November 20, 2015. www.iaea.org/sites/default/files/unsc_res1929-2010.pdf.

58 'The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-proliferation of Nuclear Weapons.' INFCIRC/153. Accessed September 2, 2015. www.iaea.org/sites/default/files/publications/documents/infcircs/1972/infcirc153.pdf, see paragraph 34 (c).

59 See 'Manual on Safe Production, Transport, Handling and Storage of Uranium Hexafluoride (IAEA-TECDOC-771).' Vienna: International Atomic Energy Agency, November 1994. Accessed October 5, 2015, www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/030/28030673.pdf, p. 41.

60 See Safeguards Policy Series, Number 18. Safeguards Measures Applicable in Conversion Plants Processing Natural Uranium. Vienna: International Atomic Energy Agency, June 2003, paragraph 8.

61 See Safeguards Policy Series, Number 18. Safeguards Measures Applicable in Conversion Plants Processing Natural Uranium. Vienna: International Atomic Energy Agency, June 2003, paragraph 10.

62 'The Present Status of IAEA Safeguards on Nuclear Fuel Cycle Facilities.' IAEA Bulletin, vol. 22, no 3/4, August 1980.

63 JCPOA, Annex 1, paragraph J.56.

64 JCPOA, Annex 1, paragraph J.57.

65 See 'Manual on Safe Production, Transport, Handling and Storage of Uranium Hexafluoride (IAEA-TECDOC-771).' Vienna: International Atomic Energy Agency, November 1994. Accessed October 5, 2015, www.iaea.org/inis/collection/NCLCollectionStore/_Public/28/030/28030673.pdf, p. 41.

66 Gonçalves, João G. M., Said Abousahl, Yetunde Aregbe, Willem Janssens, Klaus Lützenkirchen, Paul Meylemans, and Peter Schwalbach. 'The European Commission Cooperative Support Programme: Activities and Cooperation.' Proceedings of the IAEA Safeguards Symposium 2014. October 2014. Accessed October 6, 2015.