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James Acton with Joanna Little

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Glossary

Acronyms and abbreviations

CBM	Confidence-building measure
CWC	Chemical Weapons Convention (1993)
C&S	Containment and surveillance
DA	Destructive analysis
DIV	Design information verification
GCEP	Gas centrifuge enrichment plant
HWR	Heavy water reactor
IAEA	International Atomic Energy Agency
LFUA	Limited frequency unannounced access
LWR	Light water reactor
MBA	Material balance area
MUF	Material unaccounted for
NDA	Non-destructive assay
NEA	Nuclear Energy Agency (OECD)
NPT	Nuclear Non-Proliferation Treaty (1968)
OECD	Organisation for Economic Co-operation and Development
OPCW	Organisation for the Prohibition of Chemical Weapons
OSCC	Open Skies Consultative Committee
PIV	Physical inventory verification
SNRI	Short notice random inspection
SQ	Significant quantity
SWU	Separative work units
WAEM	Wide area environmental monitoring

Iranian nuclear facilities

BNPP	Bushehr Nuclear Power Plant
FEP	Fuel Enrichment Plant
FMP	Fuel Manufacturing Plant
HWPP	Heavy Water Production Plant
IR-40	Iran Nuclear Research Reactor
KEC	Kalaye Electric Company
PFEP	Pilot Fuel Enrichment Plant
UCF	Uranium Conversion Facility
ZMP	Zirconium Manufacturing Plant

Nuclear materials

DU	Depleted uranium
DUF_6	Depleted UF_6
HEU	High enriched uranium
LEU	Low enriched uranium
$LEUF_6$	Low enriched UF_6
$LEUO_2$	Low enriched UO_2
NU	Natural uranium
NUF_6	Natural UF_6
NUO_2	Natural UO_2
UF_6	Uranium hexafluroide
UO_2	Uranium dioxide
UOC	Uranium ore concentrate
UO_2F_2	Uranyl fluoride
$UO_2(NO_3)_2$	Uranyl nitrate

Mathematical symbols

(Only symbols used in the main text, not in appendices are listed here)

α	False alarm probability
β	Detection probability

δ_E	Relative error in closing a material balance
Δ	Size of material diversion that can be detected for given α and β
σ(MUF)	Standard deviation of MUF
T(M)	The throughput of material M through a given facility

Foreword

The development of nuclear energy has important benefits and applications, most notably in electricity generation and medical science. However, the same technology and materials can also be adapted and utilised in nuclear weapons, to wreak havoc on an almost unimaginable scale. It is the Janus-like nature of nuclear research and technology (as well as the possibility of a severe nuclear accident) that create concern about the development of new nuclear power programmes. This is especially so if such programmes, for whatever reason, are established under a veil of secrecy. The current controversy surrounding Iran's nuclear plans is a case in point.

Iran failed to fully inform the international community about its ambitious plans to master the nuclear fuel cycle. This secrecy has given rise to considerable suspicion and distrust of Iran's intentions with regard to its newly acquired technology. Consequently its programme may, even if it was always meant to be peaceful, have a profound impact on regional stability and, indeed, international peace and security as a whole. Therefore, it is fundamentally important that international trust in Iran's intentions is restored.

This paper, together with its companion study, collectively aim to identify a range of possible verification, transparency and confidence-building mechanisms—through which trust can be re-established and further strengthened. The two papers are written from a technical and legal perspective and are intended to give an independent, impartial and dispassionate analysis of possible measures and processes to facilitate resolution of the current situation.

The aim of verification is to establish or increase confidence that all parties are implementing an agreement fairly and effectively. However, no verification regime is ever going to be one hundred per cent effective. Such verification mechanisms in isolation would only partly address the international community's concerns. International trust in Iran's long term intentions cannot be restored simply by making sure that no nuclear material is diverted. The solution has to be broader, transparent, legally binding, and based on dialogue and respect. Additional confidence-building measures could play an important role in strengthening any agreed verification system, promoting transparency and allowing states to demonstrate goodwill.

Although these two VERTIC reports concentrate on the case of Iran's nuclear programme, we believe they are more widely applicable. The world seems to be facing a nuclear renaissance, and questions relating to the intentions of states are bound to surface again, long after the Iranian issue is solved and forgotten. It is therefore important to think in terms of what, if any, verification, transparency and confidence-building measures can be devised and applied if and when a country is attempting to develop a nuclear programme, in order to address the potential concerns of the international community.

I am grateful to our reviewers, drawn from various governments and academia on three continents, whose comments on the two reports were invaluable. Indeed, their advice, support, and enthusiasm were much appreciated by the research staff and have strengthened the final product. Finally, I wish to thank the Joseph Rowntree Charitable Trust for funding these studies—and for its unwavering support for VERTIC and its mission.

Michael Crowley
Executive Director, VERTIC

Introduction

International Atomic Energy Agency (IAEA) safeguards exist to build trust that states' nuclear programmes are exclusively peaceful in nature. In the vast majority of cases they have been successful in achieving this aim. A robust verification system, based on intrusive inspections, usually places the IAEA in a position where it can provide credible reassurance that states are complying with their treaty commitments. In a few cases, however, nuclear safeguards have failed to build trust. Sometimes this is a result of the IAEA being unable to verify compliance. More often, however, it is because the IAEA has not been able to provide sufficient evidence to convince doubters that a state's nuclear programme is exclusively peaceful.

If a state finds that existing safeguards do not enable it to demonstrate the exclusively peaceful nature of its nuclear programme, it has the option of accepting additional safeguards on a voluntary basis.[1] This paper explores how a state might use such 'transparency measures' to build trust. In order to make the discussion more concrete, it focuses on Iran—the most pertinent current example of a state suffering from a lack of trust in its nuclear programme. In this case the trust deficit is severe. Examination of Iran therefore affords an opportunity to consider some more radical confidence-building measures (CBMs) that might not be needed in other cases. None of the measures proposed here, however, is specific to Iran—they could all be applied to other states with the proviso that where the trust deficit is less extreme fewer or less radical measures will be required.

It is beyond the scope of this paper to provide a detailed history of the IAEA's investigations into Iran's nuclear programme. For current purposes it is sufficient to state that, according to the IAEA Director General in an August 2006 report on the subject, 'the Agency remains unable to make further progress in its efforts to verify the completeness and correctness of Iran's declarations with a view to confirming the peaceful nature of Iran's nuclear programme'.[2] Subsequent reports have not drawn different conclusions.

In an attempt to resolve various outstanding questions, the IAEA has requested that Iran implement further 'transparency measures . . . which extend beyond the formal requirements of the Safeguards Agreement and Additional Protocol'.[3] The UN Security Council has endorsed this request three times, in resolutions 1696, 1737 and 1747, calling on Iran 'without further delay to take the steps required by the IAEA Board of Governors'.[4]

In addition, the Security Council has demanded that Iran suspend 'all enrichment-related and reprocessing activities, including research and development'[5] as well as 'work on all heavy water-related projects'.[6] At the time of writing, Iran has not provided the IAEA with all the information requested or access. Nor has it suspended its enrichment or heavy water reactor (HWR) programmes.[7]

An additional Security Council resolution would be required for Iran to be permitted to restart its enrichment or HWR programmes—permission to restart these programmes is *not* an automatic result of an IAEA finding that Iran has come back into compliance with its safeguards agreement. In the interests of facilitating a diplomatic settlement to the current dispute, one possibility would be for the Security Council to assure Iran that it would be permitted to restart some or all of its proliferation-sensitive activities under additional safeguards as soon as it has complied with the Security Council's demands and the IAEA has resolved all the outstanding questions about its nuclear programme.[8] This paper seeks to analyse how additional safeguards and other transparency measures could be employed in these circumstances to help build trust in the exclusively peaceful nature of Iran's nuclear programme. Such safeguards would be 'voluntary' in the sense that Iran would have freely chosen to adopt them as part of a negotiated settlement. They could, however, form part of a formal agreement that would be binding once entered into.

It is important to reiterate that nothing in this paper should be taken to imply that Iran's adherence to Security Council resolutions is optional. Instead, this paper recognizes that should Iran suspend its enrichment programme, negotiations with the E3+3 (France, Germany and the United Kingdom plus China, Russia and the United States) would follow.[9] The future of the Iranian nuclear programme would certainly be discussed in such talks. Iran has frequently expressed scepticism that the Security Council would ever permit it to recommence sensitive nuclear activities—and it is highly probable that some of the E3+3 might oppose the Security Council lifting its prohibitions against such activities, even if all outstanding questions about the peaceful nature of Iran's nuclear programme had been answered. This is likely to be a serious barrier to a negotiated settlement. However, it might be possible to reach an agreement in which Iran recommenced some or all of its sensitive nuclear activities following its fulfilment of the Security Council's requirements and the introduction of agreed additional nuclear safeguards and transparency measures.

Under such an arrangement, Iran might initially limit its uranium enrichment to a small-scale pilot project under additional safeguards. In the longer term, however, once international trust had been fully restored, additional safeguards would no longer be necessary and Iran could start its own commercial enrichment facility—if it still wanted to do so. Indeed, additional transparency measures may be useful not only to create the right environment for an initial agreement on the restart of Iran's pilot enrichment facility, but also to rebuild trust in the long term.

It seems certain that much more than Iran's nuclear programme would be discussed in talks between Iran and the E3+3. In the context of these wider discussions Iran might offer to halt further development of, or to completely abandon, certain elements of its nuclear programme. To enable the international community to respond to an offer of this kind in an appropriate manner, it is necessary to establish how effective such measures would be from a confidence building perspective. For instance, if—because of the possibility of a clandestine programme—a permanent cessation of enrichment would have little effect on Iran's ability to produce nuclear weapons, there would be little point in the E3+3 making substantial concessions in order to achieve such a cessation. This paper therefore also considers how much confidence Iran could build by terminating various parts of its nuclear programme.

In summary, therefore, the aims of this paper are three-fold: (a) to identify additional safeguards and other transparency measures that Iran could implement voluntarily with the aim of building trust in its nuclear programme; (b) to analyse the measures individually and determine, from a confidence building perspective, how effective each is likely to be; and (c) to suggest which measures should be prioritized as part of a negotiated settlement.

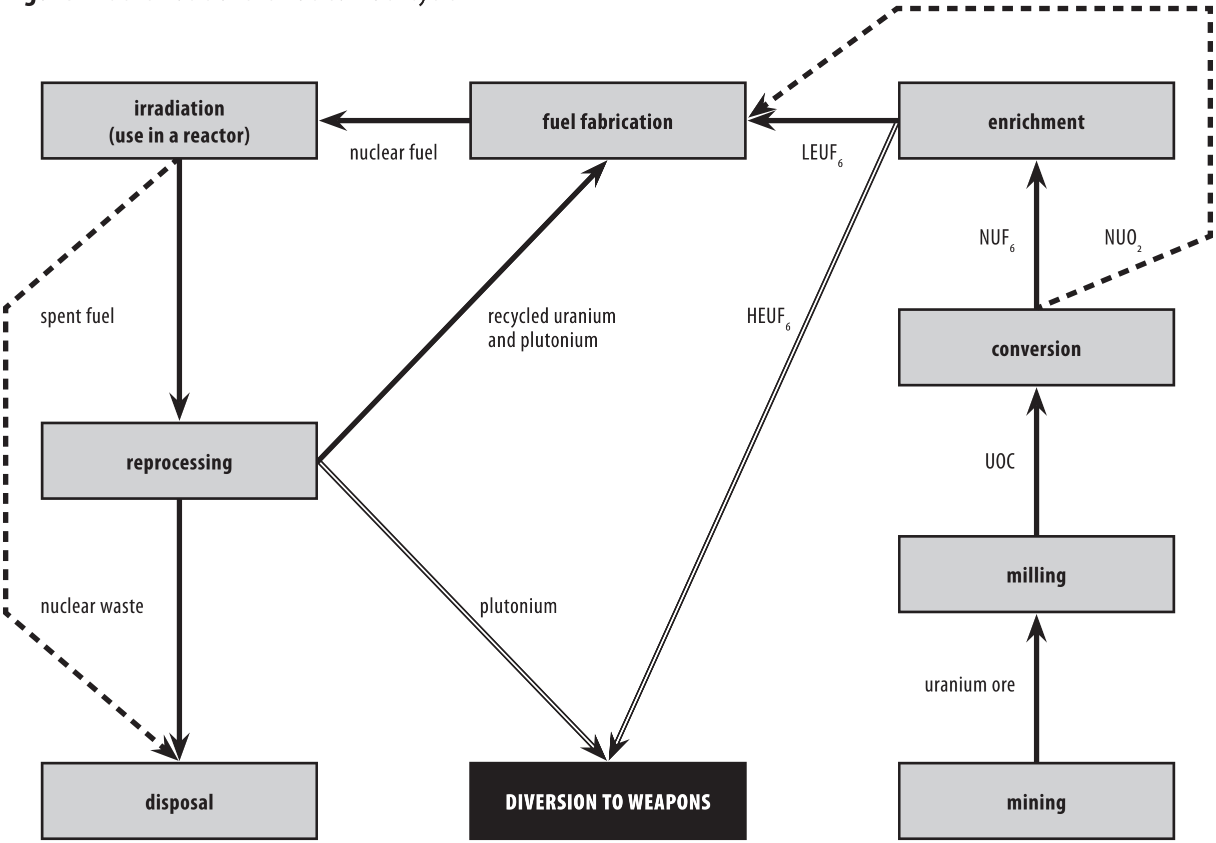
An accompanying VERTIC report examines the legal issues surrounding confidence building.[10] In particular, it presents a detailed analysis of what is required of Iran under existing Security Council resolutions and outlines a possible legal framework to facilitate the confidence-building process.

Background: nuclear proliferation and nuclear safeguards

This section briefly outlines the nuclear fuel cycle and provides a summary of how IAEA safeguards work.

The nuclear fuel cycle principally concerns two materials: uranium-235 and plutonium. These undergo fission and hence can be used as fuel for nuclear power plants and in nuclear weapons. Plutonium does not occur naturally: it is synthesized in nuclear reactors. Uranium does occur naturally, but as a mix consisting of 99.3 per cent uranium-238 and only 0.7 per cent uranium-235. Although some nuclear reactors use natural uranium, most require it to be enriched to between three and six per cent (the enrichment level of the fuel being the percentage of uranium-235 it contains). Nuclear weapons typically require uranium enriched to more than 80 per cent. Uranium with an enrichment level of below 20 per cent is termed low enriched uranium (LEU). Uranium enriched to above 20 per cent is termed high enriched uranium (HEU). The main stages in the nuclear fuel cycle are listed below and summarized in figure 1. It is important to emphasize that there are many variants on the scheme discussed here. For instance, many countries do not reprocess spent nuclear fuel; a significant proportion of reactors use natural uranium, which means that enrichment is not required;

Figure 1 Schematic of the nuclear fuel cycle



Note: The dashed lines indicate activities which are omitted in various states. The double lines indicate the points at which material directly usable in nuclear weapons can be diverted.

and conversion and fuel fabrication involve a number of sub-processes, which are occasionally split across more than one facility.

- *Mining:* uranium ore is extracted from the earth. It typically contains less than 2 per cent uranium by weight—often much less.
- *Milling:* uranium ore is chemically purified to form uranium ore concentrate (UOC, sometimes known as yellowcake). UOC is uranium oxide—normally U_3O_8 but sometimes UO_3 or UO_4.
- *Conversion:* UOC is purified further and chemically converted into a form appropriate for its use. For enrichment it is almost always converted into uranium hexafluoride (UF_6). If it is to be used in a reactor fuelled by natural uranium it is normally converted into uranium dioxide (UO_2) or uranium metal.

- *Enrichment*: a physical process such as centrifuging or gaseous diffusion is used to increase the percentage of uranium-235 in the material (by preferentially extracting those UF_6 molecules containing uranium-235). Essentially, the same technology can be used to produce LEU for a reactor or HEU for a bomb. Depleted uranium (uranium containing less uranium-235 than natural uranium) is produced as a by-product of this process.
- *Fuel fabrication:* typically, low enriched UF_6 is chemically converted into low enriched UO_2, which in turn is fabricated into reactor fuel. Depending on the type of reactor, however, fuel can also be made from a number of other materials including uranium metal (low enriched or natural) and natural UO_2.
- *Irradiation:* the fuel is used in a nuclear reactor to produce energy. Plutonium is produced as a by-product.
- *Reprocessing:* this plutonium and the unused uranium are extracted from the spent fuel and ultimately recycled. The plutonium produced in this process could be used in a nuclear weapons programme.
- *Disposal:* waste products from reactors and reprocessing are placed into casks and stored.

Under the terms of the 1968 Nuclear Non-Proliferation Treaty (NPT), the IAEA is charged with safeguarding the nuclear fuel cycle 'with a view to preventing diversion of nuclear energy from peaceful uses to nuclear weapons or other nuclear explosive devices'.[11] More detailed arrangements for safeguards are set out in an agreement, known as the Comprehensive Safeguards Agreement, which non-nuclear weapon state parties to the NPT are obliged to conclude with the IAEA. Although it does give the IAEA the legal authority to detect undeclared nuclear activities, the principal purpose of INFCIRC/153—as the Model Comprehensive Safeguards Agreement is also known—is to give the IAEA the practical tools it requires to be able to detect whether states have diverted nuclear material (uranium-235 and plutonium) from declared facilities. To this end, states are obliged to declare all facilities in which nuclear material is present, report all movements of nuclear material and accept periodic inspections. The main purpose of these inspections is to measure the amount of nuclear material present in facilities to ensure that none has been secretly removed—a technique known as nuclear material accountancy. A range of complementary tools, such as containment and surveillance (C&S) measures (the former include seals and the latter cameras and radiation monitors), are used to maintain continuity of knowledge about nuclear material inventories and reduce the overall inspection effort. During the 1990s a new safeguards instrument, the Model Additional Protocol (INFCIRC/540), was developed to enhance the ability of the IAEA to detect clandestine facilities. The powers that INFCIRC/153 gives the IAEA in this regard are fairly limited. In contrast to INFCIRC/153, states parties to the NPT are under no legal obligation to accept the additional protocol. As of March 2007, 78 states had done so.[12] A summary of some of the more technical aspects of nuclear materials accountancy is given in appendix I.

Method of analysis

In general, there are three ways in which a civilian nuclear programme can be used for military ends: first, declared nuclear material can be diverted for use in a military programme; second, the knowledge gained from running a declared civilian programme can be used in a clandestine military programme—this is sometimes known as the 'sneak-out' scenario; and, third, having developed fuel cycle capability as part of a declared programme, a state can leave the NPT, end international oversight and use that capability to produce fissile material for use in nuclear weapons. This scenario is sometimes known as 'breakout'.

The main body of this paper is organized into five parts. Part I examines the possibility of 'reducing the scope' of nuclear activities in a state (i.e. the termination or permanent suspension of particular fuel cycle activities). These measures could potentially address all three generic concerns. Parts II, III and IV deal with each of the three concerns individually. Part II examines measures which can increase confidence in non-diversion from declared facilities, part III deals with detecting clandestine activities and part IV with breakout. Successful confidence-building processes nearly always have some elements of reciprocity. Part V, therefore, considers measures that the international community could take to ensure that confidence building is not entirely a one-way process. The issue of prioritization is addressed in the conclusions.

The bulk of this report, parts I to III, consists of the detailed analysis of particular transparency measures. Each proposal is outlined and, where appropriate, the status quo is discussed to explain, in detail, the nature of the particular problem being addressed. Any relevant effects of the additional protocol are then considered. Implementation and ratification of an additional protocol would strengthen the safeguards system in certain key respects and also be a sign of good faith. Because an additional protocol would be an instrument of broad application it is not treated separately but analysed throughout the text wherever relevant. For each proposed transparency measure, an analysis of the way it supplements the existing safeguards system is presented. Finally, a brief evaluation is presented in boxed text at the end of each section.

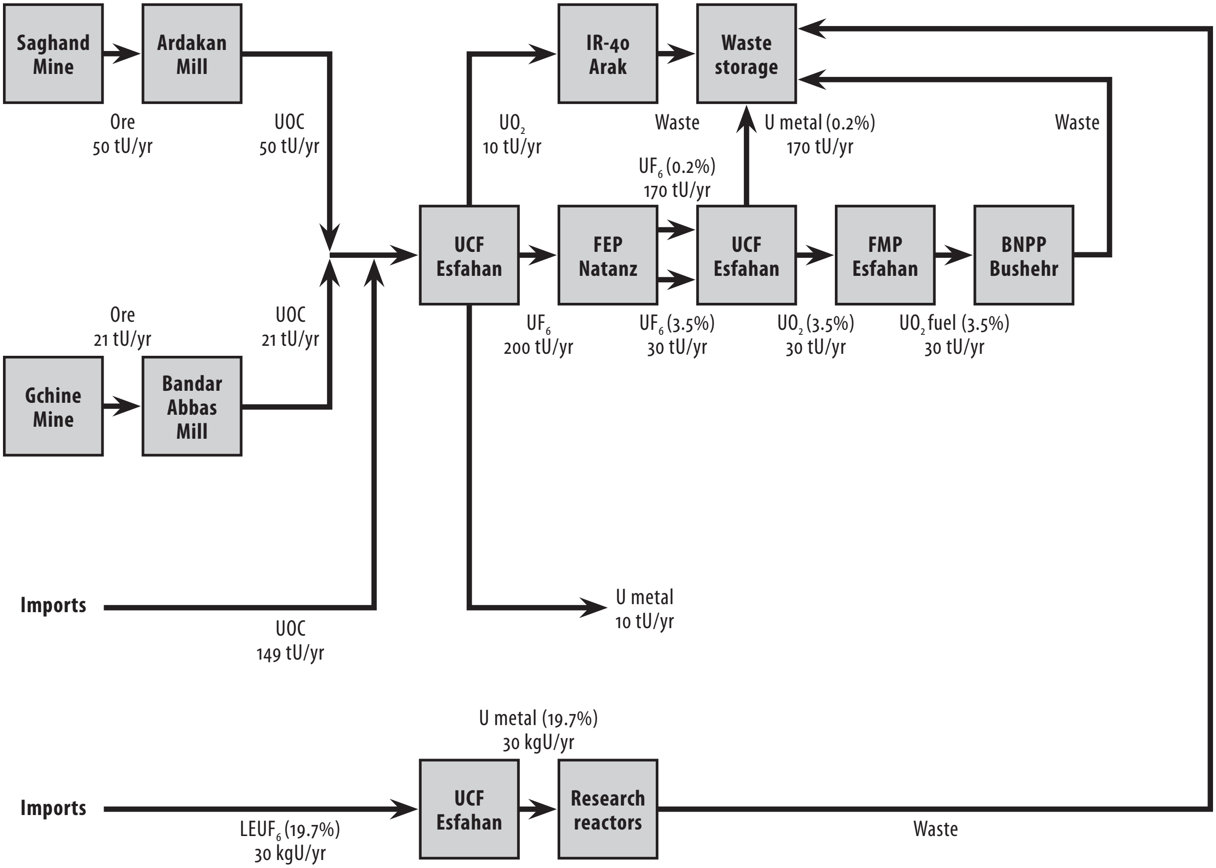
Each proposal is rated 'low', 'medium' or 'high' under the categories of 'cost of implementation' and 'increase in confidence'. The former category is self-explanatory, although it does not include the money Iran has already spent on building the facility in question. The latter category is the authors' estimate of how effective the proposal is likely to be from the perspective of building confidence. Such a simple measure is necessarily rather crude. Rating a proposal 'high' on the increase in confidence scale, for instance, does not imply that it is, by itself, likely to rebuild trust completely. For example, terminating construction of the Fuel Enrichment Plant (FEP) is rated 'high' because it is widely seen as a necessary, but not sufficient, condition for rebuilding confidence in Iran's enrichment programme. Moreover, it is necessary to consider transparency measures not in isolation but as part of a package—and rating measures in this way allows them to be compared more easily. It also provides a simple message for busy policy makers. On balance, the benefits of presenting a simple 'bottom line' for each measure do seem to outweigh the detrimental effects.

Confidence building is a subjective process. Some measures that, at an objective level, contribute very little to the safeguards system may, in practice, lead to a significant increase in the confidence of the international community.[13] Other measures that enhance the safeguards system significantly may inspire little confidence outside of the technical community. This paper does not attempt to take such external 'psychological' factors into account. It attempts as objectively as possible to analyse each particular measure on its technical merits, and does not predict how the international community will react to such measures in practice.

There is obviously a limit to the number of proposals that can be considered in this paper, and it was therefore necessary to develop criteria to select measures for inclusion. Three such criteria are used:

1. Measures that would be completely unacceptable to either party are excluded. A permanent termination of all nuclear activities in Iran, for example, is not considered here.
2. Only measures that use reliable and proven technologies are included. Although novel technologies have an important role to play in safeguards generally, demonstrating their reliability and developing a protocol for their use takes time. It therefore seems unlikely that they could be used as part of the solution to a pressing problem.
3. Only transparency measures directly related to the nuclear fuel cycle are considered. Measures to build trust more generally between states lie outside the scope of this paper. That is not to say that such measures are not important—in fact the contrary is true. Transparency measures related to a state's nuclear programme are almost certain to work best if they are part of a more general confidence-building process. The stand off with Iran, for instance, is at a fundamental level the result of a general lack of trust between the Iranian government and governments in 'the West'—particularly, but not only, successive US administrations. Accordingly, increasing transparency in Iran's nuclear programme can, at best, only be part of the solution. This is manifested most obviously in the concern that Iran will leave the NPT entirely. This fear stems not so much from any particular feature of Iran's nuclear programme as from the underlying lack of trust in the Iranian government. To allay this and other fears will require more than just the 'technical' measures outlined in this paper.

Figure 2 Schematic diagram of Iran's planned fuel cycle activities



Note: Values in brackets indicate the level of enrichment. Where no figure is given, the material is unenriched.

Nuclear activities in Iran

Iran is a signatory to the NPT and a member state of the IAEA. It has an INFCIRC/153-type safeguards agreement in force,[14] but the additional protocol Iran signed on 18 December 2003, and applied provisionally, was suspended on 6 February 2006. The starting point for this study is Iran's planned nuclear programme, shown schematically in figure 2. The arrows indicate the flow of uranium through the system. All flows are measured in tonnes of uranium per year (tU/yr).[15] Ignoring process losses (which are generally fairly small) the flow of materials around the fuel cycle, when measured in these units, is conserved; that is, a facility which can produce 200 tU/yr of natural uranium hexafluoride (NUF_6) requires 200 tU/yr of UOC.

Iran has two small uranium mines, Saghand and Gchine, and each has an associated mill—at Ardakan and Bandar Abbas, respectively. It is intended that these mines together will produce 71 tU/yr.[16] By July 2004 Gchine had started mining operations and Bandar Abbas had been hot tested.[17] Saghand was due to start production by the end of 2006, but there is no evidence that it has done so. Its associated mill at Ardakan, which was due to start operation concurrently with the mine, was described as 'at an early stage of development' in the summer of 2004.[18] Given the capacity of the two mines, it is inferred that Iran will have to import 149 tU/yr in order to meet its requirements.

The medium-scale Uranium Conversion Facility (UCF) is located at Esfahan. The process lines that are planned at the UCF are summarized in figure 3.[19] According to its design specifications, the UCF has the capacity to convert 220 tU of UOC each year into: (a) 200 tU of NUF_6; (b) 10 tU of natural uranium (NU) metal; and (c) 10 tU of natural uranium dioxide (NUO_2).

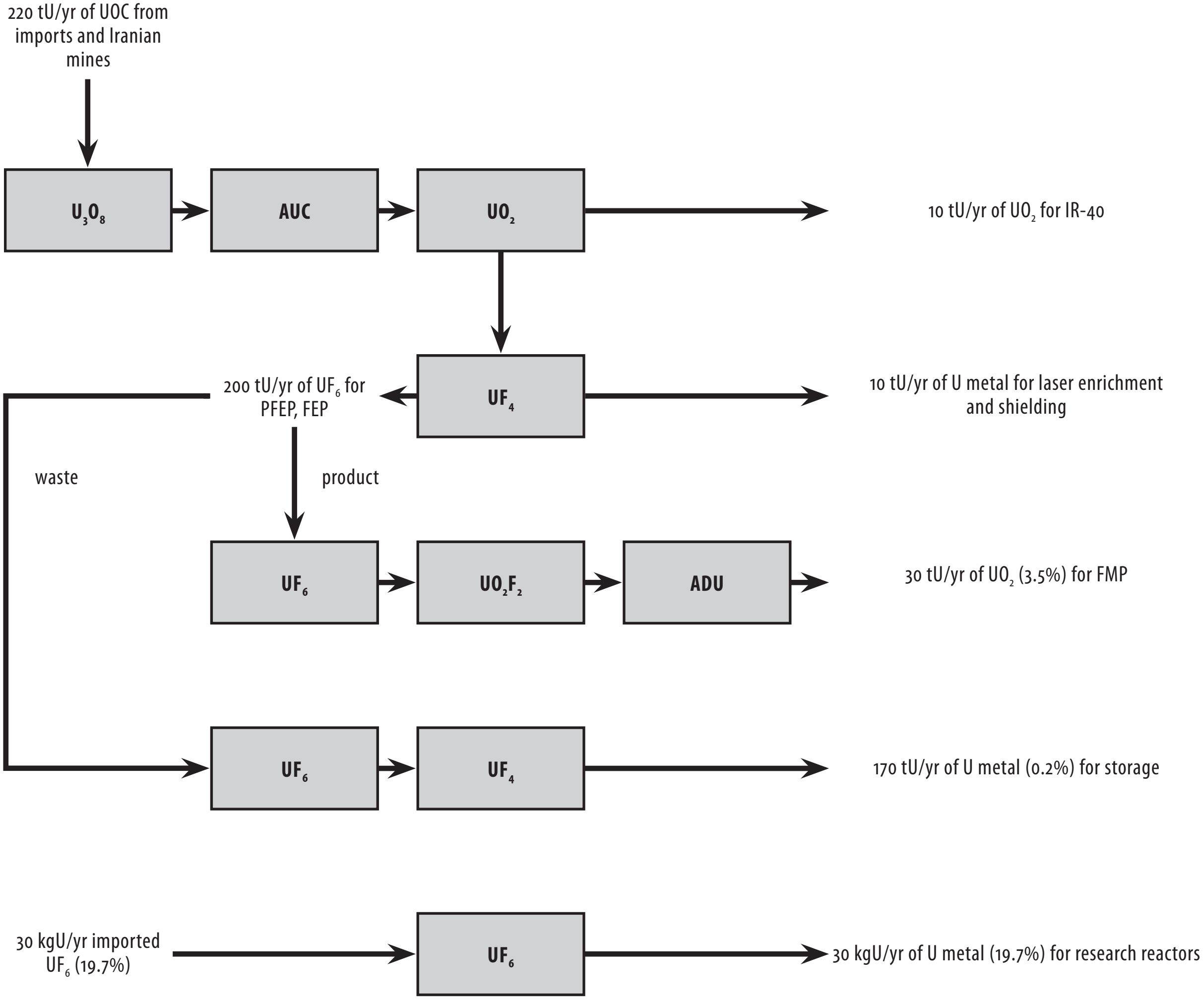
After enrichment, the UCF can convert 30 tU/yr of low enriched uranium hexafluoride ($LEUF_6$) into low enriched uranium dioxide ($LEUO_2$); and 170 tU/yr of depleted uranium hexafluoride (DUF_6) into depleted uranium (DU) metal. Finally, there is a line to convert imported $LEUF_6$ (enriched to 19.7 per cent) into 30 kilograms of uranium per year (kgU/yr) of LEU metal. It seems (from reading the open source literature) that only the line to synthesize NUF_6 from UOC is currently operational.

Iran's declared centrifuge operations are centred on Natanz. The Pilot Fuel Enrichment Plant (PFEP) is partially operational—two out of six cascades have been completed in addition to various smaller test cascades (each full cascade consists of 164 machines).[20] The FEP, which is designed to house about 50,000 centrifuges, is also under construction. According to the IAEA's most recent report, two 164-machine cascades have been installed there and a further two were 'in the final stages of installation'.[21] According to recent media reports Iran has now installed about 1,000 centrifuges there.[22]

To complete the front end of the fuel cycle Iran is currently building a Fuel Manufacturing Plant (FMP) and an accompanying Zirconium Manufacturing Plant (ZMP) at Esfahan.[23] Together the UCF, FEP, FMP and ZMP are designed to be able to meet the fuel requirements of the Bushehr Nuclear Power Plant (BNPP), a Russian-built VVER-1000 reactor. The date for Bushehr's completion has been rather fluid in the past and, at the time of writing, it is far from clear that Russia will agree to complete work on the project.

Iran's heavy water reactor programme is based at Arak. It includes the Iran Nuclear Research Reactor (IR-40), a 40 megawatt-thermal research reactor, and the Heavy Water Production Plant (HWPP). According to the

Figure 3 Schematic diagram of the process lines at the UCF



Key: AUC = ammonium uranyl carbonate, $(NH_4)_4[UO_2(CO_3)_3]$; ADU = ammonium diuranate, $(NH_4)_2U_2O_7$

Note: Values in brackets indicate the level of enrichment. Where no figure is given, the material is unenriched.

Iranian government, the HWPP became operational in 2006.[24] Construction of the IR-40 commenced in 2004. A design inventory verification on 29 January 2007 confirms that civil construction is still on-going,[25] as does satellite photography.[26] It is unclear when the IR-40 will be commissioned—estimates have varied, ranging from 2007 to 2014.[27] With appropriate reprocessing capacity, the IR-40 has the potential to produce about 9 kg of weapons-grade plutonium per year.[28] However, the IAEA has 'no indications of ongoing reprocessing activities' anywhere in Iran.[29] Finally, Iran has a number of other facilities, including research reactors, laboratories and waste-handling facilities.[30]

Table 1 shows the minimum amount of nuclear material that Iran would have to divert at each stage of its fuel cycle in order to be able to manufacture a nuclear weapon. It is constructed assuming that 10–20 kg^{235}U of HEU is ultimately required. This amount is somewhat smaller than the IAEA definition of a significant quantity (SQ) of HEU, which is set at 25 kg^{235}U (see appendix I), and reflects the approach taken in this paper—that it is prudent to consider worst case scenarios.[31]

Table 1 Minimum quantities of nuclear materials required for the manufacture of a nuclear weapon

Fuel cycle stage	Minimum quantity of U required	Minimum quantity of input material required	Assumptions
Weaponization Input: HEUF$_6$ Output: HEU metal pit	11.0–21.0 kg	16.5–31.5 kg	Lower estimate: 10 kg^{235}U at 90% enrichment Upper estimate: 20 kg^{235}U at 95% enrichment Process losses negligible
Enrichment Input: NUF$_6$ Output: HEUF$_6$	2.0–9.5 t	3.0–14.0 t	Lower estimate: tails set to 0.2% Upper estimate: tails set to 0.5% Process losses negligible
Conversion Input: UOC Output: NUF$_6$	2.0–9.5 t	2.5–11.0 t	Process losses negligible
Milling Input: uranium ore Output: UOC	2.5–11.0 t	1,500–20,000 t	Lower estimate: ore sourced from Gchine Upper estimate: ore sourced from Saghand 15% process loss

Note: Figures are given to the nearest 0.5 kg for weaponization, the nearest 500 t for ore and the nearest 0.5 t for all other values. The following example illustrates how the assumptions listed in the fourth column have been used. The lower figure for the quantity of ore required (1,500 t) is derived by assuming that (i) the pit consists of 10 kg^{235}U, (ii) the enrichment level is set to 90 per cent, (iii) the tail assay is set to 0.2 per cent and (iv) ore is sourced from the mine at Gchine.

Part I: Reducing the scope of Iranian fuel cycle activities

Since its undeclared nuclear activities were discovered in 2002, Iran has come under intense pressure to terminate some of its fuel cycle activities (such as its heavy water reactor programme) and to suspend others (such as its enrichment programme). This section analyses proposals such as these, which would reduce the scope of Iran's fuel cycle activities. The discussion is broken down into two sections. The first section considers Iran's HWR programme, its light water reactor (LWR) fuel fabrication programme, the uranium metal production lines at the UCF and the FEP. The second section considers the effect of instigating a suspension of enrichment and conversion. Because the proposals in this section build confidence by reducing Iran's ability to manufacture weapons-usable material, rather than by opening up its nuclear programme to greater scrutiny, they might more properly be called confidence-building measures rather than transparency measures. Relevant Security Council resolutions call for a suspension, rather than a termination, of Iran's proliferation-sensitive nuclear activities, but it is important to consider how much confidence Iran could hope to build by agreeing to end them permanently.

Termination of the HWR programme, FEP, LWR fuel fabrication programme and uranium metal production lines at the UCF

Proposal I.1: Termination of the HWR programme

Description: Iran terminates: (a) the line at the UCF for converting UOC into NUO_2; and (b) construction of the IR-40. Iran also confirms its earlier commitment to not undertake research and development into plutonium separation.
Purpose: To build confidence that Iran will not use its nuclear programme to produce separated plutonium.
Cost of implementation: Low
Increase in confidence: High

Proposal I.2: Termination of construction of the FEP

Description: Iran terminates construction of the FEP.
Purpose: To build confidence that Iran will not use its nuclear programme to produce weapons-usable fissile material (HEU or plutonium).
Cost of implementation: Low
Increase in confidence: High

Proposal I.3: Termination of the LWR fuel fabrication programme

Description: Iran terminates: (a) the line at the UCF for converting $LEUF_6$ into $LEUO_2$; and (b) construction of the ZMP and FMP. In addition, any $LEUF_6$ produced by the PFEP is sent to a trusted third party for fuel fabrication before being re-imported to Iran for use in its civil nuclear power programme. Any NUF_6 produced by the UCF that cannot be immediately enriched is also sent to the third party for enrichment and fuel fabrication (before being transported back to Iran).
Purpose: To build confidence that Iran will not use its LWR programme to produce separated plutonium, or to build up a stockpile of LEU.
Cost of implementation: Low
Increase in confidence: Medium

Proposal I.4: Termination of the uranium metal production lines at the UCF

Description: Iran terminates the following lines at the UCF:

1. conversion of $LEUF_6$ (enriched to 19.7 per cent) into LEU metal;
2. conversion of UOC into NU metal;
3. conversion of DUF_6 into DU metal.

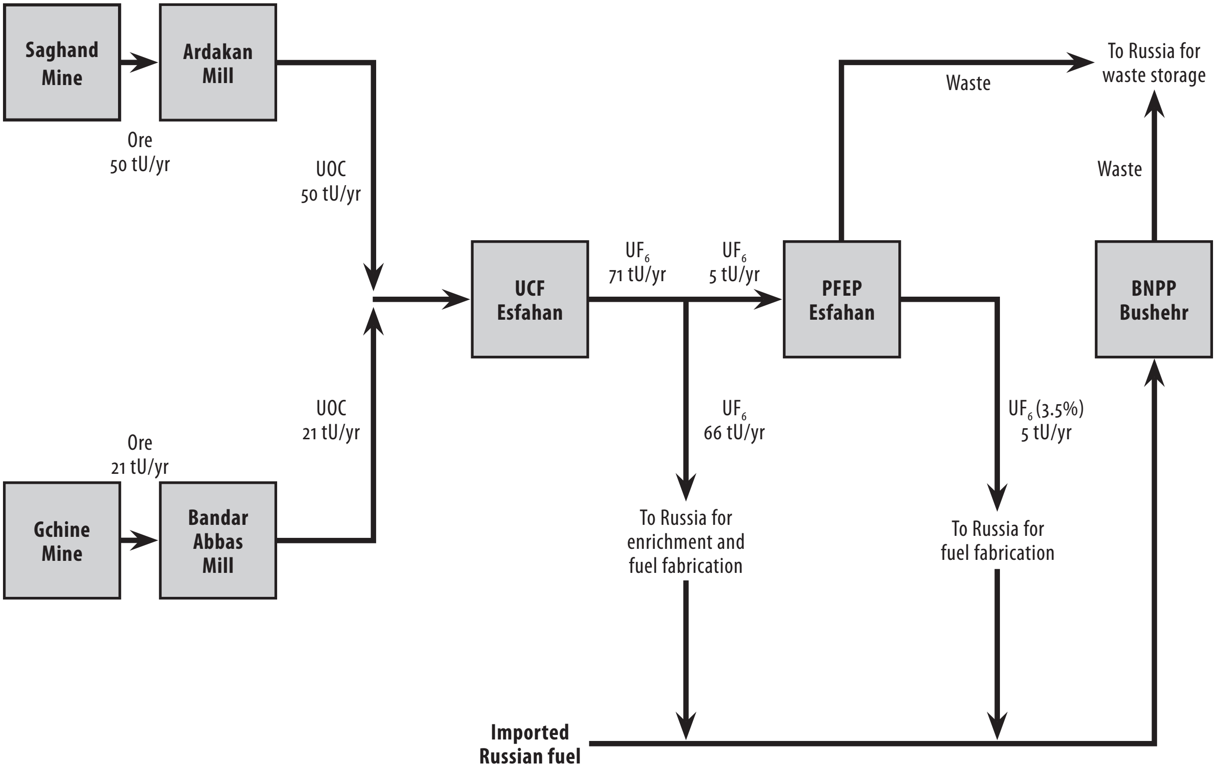
Purpose: To build confidence that Iran will not produce metallic uranium.
Cost of implementation: Low
Increase in confidence: High

Analysis: the effect of the confidence-building measures

The effects of proposals I.1 to I.4 are summarized in figure 4—a schematic diagram of Iran's fuel cycle activities with all these measures in place. Under these proposals, all the UOC from Iran's mining and milling activities (about 71 tU/yr) would be converted to NUF_6 in the UCF. As much of this as possible would then be enriched in the PFEP. Since this facility, once it is completed, would only be capable of enriching about 5 tU/yr, in order to avoid a stockpile of NUF_6 being built up the remaining 66 tU/yr of NUF_6 would have to be exported to a trusted third party (possibly Russia) for enrichment and fuel fabrication. Similarly, the product from the PFEP—about 500 kgU/yr of 3.5 per cent enriched $LEUF_6$—would also be exported for fuel fabrication.[32] Under this proposal all nuclear material of Iranian origin is ultimately re-imported as fuel for use in Iran's civil nuclear power programme. In addition, all the waste produced in the process (both the DUF_6 from enrichment and the spent reactor fuel) could be exported to the third party for storage.

As an example of how these measures might build confidence consider proposal I.1, which concerns Iran's heavy water reactor programme. As is discussed above, there are three routes by which an HWR programme could be involved in the manufacture of nuclear weapons: diversion, sneak-out[33] and breakout. Proposal I.1 addresses the first two concerns directly. Moreover, if Iran were to implement the proposal but subsequently leave the NPT, then a nuclear weapons programme could be significantly delayed pending completion of the HWR programme—it therefore also helps to build trust on the third point. For similar reasons, proposals I.2

Figure 4 Schematic diagram of fuel cycle activities in Iran after the implementation of proposals I.1–I.4



Note: Values in brackets indicate the level of enrichment. Where no figure is given, the material is unenriched.

and I.4 should also increase confidence that Iran has no intention of synthesizing HEU metal, which can be used in the manufacture of nuclear weapons.

In addition to using an HWR, Iran could also try to manufacture plutonium by reprocessing spent fuel from an LWR. There is a lively debate in the literature about the feasibility of manufacturing a nuclear weapon from reactor grade plutonium.[34] There is no doubt, however, that this is possible if the fuel is removed at a lower burn-up than is usual for an LWR. Typically, this manufacture path is plausible only as part of a breakout scenario because it would immediately be detected by inspectors.[35] By implementing proposal I.3 and curtailing its LWR fuel fabrication programme, Iran would reduce its ability to produce plutonium by this route and, as a corollary, build confidence in its intentions.

Finally, it is worth noting that it would be relatively straightforward to verify all the provisions in this section by a combination of remote monitoring and inspections (including the use of seals and swipe sampling). If Iran agreed to a termination, it would presumably also permit the IAEA to conduct relevant verification activities. States could obtain additional assurance of the termination by monitoring large-scale projects (such as the construction of the IR-40) using national technical means.

Evaluation

Proposals I.1–I.4 would significantly enhance confidence that Iran is not intending to manufacture nuclear weapons by pursuing plutonium separation technology. Terminating construction of the FEP and sending $LEUF_6$ abroad for fuel fabrication would also increase confidence in Iran's enrichment programme but because the PFEP remains unaffected, these measures would not restore confidence completely in that regard. As is discussed below, the PFEP does pose a proliferation risk and further steps will probably be needed to convince the international community of the peaceful nature of Iran's centrifuge programme.

Long-term suspension of enrichment and conversion

Proposal I.5: Long-term suspension of enrichment and conversion

Description: Iran agrees to a long-term suspension of its centrifuge development programme. It is agreed that the suspension will continue for as long as Iran receives sufficient fuel at market price for its civilian nuclear reactors, or until Iran has rebuilt trust in the peaceful nature of its enrichment programme (for this reason the phrase 'long-term suspension' rather and 'termination' is used). The suspension in enrichment could also be accompanied by a suspension in the conversion of UOC to NUF_6. A variant on this would be for the suspension to be phased in; that is, that the suspension would only come into force after Iran had produced an agreed amount of $LEUF_6$. The transparency measures outlined in part II of this paper could be used to supplement standard safeguards during enrichment.

Purpose: To build trust that Iran's enrichment programme is not intended for military use.

Cost of implementation: Low

Increase in confidence: High (if immediate); Low (if phased)

Analysis: the effect of the confidence-building measures

Closure of the FEP (as is discussed above) would significantly reduce Iran's ability to manufacture HEU quickly. The PFEP, however, also poses a proliferation risk—albeit much smaller—and so does the conversion facility at Esfahan. The risk of diversion from the PFEP, which is discussed fully in part II, is relatively small. Breakout using the PFEP also appears unlikely because producing enough material for one nuclear weapon using the PFEP would be likely to take in excess of two years—giving ample time for pre-emptive action to be taken.[36] Instead, the most significant proliferation risk posed by the PFEP is the knowledge that Iran gains from operating it.[37] Such knowledge could be applied in a clandestine military programme. Similarly, the knowledge gained from operating the UCF is a significant proliferation risk. In addition, the UCF poses more potential for diversion than the PFEP.

The efficacy of a long-term suspension of enrichment and/or conversion depends, in large part, on how highly developed that technology is. From the perspective of denying Iran the knowledge it needs to build a clandestine facility, there is little point in suspending technologies that Iran has already successfully put into operation. It therefore makes sense to discuss briefly the state of Iran's conversion and centrifuge programmes. These are controversial issues, and national governments are likely to form their own assessments based on information that is not publicly available.

It is certain that Iran has solved two of the three problems that troubled its initial efforts at conversion: a low throughput and a high loss rate.[38] Overcoming the third problem—a high level of impurities, particularly molybdenum, in the product—seems to have presented more of a challenge. Such impurities can cause damage to centrifuges, particularly at higher levels of enrichment.[39] Indeed, there are press reports that Iran's enrichment experiments in April 2006 were carried out with imported uranium.[40] It is not clear whether Iran has successfully addressed this problem. The information in the public domain is very sketchy. In May 2006 David Albright, President of the Institute for Science and International Security, reported that 'Iran is known to be working to improve the purity of the uranium hexafluoride produced at the UCF'.[41] In June 2006 Paul Kerr, an analyst at the Arms Control Association, reported that 'the agency [IAEA] assumes that the material [UF_6] is "of reasonable quality"'.[42] Moreover, the time needed to overcome this problem is typically measured in months rather than years.[43] On this basis alone, it seems probable that Iran has made significant progress with purifying its UF_6. On balance, Iran's conversion programme is probably close to being fully operational, if it is not fully operational already. A long-term suspension of conversion would, therefore, be unlikely to hinder significantly efforts to build a clandestine facility. It would, however, remove the potential for diversion from the UCF. The size of these risks and the means to address them are considered in parts II and III.

In contrast, there are three reasons to suppose that Iran's centrifuge programme is currently at a less advanced stage:

1. Iran has spent a significant amount of time operating its centrifuges under vacuum. After Iran announced in April 2006 that it had enriched UF_6 to 3.5 per cent, evidence emerged that for most of the 12 days that its 164-machine cascade had been in operation it had been run without UF_6.[44] The most recent IAEA reports on Iran confirm that UF_6 has been fed only 'intermittently' into the machines.[45] This indicates that during this period Iran was still in the process of learning how to use its centrifuges.[46]
2. Iran's centrifuge programme is significantly behind schedule. According to a recent IAEA report, the second cascade at the PFEP was finally completed and tested with UF_6 in October 2006.[47] According to Albright in May 2006, Iran's original plan was to have the second cascade installed by May 2006 and a further three

by August 2006.[48] Part of this delay may have been caused by the fact that Iran was stockpiling its available centrifuges in advance of installing them in the FEP. If this is the case, its operations in the FEP are likely to be slow because testing procedures in the PFEP were not properly completed.

3. Iran's centrifuges are probably performing significantly below their design specifications. P1 centrifuges should be able to produce between one and three kgSWU/yr. It appears that Iran's centrifuges have been operating at the lower end of this scale.[49] If this is the case, Iran may require more experience to optimize centrifuge performance.

It is clear that Iran still has some important challenges to overcome before it can enrich sufficient quantities of uranium for a nuclear weapon. An immediate suspension of enrichment has been mandated by the Security Council. The benefits of a long-term suspension in enrichment are, however, less clear. The problems facing Iran's enrichment programme are not fundamental and—given time—Iran will overcome them. An indefinite suspension of Iran's declared programme would slow progress towards a functioning clandestine facility, but it would not halt it entirely. It therefore seems unlikely that a long-term suspension of enrichment, by itself, would remove concerns that Iran is conducting a clandestine centrifuge programme.

Evaluation

A long-term suspension of Iran's declared enrichment programme would certainly slow the progress of a clandestine programme. It would not, however, prevent progress entirely. Given time, there seems little doubt that Iran would be able to build a clandestine centrifuge facility. It seems unlikely, therefore, that a suspension by itself would completely rebuild confidence in Iran's nuclear programme—in particular, confidence in the absence of a clandestine programme. The rationale for suspending Iran's conversion programme is rather different. Because Iran's conversion programme is at a more advanced stage than its enrichment programme, suspending it would be unlikely to slow significantly the development of a clandestine conversion capability. A suspension would, however, remove the possibility of a diversion from the UCF.

Part II: Measures to enhance the IAEA's ability to detect the diversion of declared nuclear material

The importance of material accountancy

This section considers the measures that Iran could take to increase confidence that nuclear material is not being diverted from declared facilities. The focus is on material accountancy. In one sense, this runs counter to the general direction of safeguards development in recent years. Although material accountancy is still described as the cornerstone of the safeguards system, the gradual introduction of integrated safeguards is moving the emphasis towards a more holistic analysis of all the information that is available to the IAEA.[50] Against this background, it is important to explain why material accountancy plays such a prominent role in this paper. There are two reasons:

1. Integrated safeguards can be introduced only after a state has adopted the additional protocol, and the IAEA has drawn its 'broader conclusion' about the absence of undeclared nuclear material in the state. This paper, however, is focused on Iran, which currently does not have an additional protocol in force. After the additional protocol has been signed and ratified, it typically takes the IAEA a few years to draw the broader conclusion and implement integrated safeguards. This section therefore focuses on how to build confidence outside the framework of integrated safeguards.
2. It is possible that, where there is international concern, the transition to integrated safeguards could actually lead to a *decrease* in confidence in a state's nuclear programme. For example, under integrated safeguards the timeliness detection goal (see appendix 1) for certain types of nuclear material is relaxed. While this is probably a sensible measure in most cases (because the verification burden on a state is reduced), it does affect the ability of the IAEA to provide timely warning of a diversion. For many types of nuclear material, integrated safeguards also rely more heavily on containment and surveillance methods. It is, however, difficult to *quantify* the effect these measures have on the probability of detecting a diversion. This is not an argument against C&S methods in general. It is an argument that in Iran's case it is probably sensible to use C&S

methods as a supplement to material accountancy rather than as a way to reduce the inspection burden. Regular and accurate material accountancy affords Iran its best opportunity to *prove* that it has not diverted nuclear material.

That said, some concepts from integrated safeguards—short notice random inspections (SNRIs), in particular—could have an important role to play in the confidence-building process, and their use is discussed below.

Mining and milling

Proposal II.1: Physical containment measures at mines and mills
Description: The IAEA places containment measures (such as fences with compromise detectors and portals to monitor the entry and exit of vehicles) around uranium mines and mills. Uranium ore and UOC is transported in sealed containers.
Purpose: To prevent the diversion of uranium ore or UOC.
Cost of implementation: High
Increase in confidence: Low

Proposal II.2: Material accountancy at mines and mills
Description: Material accountancy measures are applied to the material in mines and mills. (Note that the application of material accountancy to the UOC output of a mill is considered separately in proposal II.3.)
Purpose: To verify quantitatively the non-diversion of material from mines and mills.
Cost of implementation: High
Increase in confidence: Low

Analysis: the status quo

The IAEA does not safeguard activities, such as mining or milling, that involve uranium ore or ore concentrate. Indeed, such practice is explicitly prohibited under paragraph 33 of INFCIRC/153.[51] The possibility therefore exists that material from a uranium mine or mill could be diverted to a clandestine programme.

Analysis: the effect of the additional protocol

As part of their expanded declaration pursuant to an additional protocol, states are required to submit 'information specifying the location, operational status and the estimated annual production capacity of uranium mines and concentration plants . . . and the current annual production of such mines and concentration plants . . .'.[52] The IAEA can verify this information by comparing it with satellite imagery, reports from government regulators or pressure groups and other available sources.[53] The additional protocol also allows for complementary access, that is, access to a broader range of locations than is permitted under INFCIRC/153 for purposes including verifying the absence of undeclared activities at any location where nuclear material is declared to be present. The IAEA has conducted complementary access at mines and mills in Iran.[54] However, states are not required to use detailed material accountancy when reporting on mining and milling activities and, ultimately, 'inspectors would be able to confirm only approximate production levels (say to within an order of magnitude)'.[55]

Moreover, this kind of verification mechanism functions best in a society where there are multiple independent sources of information. There are, however, very few (if any) Iranian pressure groups with an interest in uranium mining. Furthermore, Iranian mines and mills are government owned—one, Gchine, has a military connection[56]—which reduces even further the sources of corroborating evidence.

Analysis: the effect of the additional transparency measures

In general, as Scott Kemp argues, there is little doubt that the use of material accountancy to safeguard uranium mines or mills is neither practical nor cost- effective.[57] The quantity of material produced by a uranium mine is typically very large—often about 1,000,000 t of ore per annum. Around 250 t of high grade ore is required to manufacture a nuclear weapon. For material accountancy measures to be effective, therefore, they must be able to identify a diversion representing 0.025 per cent of the annual output of a mine. This level of accuracy for such a large quantity of material would be very difficult to achieve in practice.

Iran's mines differ from the generic case considered by Kemp in two important respects. First, their ore is low grade (0.0553 per cent for Saghand and 0.2 per cent for Gchine).[58] The minimum amount of material required for a nuclear weapon is, therefore, much larger than 250 t (about 1,500 t for ore from Gchine, see table 1, or 4,500 t for ore from Saghand). Second, the quantity of material produced by these mines is relatively small (about 90,000 t/yr for Saghand and about 11,000 t/yr for Gchine).[59] Thus, the material required for one nuclear weapon amounts to approximately 5 per cent of the annual output of Saghand and 14 per cent of Gchine—and these figures may in fact be significant underestimates. These estimates are derived by assuming that the tail assay for enrichment is set to 0.2 per cent. However, the optimum material acquisition strategy for Iran probably involves setting a higher tail assay in order to reduce the number of separative work units (SWU) required, and consequently using more uranium.

The effectiveness of material accountancy measures depends on the accuracy with which the uranium content of a large quantity of ore can be calculated. More formally, it is necessary to estimate a value for the standard deviation in the material unaccounted for (σ(MUF))—see appendix 1 for more details. If (a) ore is analysed on a daily basis; (b) the errors in determining its uranium content can be approximated by the errors in assaying uranium scrap;[60] and (c) a material balance is then conducted biannually then, as is shown in Appendix II, the σ(MUF) could be as small as about 750 t for Saghand and 100 t for Gchine. In practical terms, these figures imply that the IAEA would have a 90 per cent chance of spotting a diversion of ore larger than 2,200 t from Saghand and 300 t from Gchine.[61] These quantities are smaller than the amounts required for the manufacture of nuclear weapons.

In fact, assaying uranium scrap may be a bad approximation for assaying uranium ore, and the errors associated with the latter may be much larger than the errors associated with the former. If they are, multiple ore samples would have to be analysed each day. Without knowing the mineralogical details of Iran's uranium ore, it is impossible to estimate this number.[62] It may, however, be very large—possibly unmanageably so. It might be possible to compensate for this by taking fewer ore samples, and accepting a higher value of σ(MUF) and consequently a lower probability of detecting a diversion. The amount of uranium ore required to produce a single bomb represents such a large fraction of the annual output of Saghand or Gchine that even if detailed material accountancy were not possible, some form of 'crude' material accountancy might be. It would, however, be a time-consuming, difficult and expensive process. Whether it would be a worthwhile CBM is less clear. This point is discussed further in the evaluation section below.

Many of the same considerations apply to the use of material accountancy at mills. Because it is easier to find the uranium content of UOC than uranium ore, σ(MUF) for a mill is about 30 per cent smaller than σ(MUF) for a mine.[63] In practice, however, this makes little difference. If it is not practical to apply material accountancy to mines, then it is unlikely to be practical to safeguard material at mills in this way.

An alternative to material accountancy is physical security. Kemp, for instance, points out that it would be relatively simple to construct a security system to prevent the removal of material from a uranium mine or mill.[64] He envisages a scheme in which a facility is surrounded by fences with compromise detectors and portals to monitor traffic into and out of the mine. This arrangement would almost certainly be cheaper than material accountancy. It does, however, suffer from various drawbacks. It is in some senses more invasive than material accountancy. In addition, in the IAEA's safeguards system the control of nuclear materials has, with good reason, played a supplementary role to accountancy. While it is not meaningless to have control without accountancy, it is less effective—although physical security can help to prevent diversion, it does not permit a state to *prove* the fact.

Evaluation

Any state wishing to divert nuclear material from a declared programme to a clandestine one would, in principle, like to do so as late in the fuel cycle as possible. However, safeguards are much stronger on NUF_6 and $LEUF_6$ than on material in mines and mills. The diversion of material from a mine or mill is therefore a plausible route for acquiring feedstock for a clandestine nuclear programme. Safeguards on mines and mills are expensive, hard to implement and, in the case of physical security, very intrusive. Moreover, material diverted from a mine would have to be milled, converted into UF_6, enriched and reconverted into metallic uranium—all in secret—before it could be used in a weapon. A clandestine programme of this kind would present multiple opportunities for detection. In practice, therefore, it probably makes more sense to focus on detecting clandestine fuel cycle activities rather than on safeguarding mines and mills.

The starting point of safeguards

Proposal II.3: Moving the starting point of safeguards upstream

Description: The IAEA applies material accountancy to all UOC in Iran and to any stages of the UCF that are not already subject to safeguards.
Purpose: To verify that UOC (or any subsequent material) is not diverted.
Cost of implementation: Medium
Increase in confidence: High

Analysis: the status quo

Pursuant to paragraph 34(c) of INFCIRC/153, safeguards are first applied 'when any *nuclear material* of a composition and purity suitable for fuel fabrication or for being isotopically enriched leaves the plant or the process stage in which it has been produced . . .'.[65] In the first stage of the UCF—as in almost every other commercial conversion plant—purified uranyl nitrate ($UO_2(NO_3)_2$ solution is produced.[66] The IAEA has recently announced that it considers this material to be a suitable enrichment feedstock.[67] Therefore, safeguards must start at the point at which purified $UO_2(NO_3)_2$ leaves the process stage in which it is produced. In fact, they may well start at an earlier point than this. If it is not practical for safeguards to begin with purified $UO_2(NO_3)_2$, IAEA policy specifies that the starting point for safeguards must be moved *upstream* (i.e. to an earlier process). In practice, this often entails applying safeguards to the UOC input stream of the conversion process. Safeguards are currently not applied to the UOC receipt and storage area of a conversion plant or to the product streams of mills.[68]

Analysis: the effect of the additional protocol

The complementary access provisions of the additional protocol are relevant to safeguarding conversion facilities.[69] During complementary access, inspectors may go anywhere in a conversion facility and may therefore conduct verification activities on material that is not subject to safeguards under INFCIRC/153. The verification activities that may be conducted during complementary access do not, however, significantly enhance the IAEA's ability to detect a diversion of UOC. For example, although the IAEA would be able to spot an undeclared production line during complementary access, it would also be able to do so during design information verification (DIV) pursuant to paragraph 48 of INFCIRC/153 (access during a DIV is not limited to strategic points and such visits occur on an on-going basis, at least annually in a conversion facility).[70] Moreover, the amount of UOC that is required to manufacture a nuclear weapon (about 5 tU) amounts to only about 2 per cent of the total annual throughput of the UCF. Identifying a diversion of this size would require the use of detailed material accountancy.

Analysis: the effect of additional transparency measures

As an additional transparency measure, Iran could ask the IAEA to place safeguards on all UOC, as well as any other materials in the UCF that are not already subject to them. It may already be the case that most of the UCF is under safeguards—but there is no publicly available information to confirm this. Implementation of this proposal might therefore be as simple as extending safeguards slightly to include the UOC storage areas at mills and the UCF; at most it would require applying additional safeguards to the UOC dissolution and extraction stages at the UCF. Although it is unusual for the IAEA to apply safeguards to UOC storage areas, it is a simple procedure that should be straightforward to implement. It is already standard practice at facilities which are subject to Euratom safeguards.[71]

Evaluation

Moving the starting point of safeguards upstream as far as the UOC production line at mills would be a simple step but potentially an effective one. The lack of safeguards on UOC is arguably the weakest point of the current safeguards system because the diversion of UOC (or possibly an intermediate material from the conversion process) is a very attractive diversion scenario. It is preferable to diverting uranium ore because it obviates the need to build a clandestine mill. It is preferable to diverting material later in the fuel cycle (such as UF_6 or UO_2) because there is less chance of detection. Safeguards on UOC, therefore, have the potential to be a useful CBM.

Enhanced safeguards on the front end of the fuel cycle

Proposal II.4: Increased information about IAEA safeguards

Description: With Iran's permission, the IAEA releases information about the effectiveness of its safeguards in Iran (e.g. the minimum size of a diversion that it could confidently expect to detect).
Purpose: To increase trust in the ability of the IAEA to safeguard fuel cycle activities in Iran effectively.
Cost of implementation: Low
Increase in confidence: Medium

Proposal II.5: Definition of a significant quantity lowered

Description: Iran requests that the IAEA changes its definition of an SQ to a lower value (e.g. 10 kg ^{235}U for HEU or 50 kg ^{235}U for LEU) for its safeguards work in Iran.
Purpose: To increase trust in the ability of the IAEA to detect diversion of militarily significant amounts of nuclear material.
Cost of implementation: Low
Increase in confidence: Low

Proposal II.6: Timeliness detection goal lowered

Description: Iran requests that the IAEA reduce its timeliness detection goal (for example, to six months for indirect use material such as LEU) for its safeguards work in Iran.
Purpose: To increase trust in the ability of the IAEA to provide timely warning of a diversion of nuclear material.
Cost of implementation: Medium
Increase in confidence: High

Proposal II.7: Detection probability increased

Description: Iran requests that the IAEA increases its detection probability (for example, to 95 per cent) for its safeguards work in Iran.
Purpose: To increase trust in the ability of the IAEA to detect a diversion of nuclear material.
Cost of implementation: Low
Increase in confidence: Low

Proposal II.8: Facilitation of short-notice inspections

Description: Iran could facilitate the introduction of short-notice inspections either by relaxing current visa requirements and entry procedures, or by permitting IAEA inspectors to be based permanently in the country.
Purpose: To increase trust in the ability of the IAEA to detect a diversion of nuclear material.
Cost of implementation: Medium
Increase in confidence: High

Analysis: the status quo

Assessing the effectiveness of IAEA safeguards on declared facilities in Iran would ideally involve knowing both the size of a diversion that the IAEA could confidently expect to detect and how long it would take to determine that such a diversion had taken place. This information is unfortunately classified—the IAEA does not reveal the detailed results of its inspections, such as σ(MUF) values. By making a number of assumptions, however, it is possible to make some estimates. In particular, figures are available on the accuracy of the measurement techniques that the IAEA uses.[72] If it is assumed that: (a) the in-process inventories of bulk handing facilities are small or can be accurately measured; and (b) uranium losses through waste streams are also small or can be measured accurately, an estimate for σ(MUF) can be made.

It is clearly necessary to be extremely cautious about these assumptions. They are probably reasonable in some material balance areas (MBAs), such as storage areas and the process areas of enrichment plants. For these MBAs the results of calculations based on these assumptions are probably accurate to within about a factor of two. In other MBAs, such as the process areas of conversion and fuel fabrication facilities, these assumptions are likely to be invalid. For those MBAs the dominant contribution to σ(MUF) comes from other factors such as uncertainties in the in-process inventory or the uranium content of waste streams. An alternative method is needed to estimate σ(MUF) in these cases, as is discussed below.

Table 2 presents the results of calculations on the IAEA's safeguards system for both Iran's planned fuel cycle (as shown in figure 2) and the reduced fuel cycle (as shown in figure 4). In addition to the assumptions listed above, it is also assumed that a physical inventory verification (PIV) is carried out once a year and that the most accurate destructive analysis (DA) measurements are used (the implications of this assumption are discussed below). A sample calculation is given in Appendix III. The table includes UOC storage areas which

Table 2 The estimated effectiveness of the IAEA's safeguards system for all MBAs except the process areas of the UCF and FFP

		Planned fuel cycle (see figure 2)			Reduced fuel cycle (see figure 4)		
Facility	**Material balance area**	**T(U) (tU/yr)**	**Δ (kg^{235}U)**	**δ_E**	**T(U) (tU/yr)**	**Δ (kg^{235}U)**	**δ_E**
Ardakan Mill	UOC storage	50	2	0.002	50	2	0.002
UCF	UOC storage	220	4	0.0009	71	2	0.001
	process area	Method not valid—see table 3					
	NUF_6 storage	220	2	0.0005	71	1	0.0007
FEP	NUF_6 storage	200	2	0.0005	not applicable		
	process area	200	5	0.001			
	$LEUF_6$ storage	30	3	0.001			
PFEP	NUF_6 storage	not applicable			5	0.5	0.005
	process area				5	0.2	0.002
	$LEUF_6$ storage				0.5	0.04	0.0008
UCF	$LEUF_6$ storage	30	3	0.001	not applicable		
	process area	Method not valid—see table 3					
	UO_2 (powder) storage	30	1	0.0003			
FFP	UO_2 (powder) storage	30	1	0.0003			
	process area	Method not valid—see table 3					
	UO_2 (pellets) storage	30	negligible	negligible			

would be subject to safeguards under proposal II.3. It is assumed that, with the exception of the mills, each facility has three material balance areas: one for the storage of the feed material, one process area and one for the storage of the product. For each MBA the table shows:

- T(U), the throughput of the facility measured in tU/yr;
- Δ, an estimate of the size of a diversion of ^{235}U that the IAEA has a 90 per cent chance of detecting (assuming a false alarm rate of 5 per cent).[73] Note that, to permit easy comparison, values of Δ are given in kg^{235}U;
- δ_E, an estimate of the measurement uncertainty in closing a material balance, given by the formula $\delta_E = \sigma(\mathrm{MUF}) / T(^{235}\mathrm{U})$ where $T(^{235}\mathrm{U})$ is the throughput of ^{235}U through the MBA.

Before commenting on the significance of these results it is useful to compare them with what is known about the effectiveness of IAEA safeguards in practice. According to the Safeguards Glossary, the 'expected' value of δ_E for enrichment is 0.002.[74] This compares very well to the estimates given in table 2 (exact agreement is not always expected because the values quoted in the Safeguards Glossary are fairly generic). This agreement helps to validate the assumptions made above. Since these assumptions are probably also valid for material storage MBAs, estimates of Δ for such MBAs are therefore probably also reasonable.

It is also necessary to estimate Δ for the process areas of the UCF and FFP. Without access to classified information it is impossible to do this in a 'first principles' way. For these MBAs it is probably best to estimate Δ by taking δ_E=0.003, the expected value for closing a material balance in a fuel fabrication facility.[75] These estimates are shown in table 3.

The principal conclusion from tables 2 and 3 is that the IAEA is almost certainly able to meet the quantity component of its safeguards goal in Iran. Indeed, it can probably significantly exceed this goal. This is because the throughput of uranium in Iran's nuclear facilities is very small. The IAEA's safeguards system is designed to be able to safeguard facilities with throughputs upwards of 20,000 tU per year. When that same system is applied to much smaller facilities—such as those in Iran—there is a corresponding decrease in material balance uncertainties. There is one important caveat to be added to this conclusion. As is mentioned above, the figures in table 2 were calculated by assuming that more accurate DA measurements, rather than less accurate non-destructive assay (NDA) measurements, are used in calculating the inventory of nuclear material. This assumption is probably reasonable because although the IAEA uses DA measurements on only a subset of samples, facility operators tend to use DA more heavily for their own internal accountancy. Where the IAEA does not

Table 3: The estimated effectiveness of the IAEA's safeguards system for the process areas of the UCF and FFP

		Planned fuel cycle (see figure 2)			Reduced fuel cycle (see figure 4)		
Facility	**Material balance area**	**T(U) (tU/yr)**	**Δ (kg^{235}U)**	**δ_E**	**T(U) (tU/yr)**	**Δ (kg^{235}U)**	**δ_E**
UCF	process area ($UOC \rightarrow NUF_6$)	220	14	0.003	71	4	0.003
UCF	process area ($LEUF_6 \rightarrow LEUO_2$)	30	9	0.003	not applicable		
FFP	process area ($LEUO_2$ powder → $LEUO_2$ pellets)	30	9	0.003			

verify the contents of a cylinder, it accepts the operator's measurement. If, however, a significant amount of NDA is used for inventory taking the values of Δ in table 2 will be increased somewhat.

It is much less clear whether the IAEA is able to meet its timeliness criteria because there is no data available on how quickly the IAEA reaches its conclusions. However, if a physical inventory is taken annually then it seems unlikely that the IAEA would be able to provide timely warning of a diversion that took place at the beginning of a material balance period.[76]

Analysis: the effect of the additional protocol

The primary purpose of the additional protocol is to provide the IAEA with increased means to be able verify the absence of clandestine nuclear facilities in a state. Some provisions (such as the expanded declaration and the right of complementary access) may lead to a slight increase in confidence in the IAEA's ability to detect diversion from declared facilities but the overall effect in this regard is unlikely to be significant.

Analysis: the effect of the additional transparency measures

Proposal II.4, which calls for the IAEA to reveal details of the efficacy of its safeguards operations in Iran, is a reflection of the fact that, at least for the quantity component of its inspection goal, the IAEA probably already surpasses its target—possibly by a significant amount. By permitting the IAEA to make normally confidential details of its safeguards evaluation public, Iran could reasonably hope to rebuild some confidence. In its regular reports on Iran, the IAEA has released an unprecedented amount of information about its safeguards operations. It is therefore natural to question whether disseminating more information would increase confidence in the IAEA's ability to safeguard declared nuclear activities in Iran.

Regular IAEA reports on Iran would not normally be published after it has been found to have come back into compliance with its safeguards agreement—the situation considered in this paper. For Iran to ask the IAEA to disseminate details of safeguards operations in these circumstances would, therefore, be a significant increase in transparency. Moreover, current IAEA reports generally focus on the IAEA's attempts to resolve outstanding questions about Iran's nuclear programme and report on its compliance with Security Council demands. They discuss routine safeguards operations—but in much less detail. For instance, following a PIV the IAEA will typically conclude that 'the inventory of nuclear material, as declared by Iran, was consistent with the results of the PIV',[77] but the σ(MUF) value is not stated. Releasing detailed information about standard safeguards operations on a routine basis could help to build confidence.

Proposals II.5—II.7 suggest three technical changes in the IAEA's safeguards system in Iran—a reduction in the definition of an SQ, a reduction in the timeliness detection goal and an increase in detection probability.

As is discussed above, the weakest aspect of current safeguards on declared material is most likely to be the IAEA's ability to provide timely warning of a diversion. It is unclear whether the IAEA is able to meet its goal of detecting a diversion within 12 months, and a state with clandestine facilities in place that has already undertaken research into weaponization could probably manufacture a nuclear weapon from indirect use material in less than a year.[78] For this reason it is the implementation of proposal II.6 (reducing the timeliness detection goal) that would bring about the greatest increase in trust.

Proposals II.5 and II.7 are likely to be less effective. Given that the IAEA is probably already in a position to be able to detect a diversion much smaller than one SQ, it is unlikely that confidence would be significantly enhanced by formally lowering the definition (proposal II.5). Similarly, it seems unlikely that proposal II.7 (increasing the detection probability) would have a significant effect on confidence building. With the detection probability, β, set to 0.9, the diversion of nuclear material is already strongly deterred. It seems unlikely that the deterrence effect would be materially enhanced by increasing β to 0.95 or 0.98. There is an argument that even if increasing β did not increase the deterrent against diversion, it could still be worthwhile because the IAEA would be more likely to detect a diversion. However, as is indicated below, increasing β further would involve very substantial costs for little actual improvement in the safeguards system—available funds would be better used elsewhere.

The IAEA has a number of practical options at its disposal to put proposals II.5–II.7 into effect:

1. *Reduce the material balance period:* Reducing the material balance period would clearly enhance the IAEA's ability to provide timely warning of a diversion. In addition, because a smaller amount of material is passing through each MBA between physical inventories, it would also lead to a smaller value of σ(MUF). This could enable the IAEA to reduce the definition of an SQ or increase β.
2. *Improve measurement techniques:* Currently, when performing a PIV, the IAEA uses a mix of DA and NDA. By increasing its use of DA, the IAEA's estimate of σ(MUF) would be decreased,[79] thereby allowing it to reduce the definition of an SQ or increase β. Since the results from NDA measurements are available in near real-time, while DA measurements typically take months to process, in order to avoid any loss of timeliness any increase in DA should be in addition to, rather than at the expense of, NDA. Such a step would be extremely resource-intensive and therefore unlikely to be worthwhile unless the estimates for σ(MUF) presented in this paper are substantial underestimates.
3. *Make independent measurements on all items of nuclear material:* In general, the IAEA does not make independent measurements of all items of nuclear material in a state, although it has the legal right to do so pursuant to paragraph 74.b of INFCIRC/153. To reduce costs, it performs verification procedures on a subset of items selected at random. This increases the probability that a state could successfully 'divert to D'.[80] In

this scenario, a state removes material from a container but does not reflect that fact in its declaration. The more items the IAEA selects for verification, the greater the probability that it will successfully uncover a diversion of this type. For this reason, the IAEA could perform independent measurements of all nuclear material in Iran. This would entail a substantial amount of effort, and given that β is already set as high as 0.9 it seems unlikely to be worthwhile.

4. *Increase the false alarm probability,* α: By accepting an increase in the value of α, the IAEA could reduce the definition of an SQ or increase β with no additional work. This suggestion is obviously the least desirable from an Iranian point of view since it would involve more frequent false alarms.
5. *Use of short notice random inspections:* Rather than conduct interim inspections (or indeed PIVs) on a pre-agreed schedule, the IAEA could conduct them randomly with little or no notice. The introduction of SNRIs as part of integrated safeguards is usually accompanied by a decrease in the number of inspections. This is potentially undesirable in Iran's case and it would probably be more appropriate to implement SNRIs without decreasing the average inspection frequency. With SNRIs in place a facility can be inspected at almost any time. They permit a diversion to be detected at shorter intervals than with routine inspections in place,[81] and arguably present a greater deterrent to diversion than routine inspections. SNRIs are not possible in Iran at the moment because of the visa requirements and entry procedures that Iran imposes on inspectors. Proposal II.8 attempts to address this problem. There are two ways in which Iran could facilitate SNRIs—either by relaxing its entry procedures for inspectors, or by permitting them to be permanently based in the country.[82] Whether relaxing entry procedures would be a sufficient step to facilitate SNRIs depends on how quickly inspectors can travel inside Iran. After all, Iran would realize that an inspection was imminent when inspectors arrived in the country. SNRIs would therefore only be feasible if inspectors could travel from their point of entry to the facility in less than, say, two hours. Otherwise short notice inspections would only be possible if inspectors were based permanently in Iran.

Evaluation

There is reasonable doubt about whether the IAEA can meet its current timeliness target in Iran and, more importantly, whether that target is ambitious enough. In the light of this, an effective way of enhancing confidence in IAEA safeguards would be for the IAEA to reduce the time it takes to detect a diversion (proposal II.6). In practice, the IAEA could accomplish this in a number of ways (e.g. by reducing the material balance period for Iranian facilities). A second, equally important, step would be for Iran to facilitate short notice inspections (proposal II.8). Being more transparent about the current system (proposal II.4) could also have a useful role to play. On the other hand, the IAEA is, in all likelihood, already able to detect a diversion much smaller than 1 SQ at the 90 per cent confidence level. For this reason, the benefits of formally reducing the definition of an SQ or increasing the detection probability, β, are much more limited.

Many of the proposals in this section entail an increase in the intensity of IAEA verification activities. Although this would have budgetary consequences, it is worth bearing in mind that even if all the proposals in this section were implemented the IAEA's verification burden in Iran would still be considerably smaller than for a single ultra-large fuel cycle facility elsewhere in the world.[83]

Enhanced safeguards on enrichment

Because of their commercial and proliferation sensitivity, gas centrifuge enrichment plants (GCEPs) have historically been singled out for special safeguards measures. Centrifuge plants in Europe and Japan, for example, have been subject to a special arrangement known as the Hexapartite Agreement since the mid-1980s.[84] Currently, the IAEA is in the process of developing a new model safeguards approach.[85] Safeguards specific to GCEPs, should Iran decide not to suspend its enrichment programme, are discussed in this section.

Proposal II.9: Enhanced safeguards on enrichment

Description: The IAEA implements enhanced safeguards on Iranian enrichment facilities. The approach would necessarily have to be tailored to the individual facility in question, but the measures that could be adopted include:

- Remote monitoring of the cascade hall;
- Limited frequency unannounced access (LFUA) into the cascade hall;[86]
- Remote monitoring of feed and withdrawal stations;
- SNRIs of the feed and withdrawal stations;
- Inline flow and enrichment monitoring;
- Regular use of DIV.

Facilitating effective SNRIs and LFUA would entail implementing proposal II.8.

Purpose: To increase confidence in the IAEA's ability to safeguard enrichment facilities in Iran; in particular in its ability to detect 'excess' production (enrichment of undeclared material) and undeclared HEU production.
Cost of implementation: Medium
Increase in confidence: Medium

Analysis: the effect of the additional transparency measures

Apart from a simple diversion of material, which could occur at any fuel cycle facility, there are two diversion scenarios that are specific to enrichment: production of HEU and 'excess' production. The former is of concern because, although it would be likely to be detected, HEU is a direct use material with a short conversion time. The latter involves introducing unsafeguarded feedstock into an enrichment facility and not declaring the output. In theory, it is possible to detect excess production by performing a 'SWU balance';[87] in practice, this procedure is of questionable effectiveness because there is no way to verify independently the separative capacity of a GCEP. In fact, a state could plausibly facilitate excess production by deliberately understating the separative capacity of its enrichment facility. Moreover, if the enrichment level of the product is the same during excess production as declared production, it would be impossible to detect by using environmental sampling.[88]

Because of the small size of the PFEP, it seems unlikely that it would be used to produce HEU directly. The principal fear concerning the PFEP (apart from the knowledge Iran gains by operating it) is excess production of LEU that could be rapidly converted into HEU. For this reason, the most effective safeguard (from a confidence building perspective) in the PFEP would be verification of feed and withdrawal stations. This could be achieved with remote monitoring and possibly SNRIs (if facilitated by proposal II.8).

Although the direct production of HEU in the PFEP is less likely than excess production of LEU, it is still a valid concern. In this regard, the installation in the centrifuge hall of remote monitoring equipment—a step thus far resisted by Iran[89]— would be an important transparency measure because it would allow the IAEA to verify more easily that there has been no reconfiguration of the centrifuge cascade. Cameras are currently installed in the cascade hall of the PFEP but they do not transmit data off-site. Inline enrichment monitors to detect the production of HEU would be an important secondary safeguard. Environmental sampling can provide additional assurance—but that already takes place.[90]

LFUA for the cascade hall would also be a desirable step. As is discussed above, however, unannounced inspections are currently not possible in Iran. They could be facilitated by proposal II.8, but it is worth considering whether this would be necessary for safeguarding the PFEP when remote monitoring and the use of inline enrichment monitors, which are cheaper and less intrusive, are just as effective. In fact, since they provide continual monitoring of the cascade they are arguably more effective.

For the FEP, it is probably the direct production of HEU that constitutes the biggest fear, although excess production is still a concern. As is discussed above, the strongest CBM that Iran could adopt with regard to the FEP would be to terminate its construction entirely. If Iran decides against this option then the IAEA's new model safeguards approach would be a good starting point for developing an appropriate set of safeguards. This approach, which is currently being developed and has not yet been applied to any facility, differs from Hexapartite Safeguards in two major respects:[91] first, it is designed to detect excess production, which was not considered in the Hexapartite Project; and, second, it aims to 'tailor' safeguards to individual enrichment facilities to a greater extent.

Within the new model approach, safeguards are built around the principle of 'defence in depth', that is, adopting multiple measures to guard against the same diversion scenario. For instance, in addition to permitting LFUA to verify that there has been no HEU production,[92] Iran could also install inline enrichment monitors and permit the IAEA to withdraw material from the cascade for analysis. Remote monitoring of the cascade hall would also be an important step—but, as with the PFEP, it is one that Iran is resisting at the moment.[93] The IAEA's new model approach is designed to safeguard a facility with a separative capacity some 40 times larger than the FEP. By choosing to adopt it (perhaps with more 'layers of defence' and more frequent inspections than usual) Iran might go some way towards increasing trust. No set of transparency measures, however, can be as effective at rebuilding trust as termination of the FEP programme.

Evaluation

By international standards the PFEP is a very small enrichment facility. With a throughput of some 5 tU per year, material accountancy is likely to be an effective means of detecting a diversion of any significance. Moreover, with the enhanced safeguards discussed in proposal II.9 in place, it should be possible to guard against excess production or reconfiguration. It is important to keep in mind, however, that (as is discussed in part I) continued use of the PFEP will enhance Iran's ability to conduct a successful clandestine programme. These and other competing factors are weighed up in the conclusions to this paper.

The FEP's separative capacity is over an order of magnitude larger than the PFEP's. Although still small by international standards, the FEP poses much more of a proliferation risk than the PFEP. Continuation of the FEP programme is likely to damage international trust in Iran even further. It seems unlikely that any set of safeguards would be able to rebuild that trust.

Part III: Measures to assist the detection of clandestine facilities

The most important step that Iran could take to build confidence in the absence of undeclared nuclear activities on its territory would be to recommence provisional implementation of its additional protocol and to ratify it as soon as possible. Indeed, this is a requirement of the UN Security Council.[94] The model additional protocol is designed to give the IAEA the authority it needs to be able to draw credible conclusions about the absence of undeclared nuclear material in a state. It increases the powers of the IAEA in various respects, most importantly with regard to the amount and type of information it can request from states. There are, however, limits to its effectiveness and, for this reason, this paper considers additional measures to enhance the IAEA's ability to detect clandestine nuclear activities. The discussion is divided into three sections. First, the efficacy of the additional protocol as a means for detecting undeclared nuclear activities is discussed. In particular, the types of undeclared activities that it would be *least* effective at detecting are identified. This discussion highlights that it could be possible for Iran to operate a clandestine nuclear programme without detection even with an additional protocol in force. Second, an enhanced methodology for detecting clandestine facilities, which builds heavily on the IAEA's current system, is briefly presented. Third, particular CBMs are outlined and their effectiveness discussed.

The IAEA's current system

Before 'Programme 93+2' (the project to examine ways to enhance the ability of the IAEA to detect undeclared nuclear activities), the IAEA's safeguards role was largely limited to detecting the diversion of material from declared facilities.[95] In the event that the IAEA obtained evidence of undeclared nuclear material in a state, it could, in theory, investigate further by requesting voluntary access or a special inspection. This system suffered from two major flaws. First, the IAEA had almost no independent capacity to gather evidence of undeclared nuclear activities and hence could almost never be in a position to request voluntary access or instigate a special inspection. Second, even if the IAEA did obtain such evidence, it lacked an appropriate response. A request for voluntary access can be denied by a state. Because a demand for a special inspection is likely to inflame an already tense situation, the IAEA is generally reluctant to make one.[96] It is telling that a special inspection has only ever been requested once by the IAEA—in North Korea in 1993 on the basis of satellite imagery provided by the United States.[97] In addition, a special inspection was conducted in Romania but that was at the request of the Romanian government not the IAEA.

The measures developed by programme 93+2 were split into two parts.[98] Part I measures were those that did not require additional legal authority. Part II measures did require an additional legal instrument—the additional protocol. This division is significant today because in a state with no additional protocol in force the IAEA's powers are limited to those specified in part I.

The tools that the IAEA has to detect clandestine facilities are summarized in box 1. These can be grouped under three main headings: information gathering and analysis, environmental monitoring and access rights. The box illustrates the tools available under an INFCIRC/153-type safeguards agreement (part I measures) and those which require an additional protocol (part II measures).

A number of the tools indicated in box 1 (those marked *) are useful in detecting undeclared activities at declared locations (the term 'declared location' is used here as shorthand to denote any facility, site or other location declared pursuant to either a comprehensive safeguards agreement or an additional protocol). Indeed, by using a combination of complementary access and DIV, backed up by environmental sampling, the IAEA's prospects for detecting undeclared activities at declared locations are excellent.

The main challenge for the IAEA is detecting undeclared activities at undeclared locations. There has been little analysis of how effective the IAEA's system in that regard is. One method for assessing its efficacy is to analyse the difficulty a state faces in creating a clandestine nuclear programme that would have a good chance of avoiding detection. To that end, the attributes listed below would all be desirable in a clandestine programme:

Box 1 Summary of key methods to detect clandestine facilities

Information gathering and analysis

INFCIRC/153: 'Basic' state declarations; open source data (e.g. scientific literature and satellite imagery); information provided by member states; all information analysis techniques

INFCIRC/540: Expanded state declarations

Environmental monitoring

INFCIRC/153: Site-specific environmental sampling (during an inspection or visit pursuant to INFCIRC/153)*

INFCIRC/540: Site specific environmental sampling (during complementary access)*; Wide area environmental monitoring (subject to approval by the IAEA Board of Governors)

Access rights

INFCIRC/153: Special inspections; Design information verification*

INFCIRC/540: Complementary access*

1. All activities take place away from declared locations.
2. Facilities 'blend into' their environment (e.g. by building them alongside existing industrial activities).
3. Equipment used in the programme is: (a) manufactured domestically; or (b) manufactured entirely from sub-components and materials that do not feature on any export control list; or (c) imported secretly from a state that will not report the sale; or (d) procured by a non-state actor whose activities are not known to states.
4. There are no interconnections (either administrative or in terms of the flow of nuclear material) between the clandestine programme and a declared one.
5. There is tight information security around the clandestine programme.
6. There are few independent sources of information (pressure groups, independent media agencies etc.) on nuclear or military activities in the state.[99]

In general, the more of these attributes that a clandestine programme has, the harder it will be for the IAEA (or a national government) to uncover it. At one extreme, it seems highly unlikely that a programme with none of these characteristics will avoid detection. At the other extreme it is unlikely—although not inconceivable—that a programme with all of these attributes will be detected.

The relevance of these criteria can be illustrated by considering how Iran's undeclared activities were originally discovered. Iran's centrifuge activities at Natanz were first publicly disclosed by an opposition group—the National Resistance Council of Iran—in 2002. The source of their information is unclear. One suggestion is that they were able to obtain the information themselves as a result of poor information security.[100] Another suggestion is that they received the information from US intelligence which, in turn, learned of the programme through its investigations into the AQ Kahn network and from satellite imagery of construction work on the FEP.[101] Either way, it appears that the discovery of Iran's centrifuge programme was a result of failures with regard to some combination of points 2, 3d or 5. Similarly, interconnections between different parts of Iran's programme (point 4) have been useful in discovering the extent of undeclared activities. For example, some of the initial evidence for what turned out to be enrichment experiments originated from the discovery that 1.9 kg of UF_6 was 'missing' from a particular cylinder.[102] More recent IAEA reports also suggest that 'administrative interconnections' are important to gaining an understanding of the full scope of Iran's nuclear activities.[103]

Using these criteria it is possible to analyse how much confidence states should have in the ability of the IAEA to detect undeclared activities in Iran should an additional protocol to be put in place. The additional protocol works best in a state where there are multiple independent sources of information. This is, by and large, not true of Iran and would therefore reduce its effectiveness. Designing a clandestine programme that possesses characteristics 1–5 listed above is difficult and would add to the cost of the programme—but it is not impossible.

In particular, the expertise that Iran already has with centrifuge technology would help it to build centrifuges indigenously. There is a real possibility, therefore, that Iran could successfully conceal a clandestine nuclear programme even with an additional protocol in place.

In addition, the 93+2 Programme did little to address the lack of investigative options that the IAEA has at its disposal should it obtain evidence of undeclared nuclear activities. The political sensitivities around special inspections still remain and, although the IAEA can request voluntary access to any site, a system based entirely on voluntary inspections is unlikely to inspire much confidence because Iran could deny a request for access at any time. The possibility of developing a protocol for special inspections and thereby reducing the sensitivities that surround them is therefore also examined below.

Improving the system for detecting clandestine nuclear activities

Clandestine nuclear activities can be uncovered by detecting characteristic 'indicators'. In the case of a nuclear reactor, for example, such indicators include the presence of fission products in its effluent, the importation of reactor components and the presence of distinctive physical features, such as cooling towers, thermal emissions or unusually high security. The IAEA's capability to detect clandestine nuclear activities can be enhanced by increasing not only the range of indicators that it is able to detect but also the reliability with which it can detect them. Table 4 summarizes some indicators of nuclear activities (in particular effluent and external physical features). Some of these indicators, in particular the physical features of facilities, can be detected using existing techniques such as satellite monitoring. Others, namely distinctive chemicals or elements in effluent, cannot because the use of environmental monitoring away from declared locations has not yet been approved. This section discusses two verification techniques—wide area environmental monitoring (WAEM) and overflights—which could be used to detect these categories of indicators.

Some of the indicators in table 4 (e.g. the presence of enriched uranium, plutonium or certain radionuclides) can, by themselves, provide unambiguous evidence of nuclear activity. Where possible, it makes sense to focus on these indicators. Other indicators, however, are ambiguous in the sense that they are also associated with non-nuclear activities. For instance, piles of ore and tailing at mines are associated with the extraction of materials other than uranium. The presence of a number of the ambiguous indicators, however, would provide strong evidence of clandestine nuclear activity. It is important to remember that the primary aim of this analysis is *not* to provide incontrovertible evidence of clandestine nuclear activity but to find enough evidence to justify some kind of inspection. The discussion below outlines the most appropriate indicators for each stage of the fuel cycle.

Mining and milling

The simplest method of mining uranium is opencast mining (Iran's two existing mines—Saghand and Gchine—are of this type). This technique, however, is used to mine a number of metals (sometimes in combination) and, although it is relatively straightforward to identify an opencast mine using satellite photography, it is harder to identify the material that is being mined.[104] However, this may not be as much of a problem as it first seems. Mines, other than undeclared uranium mines, are unlikely to be kept secret. The discovery of a secret mine in Iran may be enough, by itself, to merit further investigation. Perhaps the best way to positively identify an opencast uranium mine is to look for its associated mill. Possible indicators of a uranium mill include mixer/settlers, thickeners, a stockpile of sulphur and a constant stream of ore carriers from the mine.[105] Moreover, there is also information about Iranian uranium deposits in the public domain and, although there is no guarantee that it is complete (e.g. Gchine was kept secret for many years), such information would certainly help to guide a search.[106] Overall, the prospects for detecting a secret opencast mine in Iran are reasonable.

Table 4 List of selected indicators for nuclear activities

Activity	Effluents potentially useful for WAEM	Distinctive external physical features
All		High security, isolated site, good transport links
Mining and milling	None identified (see footnote 109)	**Mining:** piles of ore and tailings, large ore trucks, discriminator stations **Milling:** mixer/settlers, thickeners, sulphur stockpile ***In-situ* leaching:** injection and product wells, evaporation ponds
Conversion	Molecular unenriched UO_2F_2	On site UF_6 canisters
Enrichment	Concentration of ^{235}U raised relative to ^{238}U	**Gas centrifuge plants:** none identified **Gaseous diffusion and aerodynamic enrichment plants:** power plant, high voltage power lines, large switchyards, cooling towers **EMIS:** high voltage power lines, transformer stations
Fuel fabrication	Molecular UO_2F_2 (enriched or unenriched), hafnium-free zirconium	None identified
Reactor activity	Gaseous and liquid effluents containing nuclear fuel, neutron activation products, fission products and decay products	Cooling towers, high stack, reactor building, thermal emissions. Can be distinguished from conventional power plant by lack of storage for coal, gas, or oil.
Reprocessing	Uranium, plutonium, fission, activation and decay products in solution	Long building, very high stack, waste/sludge holding ponds, water supply, cranes, power supply, transport canisters

Note: In addition to zirconium, a large number of non-radioactive materials are also involved in fuel cycle activities, especially reprocessing. These might be detectable in effluent. Moreover, the purchase of these materials (especially in combination) is also an indicator of nuclear activities. They have not been listed in the table, however, because radioactive materials are both easier to detect and less ambiguous.

The prospects for detecting an underground mine are not much worse.[107] An underground mine would almost certainly be attached to an above ground mill, which would provide a good target for detection. Moreover, ore trucks and piles of ore as well as tailings on the surface would still be visible. Indicators of *in situ* leaching, another uranium 'mining' technique, include a characteristic pattern of injection and production wells as well as evaporation ponds.[108] In fact, the only method of uranium extraction that it would be effectively impossible to detect through satellite imagery is where uranium is produced as a by-product of phosphate extraction.[109]

Conversion

Conversion facilities are large-scale chemical plants. It is inevitable that some UF_6 would be released from them into the atmosphere, where it reacts with water vapour to form uranyl fluoride (UO_2F_2), probably in the form of an aerosol.[110] The use of environmental monitoring to detect conversion facilities is usually discounted because of the background levels of uranium.[111] However, Kemp has recently suggested that it might be possible to detect clandestine conversion facilities by looking for molecular UO_2F_2 specifically, rather than just the presence of uranium in general. UO_2F_2 is potentially a useful signature because it is highly stable and its lifetime in the environment as an aerosol is probably brief enough to enable background effects to be discounted. Numerical modelling has suggested that environmental monitoring could potentially be used to detect a small conversion facility with a throughput of 12.5 tU/yr at significant distances, possibly as much as 200–300 kilometres (km). This method would obviously have to be tested in field trials before it could be employed in practice.

Detecting conversion facilities through their appearance is difficult because there is little that distinguishes them from non-nuclear chemical plants.[112] The presence of canisters to store UF_6 might be observable but similar containers could be found at many other industrial facilities. Physical evidence such as this, or proximity to a suspected enrichment facility, is therefore best used as supplementary evidence to back up WAEM. The one exception might be an underground facility. Such a facility would be extremely difficult to detect once completed, but its construction would be very difficult to conceal. The construction of a large underground chemical facility is by itself suspicious, irrespective of any supporting evidence.

Enrichment

The ease of detecting an enrichment facility depends strongly on the type of enrichment process being used. Gaseous diffusion plants, for instance, produce large quantities of heat which could be observed by infra-red satellite imagery.[113] The technology of concern in Iran, however, is the gas centrifuge. Apart from heightened security a GCEP has few, if any, distinguishing features. In theory, it is possible to detect the presence of enrichment from the abundance ratio of ^{235}U to ^{238}U (which is otherwise almost totally uniform across the globe). Whether this is feasible in practice depends on how much UF_6 leaks from the plant. The leakage from the most modern and sophisticated GCEPs is very small—too small to give them a significant detection radius.[114] There are, however, a number of reasons to suppose that leakage from Iranian facilities might be larger. First, states without extensive enrichment experience, such as Iran, may have neither the experience nor the technology to reduce UF_6 emissions from a GCEP to a negligible level (after all, the drive to prevent emissions from GCEPs in Western countries was a result of environmental considerations which have been largely absent in Iran). Second, there is always the possibility of an accidental release, especially in a clandestine programme run by the military, which is not subject to typical civilian safety standards. An accidental release need not be a catastrophic event—much smaller occurrences, such as the failure of a seal resulting in the emission of a few tens of grams of UF_6, could be detectable.

Fuel fabrication, reactor activity and reprocessing

Fuel fabrication, reactor activity and reprocessing are considered more briefly because they are relevant only to an attempt to manufacture nuclear weapons via the plutonium route and this is less of a concern in Iran than enrichment. In particular, because of the difficulties in concealing a reactor, it seems highly unlikely that any state would risk attempting to build an entire clandestine fuel cycle in secret. One possible proliferation pathway would be for a state to develop reprocessing in secret and use this capability to reprocess fuel from an HWR. The detection of clandestine reprocessing facilities will therefore become more important if Iran does not terminate its HWR project.

The most useful indicators of reactor activity are physical characteristics, in particular cooling towers and thermal emissions. Significantly, reactor sites are also distinguishable from normal commercial power plants because they lack storage areas for coal, gas and oil.[115] Reprocessing plants also have characteristic features such as a high stack, a long building, heavy lifting equipment, a high-capacity water supply and the presence of transport canisters for spent fuel.[116] In either case an isolated site, high security and good transport access (possibly a railway line) would also be suggestive of clandestine activity. WAEM is also useful for detecting both reactors and reprocessing facilities.[117] Radionuclides (such as those listed in table 4 under effluents) can be detectable at distances of about 100 km in air or 1000 km in water.[118] In contrast, identifying a fuel fabrication plant is much harder—like enrichment the best indicator is an increase in the abundance ratio of ^{235}U to ^{238}U. Given that fuel fabrication is inevitably accompanied by reactor activity, which is much easier to spot, there seems little point in attempting to detect it.

Wide area environmental monitoring

Before discussing specific verification methodologies in detail, it is worth emphasizing that their effectiveness can be increased and costs can be reduced if technologies are used in combination. This is true of many aspects of nuclear verification, but is particularly important with the detection of clandestine facilities. For example, the size of an area for WAEM can be reduced by using overhead imagery combined with information from maps to screen for suitable sites.[119] As well as saving costs, this procedure can also enhance effectiveness; since effluents are diluted with distance WAEM works best at locations close to and down wind—or downstream—from a suspect facility.

Proposal III.1: Wide area environmental monitoring

Description: The IAEA collects and analyses environmental samples to look for materials that are indicative of nuclear activities. The samples could be taken from the air, water, soil, vegetation or sediment.
Purpose: To verify the absence of clandestine nuclear facilities in Iran.
Cost of implementation: High
Increase in confidence: Medium

Analysis: the status quo and the effect of the additional protocol

Under INFCIRC/153 the IAEA is allowed to use site-specific environmental monitoring.[120] As is discussed above, article 9 of the additional protocol permits wide area environmental monitoring once ‘procedural arrangements . . . have been approved by the Board.’[121] Approval has not yet been granted.

Analysis: The effect of additional transparency measures

Wide area environmental monitoring is a generic term that encompasses a range of different technologies including air, water, sediment and deposition sampling. Although there has been considerable research into relevant sampling and analytical technologies, much less effort has been expended on developing a protocol for the implementation of WAEM on a countrywide scale.[122] It is therefore important to acknowledge at the outset that, even ignoring cost considerations, the development of a WAEM system for Iran would be a major task that would take time to implement.

The technology that holds the greatest promise for WAEM is generally considered to be air sampling.[123] Garry Dillon, a former leader of the IAEA Iraq Action Team, recently analysed the feasibility of setting up a network of air sampling stations in Iran.[124] Dillon points out that if a detection range of 10 km is required (a reasonable figure for a GCEP) then an ‘unmanageable’ 34,000 sampling stations would be needed for complete coverage of Iran. He assumes a detection radius of 100 km and hence envisages a network of 400 sampling stations to ensure complete coverage. In the absence of any information to guide the deployment of the network, the samplers would be arranged in a square grid altered, where necessary, to take account of Iran's terrain. Ideally, however, the samplers would be mobile so that the network's shape could be altered in the light of new information. Dillon is primarily interested in obtaining a cost estimate for WAEM in Iran. He acknowledges that his analysis 'should not be interpreted to suggest that the exampled network is capable of providing meaningful detection sensitivities'. Here we consider the key question of whether such a network would, in fact, have a reasonable chance of detecting a clandestine nuclear facility.

The detection radius for reactors and reprocessing plants is around 100 km. The detection radius for a conversion facility might be even larger, if molecular UO_2F_2 can be used as an indicator. Such a network would, therefore, probably be able to detect these types of fuel cycle facilities. Because enrichment is the primary concern in Iran, the ability to detect clandestine reactors and reprocessing facilities, although useful, is not enough to justify the use of WAEM. The ability to detect a clandestine conversion plant, however, is potentially more significant because such a facility could be used to supply feedstock for enrichment.

The detection radius for a typical GCEP is much smaller—about 10 km. A static WAEM network of 400 stations covering the whole of Iran would only have, very approximately, a 0.02 per cent chance of detecting such a plant.[125] This figure can be increased, however, by deploying the network 'intelligently'. First, the network need only be deployed in areas of the country that are suitable for clandestine nuclear activities. Realistically, a nuclear facility needs good transport links, a nearby population centre to supply workers and access to water and electricity supplies, and so on.[126] A survey of Iran could be conducted to determine which areas of the country meet these criteria. Second, if the network consisted of mobile sensors it could be redeployed regularly, thereby increasing its effective coverage. Once the optimum atmospheric conditions for detection have occurred twice, say, there is probably a strong case for redeploying the network.[127] If it is assumed that only 10 per cent of the land area of Iran is deemed suitable,[128] and that the network is redeployed once every eight weeks, the probability of detection over the course of a year rises to about 1 per cent.

Further improvements could be gained from the use of intelligence or other information such as satellite imagery to help design the network. It is hard to quantify such effects, but good intelligence could make a significant difference. It is also possible that the detection radius of an Iranian GCEP is bigger than 10 km because, as is discussed above, UF_6 leakage might be a significant problem for a state like Iran, which lacks experience in enrichment. In this case the detection probability would also be increased. In fact, because the number of detectors required for complete coverage scales inversely with the square of the detection radius, this effect can be quite significant. The final way to increase the detection probability would be to improve the detection technology itself. However, because the background level of uranium is the limiting factor in detection, this process is difficult and technological improvements cannot be relied on.[129]

In the event that the WAEM network did detect evidence of clandestine nuclear activities, the next step would be to take several more environmental samples at different points. This would help to verify the earlier result and allow a better estimate of the location of the facility to be made. Finally, it would be necessary to carry out an inspection in order to confirm the existence of a clandestine facility. A possible protocol to facilitate such an inspection is outlined below (proposal III.3).

Beyond questions of efficacy, WAEM has various practical problems associated with it. First, air sampling is intrusive—Iran would have to be prepared to accept the deployment of a large number of sampling stations on its territory and permit them to move freely. Second, air sampling stations need to be protected from tampering. In practice this means an alarm system. Third, there is the issue of cost. Dillon estimates that a network of 400 samplers would cost about $30 million annually.[130] It is, however, difficult to imagine that if Iran were willing to accept WAEM, the E3+3 would not provide the necessary funding.

Up to this point, only air sampling has been considered. Other WAEM technologies are also available. Water sampling, for example, is potentially useful because, as is discussed above, radionuclides travel 10 times further in water than they do in air. If Iran were unable to prevent radionuclides being released into the water system, then water sampling might have a role to play. However, no technology is likely to be significantly better than air sampling—even if one does offer slight improvements at the margins. Using a different technology is therefore unlikely to change the basic calculation of the feasibility of WAEM. However, as Dillon points out, using other sampling techniques to complement the results from air sampling would certainly be helpful.

Evaluation

The prospects for WAEM are mixed. WAEM would be most useful if it were able to detect a clandestine enrichment programme. With current technology it is unlikely that a clandestine GCEP could be successfully uncovered unless either significant UF_6 leakage occurred or intelligence could guide the search—both of which are distinct possibilities. Moreover, implementing any system of WAEM would be expensive, intrusive and time-consuming. On the other hand, if it is feasible to detect molecular UO_2F_2, the prospects for uncovering a clandestine conversion facility with WAEM are much better. This is significant because it would be hard, but not impossible, for Iran to operate a clandestine GCEP without running a clandestine conversion facility. WAEM would also be useful, in a supplementary role, for detecting clandestine reactor activity and reprocessing.

Overflights

Proposal III.2: Overflights

Description: Overflights are conducted in Iran. Such flights would probably have to be carried out by a state party, but they would be scheduled and the results analysed by the IAEA. Planes would be equipped with both electromagnetic sensors and air sampling devices.
Purpose: To verify the absence of clandestine nuclear facilities in Iran.
Cost of implementation: High
Increase in confidence: Low

Analysis: Status quo and the effect of the additional protocol

The use of overflights is not authorized by either INFCIRC/153 or INFCIRC/540. Although the IAEA is permitted to collect and analyse overhead imagery, such imagery has in the past been acquired using satellites.

Analysis: The effect of the additional transparency measure

Overflights, in certain respects at least, offer some modest advantages compared to satellites for the purpose of acquiring overhead imagery.[131] Images from overflights can be higher resolution than those from satellites. Commercial satellites offer a maximum resolution of about 0.6–1 metres (m) for panchromatic images whereas those taken from aircraft can have a resolution of about 0.3 m.[132] The difference is even more marked with thermal (infra-red) imagery, where the resolution of 0.5 m afforded by aircraft-based sensors is much better than anything offered by satellites. In addition, there is greater freedom in choosing the flight path of an aircraft compared to the orbit of a satellite. Aircraft imagery is also less affected by clouds and there is greater flexibility in aircraft scheduling than satellite scheduling.

In practical terms these advantages make only a limited difference. Although the principal advantage of overflights—higher resolution imagery—may sound quite significant, there are, in reality, comparatively few indicators of nuclear activity that would become accessible through this extra resolution. One example might be discriminator stations used in uranium mining.[133] These facilities are unique to uranium mines and are thus an unambiguous indicator of uranium mining, but appear similar to ore carrier refuelling stations which are common to many other types of mine. It is possible to envisage overflights being used to help ‘fill the gap’ between satellites and on-site inspections. Should a suspect facility be discovered using satellites, an overflight could be dispatched to obtain higher resolution imagery prior to requesting an inspection. However, this role, by itself, is not sufficient to justify the use of overflights.

Overflights would, however, be a highly valuable verification tool if they could be used for air sampling. They could be used for this purpose in two ways. First, they could be used to take air samples at certain places. This is conceptually similar to the air sampling network described above, only it is less intrusive and would not require the deployment of multiple air sampling stations. Alternatively, air could be sampled continuously during an overflight. In the event that an indicator of nuclear activity was detected, possible sources could be identified by using observation data from the flight and environmental samples taken from the ground. There has even been some discussion in the past about real-time radionuclide monitors being placed on-board aircraft.[134] While it seems extremely unlikely that such monitors could be sensitive enough to detect enrichment facilities, it is possible that they could be used to track down reactors, reprocessing facilities and possibly conversion facilities by detecting molecular UO_2F_2 (as is discussed above).

Unfortunately, all these schemes are highly speculative, which is why this proposal has been assigned an increase in confidence rating of ‘low’. There are a number of important questions concerning the feasibility of environmental monitoring from aircraft and there is very little in the published literature to help answer them. The most fundamental question is whether the concentration of radionuclides resulting from nuclear activities is sufficient to permit detection at the relevant height. There has been much research into the optimum atmospheric conditions for ground-based environmental monitoring, but much less effort has been expended in answering the same question for aircraft-based monitoring. Monitoring from aircraft is potentially much harder than ground-based monitoring because sampling times for aircraft are likely to be much shorter. Nevertheless, the fact that aircraft have long been used to detect small quantities of fallout from nuclear tests does give some credence to the idea.

On a more practical level there is also the question of which organization or state would conduct the overflights. The IAEA does not have its own capability in this regard and it would probably be prohibitively expensive for it to acquire one. A possible division of labour could therefore be that overflights would be operated by a state but scheduled by the IAEA. The IAEA would be solely responsible for analysing the results obtained from flights. It would also be desirable for IAEA staff to be present on the aircraft during a flight. Using state-based assets does create certain problems. First, it might be difficult to integrate the technology used to take samples during a flight with the technology the IAEA uses for analysis. Second, a state would have to be identified that is willing and able to conduct the overflight and that all parties to the process find acceptable.

Evaluation

Overflights can serve two verification functions. First, they can be used to obtain overhead imagery. They offer slightly better resolution than satellites although this advantage, by itself, is not enough to justify their use. Second, they can, in theory, be used to collect air samples for environmental monitoring, although it is far from clear that this technique is feasible in practice. *If* it is feasible then overflights could be a valuable transparency measure. Moreover, because overflights are less intrusive than ground-based environmental monitoring, they are potentially more acceptable to Iran.

Development of a protocol for special inspections

Proposal III.3: Development of a protocol for special inspections

Description: The IAEA and Iran could agree a protocol for special inspections in advance of it being needed. This protocol could be modelled on the challenge inspections provided for by the 1993 Chemical Weapons Convention (CWC); in particular

- a special inspection can be carried out anywhere;
- Iran is permitted to manage the access by, for example, shrouding displays, computers and equipment;
- negotiations over the perimeter of an inspection area are permitted;
- during an inspection the IAEA has the right to take environmental samples and to monitor the exit of vehicles from the building.

Purpose: To build confidence in the absence of undeclared nuclear activities.
Cost of implementation: Low
Increase in confidence: High

Analysis: the status quo

Although special inspections provide the IAEA with a means of inspecting an undeclared facility they are problematic—not least because the IAEA is so reluctant to use them (as is discussed above). Moreover, the IAEA's access rights during a special inspection, outlined in paragraph 77 of INFCIRC/153, are not set out in any great detail. The exact terms of reference for a special inspection are to be agreed through negotiation between the IAEA and the state.[135] Such negotiations could, however, be seen as an attempt by the state to stall the start of an inspection and this could inflame an already tense situation. It might therefore be sensible for the IAEA and Iran to agree a protocol for special inspections before a request for such an inspection has been made. The existence of an agreed protocol might make the IAEA more willing to request special inspections and Iran more willing to accept them. The existence of such a protocol would not prejudice future negotiations between the IAEA and other states over access rights during special inspections.

Analysis: the effect of the additional transparency measure

Special inspections provide the IAEA with the best means of being able to validate or disprove a claim about the existence of a clandestine facility. For any number of reasons—but not least because inspections can jeopardize the secrecy of legitimate military programmes—any state is likely to insist on limits to inspectors' access rights. Indeed, this is recognized in paragraph 77 of INFCIRC/153, which states that for the purposes of special inspections the IAEA 'may obtain access *in agreement with the State* to information or locations in addition to the access specified . . . for ad hoc and routine inspections'.[136] Limits on special inspections can take two forms: limits on where inspectors can go and limits on what inspectors can do. The more limits are placed on special inspections, the more their value as a CBM is reduced. The challenge is to devise a protocol that respects the rights of the state being inspected but also permits the IAEA to conduct effective verification activities.

The solution proposed in this paper is for special inspections to take place anywhere in Iran, but for Iran to be entitled to manage access. No limits on where inspections can take place have been suggested in order to not undermine the credibility of the inspection regime. On the other hand, Iran is permitted to manage the access so that it can protect legitimate security interests and keep commercially sensitive information secret. Crucially, recent developments in nuclear forensics—in particular in environmental sampling—enable managed access to be effective.

The details of a protocol for special inspections would need to be decided in negotiations between Iran and the IAEA. However, for special inspections to be worthwhile inspectors would, at the very least, need the right to take environmental samples, conduct visual observations and use radiation detection devices. It would also be helpful if the IAEA were entitled to take other NDA measurements and remove samples for DA. The protocol for challenge inspections pursuant to article IX of the CWC would seem to be a good starting point for developing the rules of managed access.[137] In fact, many of the features of CWC challenge inspections could be almost directly imported into the protocol for special inspections:

- Negotiations between the state and the inspectors over the perimeter of the site to be inspected are permitted. Any negotiations are, however, subject to strict time limits.
- For the duration of an inspection (including during negotiations over the perimeter), the inspection team is required to monitor the exit of vehicles from the site and has right to inspect vehicles 'on a managed access basis' to ensure that no sensitive equipment or material is removed.[138]
- The inspected state is required to give the inspectors the 'greatest degree of access' consistent with any 'constitutional obligations it may have with regard to proprietary rights or searches and seizures'.[139] Access may also be limited in order 'to protect national security'.[140] Where such considerations prevent the inspected party from giving the inspection team free access, it is entitled to manage access by, for example 'shrouding of sensitive displays, stores and equipment'.[141]

However, given the importance of the 'paper trail' in linking undeclared nuclear activities to a nuclear weapons programme, it might not be desirable for Iran to have the right to hide sensitive documents—in contrast to the protocol for CWC challenge inspections.

Having outlined the basis for a suggested inspection protocol, two questions must be addressed: first, with this form of managed access in place, would Iran be able to protect information that it had a legitimate right to keep secret; and, second, would managed access compromise the effectiveness of IAEA inspections?

In answer to the first question, it is important to note that managed access was originally designed to enable states to permit international inspectors to enter any facility—however sensitive. In the years before the CWC was concluded (and again in 2003), the UK government simulated challenge inspections at facilities involved in its nuclear weapons programme.[142] It concluded that Organisation for the Prohibition of Chemical Weapons (OPCW) inspectors could be granted access to all buildings on such a site without adversely affecting national security or breaching the UK's obligations under article I of the NPT. Given the exceptional sensitivity of the facilities involved, the simulated inspections provided strong evidence that managed access is effective. Moreover, Iran (in addition to 181 other states) has signed and ratified the CWC. It has therefore already indicated that it would be willing to accept challenge inspections conducted by the OPCW. Presumably, Iran would not have acceded to the CWC if it felt that challenge inspections would damage its national security or compromise proprietary information.

In answer to the second question, evidence is available that managed access would not compromise the effectiveness of environmental sampling. A useful illustration of the power of environmental sampling comes from the IAEA's safeguards work in Iran. In March 2003 IAEA inspectors visited the Kalaye Electric Company (KEC) workshop in Tehran but were denied permission to take environmental samples. By the time that permission was granted, in August that year, 'Iran had tried to "decontaminate" the premises, for example, by painting all the interior spaces, replacing the flooring, and removing all of the equipment . . .'.[143] Nonetheless, the samples that were taken proved unequivocally that uranium enrichment had taken place in the building—a fact that Iran subsequently admitted.[144] Environmental sampling can detect nuclear materials in nanogram amounts or smaller. Given that detectable traces of UF_6 remained in the KEC workshop even after five months of cleaning, it seems extremely unlikely that any facility could be effectively decontaminated in the time between the request for a special inspection and its start. It may be possible to decontaminate a facility by razing it to the ground and removing the topsoil—but again this would be impossible in the time between the request and start of a special inspection.[145]

Given the power of environmental sampling, it might be possible for Iran to manage special inspections to a greater degree than is permitted under the CWC. For instance, one way of facilitating access into a particularly sensitive area might be for inspectors to be admitted into a small curtained-off part. They would be permitted to take swipe samples but not to make visual observations of the area behind the curtain. This solution would not be ideal (especially because it would not allow weaponization activities not involving nuclear material to be detected) but it might be an acceptable compromise because visual observations, although important, play a secondary role to environmental sampling in the detection of undeclared nuclear activities.

Evaluation

The development of a protocol for special inspections has the potential to be an effective CBM. Crucially, advances in environmental sampling enable managed access to be effective access. A protocol for special inspections modelled on CWC challenge inspections could therefore permit the IAEA to carry out a rigorous investigation into evidence of undeclared nuclear activities while ensuring that Iran's rights were respected. However, the IAEA would need evidence before it could request an inspection. For this reason, the effectiveness of special inspections is limited by the IAEA's ability to collect preliminary evidence of undeclared activities.

Enhancing transparency in scientific and industrial activities

Proposal III.4: Interviews with Iranian scientists and officials

Description: The IAEA is permitted to interview Iranian scientists and officials for the purpose of verifying the absence of undeclared activities. Interviews are to take place in Iran but without any other Iranian officials present. Interviews may be recorded.
Purpose: To build confidence in the absence of undeclared activities.
Cost of implementation: Low
Increase in confidence: Medium

Proposal III.5: Verification of centrifuge production and the disclosure of sensitive industrial and scientific projects

Description: Iran permits the IAEA to verify the production of centrifuges and discloses to the IAEA details of any industrial or scientific activity which fabricates components or key materials that could be used in the production of centrifuges or other fuel cycle technologies.
Purpose: To build confidence that Iran is not secretly manufacturing fuel cycle technology.
Cost of implementation: Medium
Increase in confidence: High

Analysis: the status quo and the effect of the additional protocol

The IAEA has no legal right under either INFCIRC/153 or INFCIRC/540 to conduct interviews with scientists or officials. The IAEA can request access but, in general, it is entirely at the state's discretion to grant such a request. The case of Iran is somewhat different because the Security Council has backed the IAEA's requests for interviews—but only in so far as such interviews are necessary to resolve those questions which are currently outstanding.[146] Interestingly, article XII A.6 of the statute of the IAEA does give IAEA inspectors the right to have access to 'any person who by reason of his occupation deals with materials, equipment, or facilities which are required by this Statute to be safeguarded . . . to determine whether there is compliance with the undertaking against use in furtherance of any military purpose . . .'. However, under the legal principal of *lex specialis derogat legi generali* (the special law overrides the general one), the more specific provisions of the safeguards agreement are recognized as superseding the more general provisions of the statute. It is therefore hard to argue that the right of interview contained in article XII A.6 is enforceable.

Under an INFCIRC/153 agreement, there is no requirement on states to submit information about the manufacture or development of fuel cycle technology when no nuclear material is involved. This situation is altered somewhat where an additional protocol is in force. For example, in an expanded declaration states are required to provide the IAEA with 'a general description of and information specifying the location of *nuclear fuel cycle-related research and development activities* not involving *nuclear material* . . .'[147] and 'a description of the scale of operations for each location engaged in the activities specified in Annex I to this Protocol'.[148] Annex I includes, for instance, 'the manufacture of *centrifuge rotor tubes* or the assembly of *gas centrifuges*'.[149] Although the IAEA can conduct complementary access at locations where these activities take place, it cannot verify the number of centrifuges being produced. Nor can it supervise the production of centrifuge components (except the rotor tube itself) or precursor materials, such as maraging steel.

Analysis: the effect of the additional transparency measures

Scientific research plays a key role in the development of nuclear technology, whether for civilian or military purposes. A lack of transparency can lead to a lack of trust because of the concern that an overtly civilian research programme might actually be cover for a nuclear weapons programme. Proposal III.4 would allow Iran to address that concern by permitting the IAEA to interview Iranian scientists and officials, giving them the opportunity to explain why potentially sensitive research is being conducted.

Interviews are primarily of use in verifying that undeclared activities do not breach the terms of any safeguards agreement. To illustrate this point, consider the following scenarios:

- Evidence comes to light of an Iranian research and development programme that has not been declared to the IAEA in the state's expanded declaration pursuant to an additional protocol, but which is dedicated to the development of materials, such as maraging steel or certain types of carbon fibre, that could be used in the manufacture of centrifuges. Interviews could be useful in establishing whether this programme is part of a clandestine nuclear programme.
- Certain pieces of equipment, which are typically used in experiments involving nuclear material, are found at a facility that has not been declared to the IAEA. Again, interviews could help to determine why such equipment is needed if nuclear material is not present.

Of course, the IAEA must have good evidence to request an interview and, as with all investigative work related to undeclared activities, the principal challenge is obtaining this preliminary evidence. In this regard, it is important to recognize that uncovering small-scale undeclared research and development activities is even harder than detecting a large-scale undeclared fuel cycle facility. This does limit somewhat the increase in trust that would be likely to result from proposal III.4.

Even with an additional protocol in force, a state could use a declared centrifuge production facility to manufacture centrifuges for a clandestine programme. The existence of a declared centrifuge enrichment programme therefore makes it harder for the IAEA to detect a clandestine one. Proposal III.5 aims to overcome this problem by giving the IAEA permission to verify the production of centrifuges. This would involve inspectors counting and tagging centrifuges as they were produced to ensure that they were installed at declared facilities and that none was diverted for clandestine use. This could potentially be a strong CBM if Iran were to continue its enrichment programme, even on a pilot scale.

Proposal III.5 also aims to increase transparency in industry and science in Iran more generally (and hence to obviate the need for interviews, such as those provided for under proposal III.4). In the scenarios discussed above, for example, Iran could pre-empt suspicion by declaring work on maraging steel or the acquisition of potentially sensitive equipment. It would be logical to base the list of components and materials that Iran would be required to declare on either Annex II of the Model Additional Protocol or the Nuclear Suppliers Group's Trigger List.[150]

The value of this proposal from the point of view of the E3+3 can be assessed by considering the evasion strategies that Iran could adopt if it were carrying out undeclared experiments for military nuclear ends. First, Iran could declare the activity but mis-state its purpose. This would be a dangerous strategy, however, because it would draw attention to the existence of the activity. Second—and more likely—would be for Iran to decide not to declare the activity at all. In this case, if the activity were subsequently discovered there would be a strong presumption that it was part of a clandestine nuclear programme, although this would still be hard to prove. The fact that this kind of discovery would be hard to make, however, does limit the value of the measure.

Evaluation

Enhancing the transparency of scientific and industrial activities in Iran could serve two functions. First, by permitting the IAEA to verify the production of centrifuges, and by declaring the production of components and precursor materials that could be relevant to fuel cycle technology, Iran could reasonably hope to avoid being falsely accused of conducting a clandestine nuclear programme. Second, should a potentially sensitive research project be discovered, Iran could permit the IAEA to interview scientists and officials to enable the IAEA to clarify its nature. The extent to which these proposals are likely to build confidence, however, is limited by the IAEA's difficulty in detecting small-scale research and development.

Part IV: Measures to increase trust in Iran's intention to stay in the NPT

More than any other concern about Iran's nuclear programme, the fear of breakout is motivated by the lack of trust between the governments of the US and Europe and the government of Iran. Although the size of the FEP and its underground location exacerbate this concern, they are not its cause. Accordingly, building confidence in Iran's intention to stay in the NPT must be addressed as part of a wider political process. In general, there is little that the 'technical' measures considered in this paper can do in this regard.

One possible exception is the idea that Iran could 'enshrine' the NPT in its national law, for example, by making Iran's membership of the NPT a constitutional obligation or by renouncing its article X right to withdraw from the NPT.[151] This measure would not be a replacement for broader political confidence building, but it might contribute to it by 'raising the bar' for Iran to leave the NPT. Its value depends, in part at least, on a legal analysis of how hard it would be for Iran to reverse this measure—something that is beyond the scope of this paper. Nevertheless, it is certainly an idea that merits further consideration.

While it is not possible, within the scope of this paper, to present a comprehensive list of measures to increase trust in Iran's intention to stay in the NPT, it would be useful, at least, to assess the likelihood of Iran not doing so. An analysis of which of the measures presented in this study should be prioritized, which the conclusions to this paper attempts, requires an assessment of the relative likelihood of Iran manufacturing nuclear weapons by diverting material from declared facilities—by sneak-out or by breakout. It is our conclusion that if Iran attempts to manufacture nuclear weapons it is unlikely to do so through breakout. There are two reasons for this.

First, an Iranian decision to leave the NPT at the moment would almost certainly be met with robust preventative action, especially if it were coupled with evidence of an active Iranian nuclear weapons programme. It is likely that the United States would take military action against Iran, probably in the form of air-strikes against both nuclear and conventional military targets. Moreover, because renouncing the NPT would send out a clear signal that Iran intended to develop nuclear weapons, it is possible that such a response would be supported by a number of other states.

Regardless of the rights and wrongs of such military action under international law, its threat is likely to be a strong deterrent to a state considering whether to develop nuclear weapons by breaking out of the NPT. In its determination of whether to do so the state would have to calculate whether it could succeed in manufacturing its first nuclear weapon before the commencement of military action.

This hypothetical scenario can be explored further in the case of Iran by estimating the likely time required to manufacture a nuclear weapon. If Iran were to leave the NPT with the intention of developing nuclear weapons, it would almost certainly attempt to produce HEU for use in such weapons in its declared facilities.[152] Starting from NUF_6, it would take over two years for the PFEP to produce enough HEU for a weapon.[153] This would allow ample time for military action. The time to produce HEU could be reduced either by using $LEUF_6$ feedstock in the PFEP (which would shorten it to around 10 months),[154] or by using a 3,000-machine cascade in the FEP (which would reduce it to around 9 months if starting from NUF_6 or 3 months starting from $LEUF_6$). Given that air-strikes can be arranged in weeks—or even days—there would still be enough time for preventative action to be taken. However, even though the risk of breakout remains small in absolute terms, if Iran had a stockpile of LEU to hand, or if the first module of the FEP were completed, it might well feel more inclined to risk leaving the NPT. This underlines the importance of Iran terminating construction of the FEP (proposal I.2) and, if Iran does continue to enrich in the PFEP, of all $LEUF_6$ being sent to a third party for fuel fabrication to prevent the build up of an LEU stockpile (see proposal I.3).

A second, subsidiary, argument for why breakout is unlikely is that—in stark contrast to North Korea, the only state thus far to have left the NPT—Iran does not court international isolation. As well as being a state party to the NPT, it has also signed and ratified both the CWC and 1972 Biological Weapons Convention. Iran has lobbied hard to gain support during the current stand-off and to try to prevent the UN Security Council from passing resolutions against it. If Iran were to develop a nuclear weapon, it might well seek to do so in secret and then present its nuclear status as a fait accompli. In so doing, Iran would hope that other states would feel they had little choice but to deal with it on that basis. However, if Iran were to leave the NPT before developing a nuclear weapon, there would be a greater chance that other states would attempt to pressure it into desisting. It is important not to push this argument too far. After all, if Iran is developing nuclear weapons, it is clearly willing to risk international opprobrium. Nevertheless, it is reasonable to suggest that Iran will attempt to mitigate the consequences of it doing so.

Part V: Co-operative CBMs

Steering committee

Any confidence-building process with Iran would certainly benefit from a steering committee to oversee it and provide a forum for discussion. A legal analysis of how such a steering committee would function and what its remit should be is beyond the scope of this paper but is considered in detail in the accompanying VERTIC publication.[155]

Nuclear Co-operation

Assisting Iran to develop civilian nuclear technology has always been an element of the EU3's approach to finding a diplomatic settlement with Iran.[156] Initially, the United States opposed any kind of nuclear power programme in Iran but, by early 2005, it had dropped its objections to Iranian acquisition of LWR technology. The most recent proposal made to Iran by the E3+3 (presented in June 2006) offers it co-operation with waste management and the development of LWR technology as well as a guaranteed fuel supply.[157] The specifics of a possible fuel guarantee arrangement are discussed in the section below. This section outlines how Iran stands to gain in general from nuclear co-operation.

Iran has ambitious plans to expand its civilian reactor programme.[158] To implement them it faces at least five challenges—all of which could be mitigated by international assistance. First, Iran's current uranium mining capacity is extremely limited. Its two existing mines can produce 71 tU/yr. Because of the inevitable losses from centrifuging, this amounts to only about one-third of Bushehr's annual fuel requirements. Unless Iran can quickly commission a new mine—or significantly increase the output from existing mines—it will be reliant on foreign uranium to fuel Bushehr or any other reactor.

Second, Iran's uranium resources appear to be insufficient to support its proposed reactor expansion programme. If Iran expands its reactor programme as planned, the authors' estimate is that its uranium resources are likely to run out some time between 2011 and 2016. Unless Iran discovers significant new uranium reserves, its reliance on foreign uranium will only increase. Co-operation with major uranium supplying nations, therefore, appears to be important to the development of nuclear power in Iran. In particular, a robust fuel guarantee arrangement could significantly enhance the viability of Iran's civil nuclear power programme.

The third challenge Iran faces is its lack of enrichment capacity. Even if Iran were to complete the FEP, it appears that it would still not have enough separative capacity to fuel Bushehr. If the FEP is to be used to manufacture 30 tU/yr of 3.5 per cent enriched UF_6 from 200tU/yr of NUF_6 (the design capacity of the UCF), a tail assay of 0.2 per cent would be required. In turn, this would require centrifuges capable of producing 3.4 kgSWU/yr (assuming the facility consists of 50,000 centrifuges). This is an extremely high value for a P1 centrifuge, and to date it seems that Iran has only operated its machines at less than half this value.[159] Once again, international co-operation is likely to benefit Iran.

Fourth, if relations with the E3+3 were to break down to the point where Russia refused to supply reactor fuel—as it appears they might already have done—Iran would be confronted with the additional challenge of manufacturing its own fuel for the BNPP. Reactor fuel for the VVER-1000 is a proprietary Russian technology. Without Russian assistance it would be both difficult and time-consuming for Iran to design and then master the fabrication technology for this kind of fuel.

Finally, co-operation is also likely to benefit Iran in building its planned reactor fleet. Although Iran could design and build its own reactors, this would certainly prove difficult and expensive. It is likely to be both quicker and cheaper for Iran to buy foreign-made 'turn-key' reactors.

Fuel supply guarantee

Fuel supply guarantees have been the subject of intense discussion recently and a number of proposals have been put forward.[160] These range from a physical bank of UF_6 to co-ownership of a multinational facility. Any of these proposals could be used as the basis for an agreement with Iran. However, given that Iran's specific fuel requirements are known, it could also be argued that a stockpile of prefabricated fuel for the BNPP might be the optimum solution. Irrespective of the basic model chosen, however, there are a number challenges to formulating an agreement that would have to be overcome.

All fuel supply arrangements come with conditions stipulating the circumstances under which the fuel can be used. The potential for disagreement lies with the stipulations relating to non-proliferation. In the first place it is necessary to specify which legal instruments Iran must have adopted. Three requirements in this regard are likely to be relatively uncontroversial: (a) Iran continues to be a party to the NPT and does not announce its intention to withdraw; (b) it continues to have a comprehensive safeguards agreement in force; and (c) it ratifies an additional protocol.

The controversy starts with the question of whether an additional legal instrument is necessary to govern the facility in which the fuel is to be used. There is an argument that the fuel should only be transferred subject to an INFCIRC/66-type agreement that would only be 'activated' if Iran were to withdraw from the NPT.[161] INFCIRC/66-safeguards apply to individual facilities and were developed before the NPT was concluded, and at a time when the IAEA's responsibilities were limited to safeguarding particular facilities at the behest of member states (they are still in use today in states that are not party to the NPT). Crucially, an INFCIRC/66 agreement would remain binding if Iran were to withdraw from the NPT. There is no precedent for applying an INFCIRC/66 agreement to a facility in a state with a Comprehensive Safeguards Agreement in force. It is designed to try to prevent a state from legally withdrawing from the NPT, ending INFCIRC/153 safeguards and using internationally supplied fuel in a nuclear weapons programme.

Extra requirements are also needed to ensure that Iran is in compliance with any safeguards agreements to which it is subject. It would be difficult to formulate these requirements in a way that is acceptable to both Iran and the E3+3. For instance, there is the question of whether the guarantee would become void if serious unresolved questions about Iran were pending for a certain amount of time, or if it would be necessary for the Board of Governors to make a formal finding of non-compliance.[162] The E3+3 would be likely to support the first formulation and Iran the latter. Then there is the question of whether it would be necessary for the IAEA to have drawn its broader conclusion about the absence of undeclared nuclear activities in Iran.

A physical fuel bank, if that is the chosen model, requires a host, a source of funding and—if it is a bank of $LEUF_6$—a fuel fabrication arrangement. Moreover, the owner of the fuel need not be the state that hosts the store. Iran would, presumably, like to host the store itself but that is unlikely to be acceptable to the E3+3. The obvious host is Russia but that may not be acceptable to Iran because there is little point in Iran using its primary supplier as a back-up. Hosting it in the EU is a possibility, but it is unclear whether that would be acceptable to Iran (even if the fuel was owned by the IAEA and the EU had granted a generic export licence, Iran might still believe that the EU would refuse permission to ship the fuel). It might be possible for a 'neutral' country such as Switzerland or Brazil to host the store, but it seems highly unlikely that such a state would agree to be involved. China is yet another possible candidate, although it is far from clear whether that would be acceptable to either Iran or the remainder of the E3+3.

The question of ownership is perhaps easier to resolve. In this case the obvious choice, the IAEA itself, is also arguably the best choice since it is the IAEA that is likely to be given the task of deciding whether the conditions for using the fuel have been met. Iran may, however, be uncomfortable with such a high level of IAEA involvement in the process. If the bank consists of $LEUF_6$ rather than prefabricated fuel then the issue of where the fuel should be fabricated arises. In fact, there is only one option. The only facility outside Russia that is licensed to manufacture VVER-1000 fuel is located in Spain.[163] Basing the guarantee on a single facility does weaken it—after all, the Spanish facility may not have the capacity to produce the fuel when needed. This could be circumvented by having bank of prefabricated fuel.

Realistically, the only source of funding for a fuel bank for Iran (as opposed to a more general scheme) would be some or all of the states in the E3+3. Although the start-up costs would be large—maybe US$50 million for the two reloads that would be needed in this circumstance—these could probably be recouped by selling the fuel once the bank was no longer required. In summary, a fuel supply guarantee—although highly desirable in theory—may prove difficult to negotiate in practice. This is not a reason for not attempting to do so—a fuel supply guarantee could be a useful CBM—but recognition that if agreement is reached it is more likely to be an indicator of progress than a catalyst.

The Open Skies Treaty

The 1992 Open Skies Treaty permits states parties to conduct observation flights over one another's territory. Unlike almost every other inspection regime, it is not designed to verify compliance with any one particular treaty. Instead, it is a more general measure intended to build trust through greater transparency. States may use the data obtained from an overflight for any purpose, including the verification of arms control agreements. To date, 34 states have ratified the treaty.[164] The treaty is operative in North America, Europe and much of Asia: the so-called Vancouver to Vladivostok area. The conduct and number of flights is specified in detail by the terms of the treaty. Of particular relevance here is the provision that the only valid reason for denying an overflight is safety; states may not invoke national security concerns to prevent a flight passing over a sensitive facility.[165]

The use of overflights in Iran to verify the absence of clandestine nuclear activities is discussed above (proposal III.2). One possible way to facilitate such flights would be for Iran to accede to the Open Skies Treaty. This is permitted pursuant to article XVII.5 of the treaty, which states that 'the Open Skies Consultative Commission may consider the accession to this Treaty of any State which, in the judgement of the Commission, is able and willing to contribute to the objectives of this Treaty'. Such a decision would require unanimous agreement from the Open Skies Consultative Commission (OSCC). There are a number of advantages and disadvantages to Iran acceding to the Open Skies Treaty compared to proposal III.2, a bilateral agreement between Iran and the IAEA which would permit overflights to be conducted in Iran for the purpose of verifying the absence of clandestine nuclear activities.

The first advantage of the Open Skies Treaty is reciprocity; it would not only permit observation flights to be conducted over Iran, but also permit Iran to conduct observation flights over the territory of any other state party, including all the E3+3 except China. This arrangement is therefore likely to be more palatable to Iran than one in which it is obliged to accept overflights but has no right to conduct them. A second advantage is that, from a political perspective, it is likely to be harder for Iran to withdraw from the Open Skies Treaty than a bilateral arrangement. Relations between Iran and the IAEA have become increasingly tense over the past three years. In particular, Iran has implied that the IAEA has singled it out for unfair treatment.[166] The E3+3 may well believe, therefore, that Iran would be more likely to break a bilateral agreement with the IAEA than a multinational treaty concluded with 34 other states.

On the other hand, the Open Skies Treaty does place greater limits than proposal III.2 on the range of sensors that may be placed on board aircraft. Although the Open Skies Treaty allows a range of electromagnetic sensors to be deployed,[167] it does not permit the use of air sampling—one of the main advantages of proposal III.2. There is therefore an important trade-off to be made. From a purely technical point of view, the Open Skies Treaty is a less effective transparency measure than proposal III.2; it would, however, be harder for Iran to withdraw from the Open Skies Treaty than to renounce proposal III.2.

One final consideration is the effect that Iran could have on the treaty regime. The OSCC plays an important role in regulating the day-to-day workings of the treaty. All decisions made by it have to be unanimous.[168] Any country, therefore, has the potential to act as a 'spoiler' by preventing the OSCC from making decisions—in order to damage the treaty regime. For this reason, states parties would have to be convinced that Iran was willing to work towards the good of the treaty as a whole before allowing it to accede.

Scientific exchanges

Exchanges of personnel have been a feature of a number of successful confidence- building processes.[169] In these processes, where the cause of mistrust has typically been conventional forces, it was officers and military cadets who were chosen for exchange. Given the cause of tension between Iran and the E3+3 it makes sense to exchange not military personnel but scientists. Areas for co-operation could be identified by the consultative committee but, in principle, there seems to be no reason why exchanges could not take place in any non-military field, including peaceful nuclear research, except for those in which Iranian scientists would gain knowledge that would be useful for designing nuclear weapons or conducting a clandestine fuel cycle programme (e.g. shock wave compression physics or centrifuge design). Scientific exchanges have occasionally been an element of confidence-building processes in the past, most notably the Brazilian–Argentine process.[170]

Scientific exchanges aim to promote trust by enhancing transparency in scientific research. Their effects in the short term will be minimal. Since weapons-related research would almost certainly be undertaken in secret, the presence of foreign scientists at Iranian research institutions would provide little reassurance that Iran's nuclear programme was exclusively peaceful in nature. More important would be some of the long-term consequences. Scientific exchanges could, over time, help to promote transparency and a culture of openness in Iranian scientific research. Moreover, the personal links built between Iranian and international scientists could only be beneficial for long-term relations.

Iran may find this measure not only palatable but perhaps even desirable. Like the Open Skies Treaty, this is a reciprocal measure. Iranian scientists would have the opportunity to work abroad and would benefit from doing so—and *both* sides would benefit from scientific exchanges. In addition, international co-operation is integral to modern science and this measure would not 'single out' Iran in any way. In fact, it would do the opposite: it would recognize that which Iranian science has to offer and hence enhance Iran's prestige.

Table 5 Summary of confidence-building and transparency measures

Proposal number	Proposal name	Cost of implementation	Increase in confidence	package A	package B
	Immediate suspension of all enrichment-related activities (as well as a continuation of the suspension of reprocessing activities)			x	x
	Immediate suspension of the heavy water reactor programme			x	x
	Provision of sufficient access to and co-operation with the IAEA so that it is able to verify these suspensions and resolve any outstanding questions about Iran's nuclear programme.			x	x
	Implementation and ratification of an additional protocol			x	x
I.1	Termination of the HWR programme	Low	High	x	x
I.2	Termination of construction of the FEP	Low	High	x	x
I.3	Termination of the LWR fuel fabrication programme	Low	Medium	x	x
I.4	Termination of the uranium metal production lines at the UCF	Low	High	x	x
I.5	Long-term suspension of enrichment and conversion	Low	High*	x	
II.1	Physical containment measures at mines and mills	High	Low		
II.2	Material accountancy at mines and mills	High	Low		
II.3	Moving the starting point of safeguards upstream	Medium	High	x	x
II.4	Increased information about IAEA safeguards	Low	Medium		
II.5	Definition of significant quantity lowered	Low	Low		
II.6	Timeliness detection goal lowered	Medium	High		x
II.7	Detection probability increased	Low	Low		
II.8	Facilitation of short-notice inspections	Medium	High		
II.9	Enhanced safeguards on enrichment	Medium	Medium		x
III.1	Wide area environmental monitoring	High	Medium		x
III.2	Overflights	High	Low		
III.3	Development of a protocol for special inspections	Low	High		x
III.4	Interviews with Iranian scientists and officials	Low	Medium	x	
III.5	Verification of centrifuge production and the disclosure of sensitive industrial and scientific projects	Medium	High		x

* Unless suspension is phased, in which case low.

Conclusions

What measures should be prioritized?

A summary of all the transparency measures and CBMs discussed in this paper is presented in table 5. Any agreement between Iran and the E3+3 could not include every, or even most, of the measures outlined. Even apart from the fact that some proposals are mutually exclusive, there is a limit to the number and intrusiveness of the transparency measures and CBMs that Iran might be willing to accept. What should the E3+3's priorities be?

From the E3+3's point of view, a necessary—but not sufficient—condition for an agreement would be full adherence to and fulfilment of UN Security Council resolutions 1696, 1737 and 1747 and, inter alia: (a) an immediate suspension of all enrichment-related activities, as well as a continuation of the suspension of reprocessing activities; (b) an immediate suspension of the heavy water reactor programme; and (c) the provision of sufficient access to and co-operation with the IAEA to enable it to verify these suspensions and resolve any outstanding questions about Iran's nuclear programme.

In addition, if Iran is to restart sensitive nuclear activities after it has come into compliance with the resolutions, it is also very likely that the E3+3 will insist on: (a) termination of the heavy water reactor programme (proposal I.1); (b) termination of construction of the FEP (proposal I.2); and (c) implementation and ratification of an additional protocol.

These requirements go further than Security Council Resolution 1737. This resolution requires the suspension, rather than the termination, of Iran's HWR programme and of the construction of the FEP. In addition, it is debatable whether the resolution's call for Iran to ratify an additional protocol is a legally binding demand or a 'political request'.[171]

By themselves these measures are probably not enough to rebuild completely the international community's trust in Iran's intentions and actions. In analysing which other measures are most desirable, it is useful to think about the comparative likelihood of different proliferation scenarios. As is outlined in the introduction to this paper, there are three general routes by which a state can manufacture fissile material for use in a nuclear weapons programme: diversion from declared facilities, sneak-out and breakout. On the basis of the analysis presented in parts II and III of this paper, the authors argue that, even with an additional protocol in force, there is a higher probability that Iran would be caught diverting material from a declared facility than building a clandestine one. As is discussed in part IV, the authors also argue that it is very unlikely that Iran would leave the NPT before it had manufactured a nuclear weapon. Therefore, it is VERTIC's conclusion that, in the case of Iran, sneak-out poses the most significant risk. For this reason, the measures outlined in part III—those to detect clandestine activities—should be prioritized.

Much emphasis is often placed on achieving a permanent cessation of all enrichment activities in Iran. From the perspective of confidence building it would be most desirable if Iran were willing to accept this as well as additional measures to detect undeclared facilities. However, it is likely that compromise will be required as part of a negotiated solution. In this case it may become necessary to choose between these two sets of measures. It is VERTIC's conclusion that, given this choice, measures to enhance the detection of clandestine facilities will be more effective in curtailing Iran's ability to develop nuclear weapons, if it wishes to do so. Our reasoning can be illustrated by reviewing the two 'packages' of proposals outlined in table 5. There are, of course, many other possible combinations. Some would be more effective at building confidence than those highlighted, and others less so. Packages A and B are representative examples that are useful for comparison purposes. Both include the measures identified above as being central to any agreement. In addition, package A includes a permanent cessation of enrichment activities but little in the way of additional measures to detect clandestine activities. In contrast, package B focuses on the detection of clandestine activities and does not include a permanent cessation of enrichment. It is useful to examine how both packages perform under each of the three proliferation scenarios.

Diversion from declared facilities

From the point of view of diversion from declared facilities, package A is preferable to package B—but only slightly. Package A involves a cessation of all enrichment activities. Package B permits enrichment on a pilot scale. Package B presents an option for diversion, therefore, that does not exist under Package A. It seems extremely unlikely, however, that Iran could successfully divert material from the PFEP.

The PFEP is very small in comparison with many other facilities that the IAEA safeguards. It is capable of producing only about 1,500 kgSWU/yr. IAEA safeguards are designed for facilities which have separative capacities over 1,000 times larger. There is legitimate doubt about whether the IAEA can meet the quantity component of its safeguards goal in those very large enrichment plants. There ought to be much less doubt about whether it can successfully safeguard very small facilities such as the PFEP. We estimate that the IAEA has a 90 per cent chance of detecting a diversion of 0.2 kg ^{235}U from the PFEP (see table 3). Even if this figure is wrong—and we have underestimated it by a factor of 10, say—it would still be smaller than the quantity component of the IAEA's inspection goal by about the same factor.

Sneak-out

Packages A and B aim to prevent sneak-out in different ways. Package A, by stopping declared enrichment, seeks to deny Iran knowledge and expertise that would be useful in conducting a clandestine programme. Package B puts in place measures that would enhance the IAEA's ability to detect clandestine facilities.

At the time of writing, Iran has not perfected enrichment technology. Although it has installed about 1,000 centrifuges at the FEP, it is not clear whether it can operate them without crashing for periods of time long enough to enrich sufficient uranium for a nuclear weapon. However, the knowledge that Iran does have would be ample for starting a clandestine programme. Overcoming the remaining difficulties requires only time and could be done just as well in a secret facility as in a declared one. Package A, in denying Iran a declared programme, would delay a clandestine programme while Iran built a secret facility and installed centrifuges, but it would not prevent one entirely. Because a clandestine facility need only be small (e.g. 3,000 centrifuges), this delay might only amount to a year or 18 months. Moreover, the longer the dispute continues and the closer Iran comes to 'mastering' centrifuge technology, the easier it will be for Iran to put a clandestine facility into operation, thus reducing the effectiveness of package A.

It is important not to downplay the challenges associated with detecting clandestine nuclear activities using the methods advocated in package B—especially when it comes to detecting an enrichment plant. However, a clandestine programme needs UF_6 feedstock and that presents an opportunity for detection. Should Iran build a clandestine enrichment plant it would have three options for supplying it with UF_6:

1. Divert UF_6 from the UCF or the PFEP;
2. Build a clandestine conversion facility and feed that with material diverted from a declared mill;
3. Build a clandestine conversion plant and a clandestine mill and obtain the necessary ore from a declared or clandestine mine.

Under package B (which includes proposal II.3) safeguards would be in place on the UOC produced by mills (and at each subsequent stage of the fuel cycle). Because options 1 and 2 both involve diversion from a safeguarded facility, the IAEA's prospects for detecting a safeguards violation are good. Option 3 involves Iran building three clandestine facilities (a mill, a conversion plant and an enrichment facility). Presenting the IAEA with multiple targets for detection in this way significantly enhances the prospects of it detecting the programme. In addition, package B is substantially strengthened by the inclusion of proposal III.5, which would permit the IAEA to verify the production of centrifuges.

Ultimately, there can be no guarantee that the IAEA could detect a clandestine nuclear programme by using the methods suggested in package B. However, on balance, package B is likely to be more effective at denying Iran a clandestine programme than package A.

Breakout

Finally, there is the problem of breakout. Having left the NPT Iran could use a declared facility to produce weapons-usable fissile material. Under package B, Iran would have the PFEP, which it could use to produce HEU. This option is denied to it under package A. That said, although the risk from the PFEP following breakout cannot be ignored, it is limited. The PFEP has a small separative capacity. Using NUF_6 as feedstock, it would probably take the PFEP over two years to produce sufficient HEU for a weapon. This time could be shortened by using LEU as feedstock, underlining the importance of Iran agreeing to all LEU produced in the PFEP being sent abroad for fuel fabrication to avoid the build-up of an LEU stockpile. Moreover, the location of the PFEP is well known and this would permit effective pre-emptive action. Package A is more effective against breakout than package B but, because the PFEP's potential for breakout is so small, this advantage is slight.

Weighing it all up

Package A slightly outperforms package B should Iran leave the NPT or attempt to divert material from a declared facility. On the other hand, B is better at denying Iran the ability to build clandestine facilities. The final ingredient that needs to be considered is which route Iran is most likely to pursue if it decides to develop nuclear weapons. In our opinion it is sneak-out that is most likely. Diversion from a declared facility seems unlikely because of the risk of being caught. Similarly, as is discussed in part IV, leaving the NPT also seems unlikely because that would clearly signal Iran's intention to develop nuclear weapons—something that it could not accomplish before pre-emptive action had commenced. Sneak-out is, therefore, Iran's best option. Certainly, this was the conclusion that was reached in the past by Iraq and Libya. Overall, therefore, we conclude that package B is the better option.

This analysis illustrates the general conclusion that enhanced measures to detect clandestine nuclear facilities are more important than a long-term suspension of enrichment. It is, however, important to acknowledge the limitations associated with this kind of analysis. In negotiations between the E3+3 and Iran, both sides would present their own suggestions and ideas. Although the general conclusion reached in this paper may help guide their construction, it is clearly not a substitute for the detailed analysis of the suggestions made by each side. For instance, measures to enhance the IAEA's ability to detect clandestine nuclear facilities would only be preferable to the long-term suspension of enrichment if Iran were willing to accept enough of them. Indeed, it is hoped that the main value of this paper lies not in its conclusions but in the 'menu' of options that it presents and analyses.

Known unknowns

The analysis presented in this paper is based solely on open source information. It is important to acknowledge, therefore, that it is based on incomplete information. In particular, there at least two factors, details of which are largely classified, that could alter its conclusions: the effectiveness of export controls and of national intelligence assets.

Export controls

It is argued above that if Iran goes down the route of building a clandestine enrichment facility it could obtain feedstock for that facility either from a clandestine conversion plant or by diverting material from a declared facility. There is, however, an alternative. Iran could attempt to purchase nuclear material from abroad. By purchasing UF_6 Iran could obviate the need to build any additional clandestine facilities or divert from a declared facility. This would remove the IAEA's best opportunities for detecting a clandestine programme and severely affect the efficacy of the measures proposed in package B. Based on the information available in the public domain it is very hard to assess the effectiveness of existing export controls. It is therefore impossible to make any determination about the possibility of Iran secretly purchasing nuclear material. The easier it is for Iran to import nuclear material, however, the more the balance is tipped in favour of package A.

National intelligence assets

One of the IAEA's most important means for obtaining evidence of clandestine nuclear activities is on the basis of information provided by member states. It is clearly impossible for us to make any kind of determination about the availability of national intelligence assets that could provide information about Iran. However, the better the available sources of intelligence on Iran, the more chance there is of states being able to provide the IAEA with information that could be useful in helping it to uncover a clandestine nuclear programme. The existence of high quality intelligence assets therefore increases the chance of detecting a clandestine programme and consequently favours package B.

Of course, no system of safeguards can be completely effective. With any set of additional transparency measures in place there will always be some risk that Iran will successfully evade them and succeed in manufacturing a nuclear weapon. However, any policy option for Iran carries risks. It is beyond the scope of this paper to compare the risks inherent in a continuation of sensitive nuclear activities in Iran under additional safeguards to the risks presented by other options—but there is a clear need for this work to be done.

Appendix I: A technical overview of nuclear materials accountancy

Appendix I gives a brief technical overview of the basic principles behind nuclear materials accountancy. References are provided to more complete accounts.[172] It is important to remember that material accountancy is only one aspect of the IAEA's safeguards system. Other aspects, which are particularly important under integrated safeguards, are not discussed here.

There are two components to the IAEA's inspection goal: a timeliness component and a quantity component. The timeliness detection goal—the target for the length of time required to detect a diversion—is set to about one year for indirect use material, which includes all uranium with an enrichment level of below 20 per cent.[173] This value is chosen because it is broadly the same as the time that would be required to manufacture the metallic components of a nuclear warhead from this material—the conversion time.

The quantity component of the inspection goal is defined in terms of an SQ, 'the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded'.[174] The amount of material in an SQ varies depending on the level of enrichment. It is 75 kg^{235}U for LEU, 25 kg^{235}U for HEU, and 10 tU for natural uranium.

Every nuclear facility is divided into one or more material balance areas. Every so often, typically about once a year, a physical inventory is conducted by the plant operator to ascertain the amount of nuclear material in each MBA. The time between physical inventories is called the material balance period. Over the course of each material balance period, the operator measures all flows of nuclear material into and out of the MBA. Assuming that the operator has not diverted any nuclear material then, in theory, the following condition should be met

$$PB + X - Y - PE = 0.$$

In this equation PB and PE denote the amount of nuclear material present in the MBA at the beginning and end of the balance period, respectively. The total quantity of material that is transferred into the MBA during that period is given by X and the total quantity that is removed from it is given by Y. In reality, measurement errors, especially in bulk handling facilities, inevitably result in discrepancies between the amount of material that is actually present in an MBA and the amount that ought to be there. The size of this discrepancy is known as the material unaccounted for (MUF), which is formally defined as[175]

$$\text{MUF} = \text{PB} + \text{X} - \text{Y} - \text{PE}.$$

The IAEA conducts various types of inspection to verify the operator's declarations. The most important of these is a physical inventory verification—an inspection to verify the results of the operator's physical inventory taking.

At a basic level, the challenge for the IAEA is to determine whether MUF has been caused by the diversion of nuclear material or by measurement errors. To do this, the IAEA calculates the error in its estimate of MUF, σ(MUF).[176]

It is useful to sketch out, in rough conceptual terms, the reason why σ(MUF) is helpful in determining whether a diversion has taken place. If MUF is found to be much smaller than σ(MUF) the measurement is 'within the margin of error' and there is no evidence that a diversion of nuclear material has taken place. If, on the other hand, MUF is much larger than σ(MUF) then the measurement is statistically significant and there are grounds to investigate further. It is important to remember that the IAEA's safeguards goal is to detect the diversion of one SQ. For it to achieve this σ(MUF) must be no bigger than roughly one SQ.

The formal mathematics are as follows: The IAEA aims to detect a diversion of one SQ with a probability of $1-\beta$. The parameter β is normally set to 0.1, that is, the IAEA aims to have a 90 per cent chance of detecting a diversion.

There is also a chance that the IAEA will detect a diversion when there has been none. This 'false alarm' probability, α, is typically set to 0.05 to minimize the number of false alarms. With these values of α and β it can be shown that: (a) MUF should be considered statistically significant when it is larger than $1.6\times\sigma$(MUF); and (b) for the IAEA to meet its safeguards goal σ(MUF) must be smaller than SQ/2.9.[177]

Appendix II: Calculation of σ(MUF) for a uranium mine

In this calculation it is assumed that there is one material balance area inside a uranium mine: the storage area where ore is kept before it is transported to a mill. The amount of ore in this area during a physical inventory is likely to be small compared to the total flow through the area and can be neglected. The material unaccounted for is therefore given by MUF=X-Y, where X denotes the total material flow into the MBA and Y is the total flow out of it. Since each of these quantities is approximately equal then

$$\sigma(\mathrm{MUF}) = \sqrt{2}\,\sigma(X).$$

The total mass of ore produced each day is denoted by M. There are three causes of uncertainty in measuring the mass of uranium in a batch of this size: the uncertainty in measuring the total mass of the batch, the uncertainty in sampling and the uncertainty in determining the uranium concentration. According to the International Target Values the uncertainty is dominated by the sampling error, $\delta_s \approx 0.14$, which is two orders of magnitude larger than either of the other errors.[178] The uncertainty in the uranium content of each batch is therefore given by $M \times \delta_s$. Since there are X/M batches, and the measurement on each is independent then the standard deviation in MUF is given by

$$\sigma(\mathrm{MUF}) = \sqrt{\frac{2X}{M}}\,\delta_s.$$

If a material balance is closed once every six months then X=45,000 t for Saghand and X=6,000 t for Gchine. If the mine is functioning for 150 days over that period then M=300 t for Saghand and M=40 t for Gchine. These values give the results quoted in the main text (rounded to the nearest 50 t).

Appendix III: Calculation of σ(MUF) for the process area of the PFEP

This appendix presents one of the calculations used to generate table 2, as an example of the general method employed. Because of its importance, the process area of the PFEP has been chosen.

Given the small throughput of the PFEP, 7.4 t/yr of UF_6 (5 tU/yr), it seems unlikely that NUF_6 would be stored in 48Y cylinders (the usual cylinder for transporting NUF_6, which can hold up to 14 t of material). Instead, it is assumed that NUF_6 is fed into the cascade using cylinders holding 1 t of UF_6. In this case, eight reloadings would take place between PIVs.

Table 6 Error components in estimating uranium-235 abundance

Process	Technique	Natural uranium (%)		Low enriched uranium (%)		Depleted uranium (%)	
		random	systematic	random	systematic	random	systematic
Mass	EBAL	0.05	0.05	0.05	0.05	0.05	0.05
Sampling		0.1	ND	0.1	ND	1	ND
Abundance	GSMS	0.1	0.1	0.05	0.05	0.1	0.1

Note: All errors are expressed as percentages. EBAL=electronic balance. GSMS=gas source mass spectrometry. ND=not determined (taken as 0).

The errors associated with estimating the uranium content of a cylinder are shown in table 6 and are taken from the International Target Values 2000 (assuming that the most accurate techniques available are used).[179] Adding the errors for natural uranium in quadrature gives a total error of 0.187 per cent for the uranium content of a feed cylinder. Since measurements on each cylinder are independent, the total uncertainty in the uranium feed is

$$1\ \text{tUF}_6 \times \frac{0.187\%}{100} \times \sqrt{8} = 0.00529\ \text{tUF}_6.$$

At enrichment of 0.711 per cent this is equivalent to 0.0256 kg^{235}U.

By a similar method the uncertainty in the uranium content of the product and tails is found to be 0.00952 kg^{235}U and 0.0729 kg^{235}U, respectively, where it is assumed that the product is enriched to 3.5 per cent and held in cylinders containing 0.1 t of UF_6 and that the tails are depleted to 0.4 per cent and held in cylinders holding 1 t of UF_6. Given that the in-process inventory of the PFEP can be neglected, σ(MUF)=0.0778 kg^{235}U can be found by adding in quadrature the error components from the feed, product and tails. As is outlined in appendix I, the minimum size of a diversion that the IAEA can detect with 90 per cent confidence, Δ, is equal to 2.9×σ(MUF). In this case Δ is found to be 0.226 kg. Because this calculation is rather approximate the figures for Δ in table 2 are given to one significant figure.

Endnotes

1 Limitations of space do not permit a discussion of the role that voluntary transparency measures have played in the past. It is worth remembering, however, that before the 1967 Treaty of Tlatelolco and the 1968 Nuclear Non-Proliferation Treaty, all safeguards were voluntary (although they were sometimes written into bilateral agreements as a condition of the transfer of nuclear technology or materials). States that accepted safeguards chose to do so as a means of demonstrating the exclusively peaceful nature of their nuclear programmes. Japan, in particular, stands out as a nation that benefited from this. See, for example, Ben Sanders, 'IAEA safeguards and the NPT', *Disarmament Forum,* no. 4, 2004, www.unidir.org/bdd/fiche-article.php?ref_article=2189, pp. 43–50.

2 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2006/53, 31 August 2006, www.iaea.org/Publications/Documents/Board/2006/gov2006-53.pdf, para.29.

3 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2006/14, 4 February 2006, www.iaea.org/Publications/Documents/Board/2006/gov2006-14.pdf, para.1.

4 UN Security Council Resolution 1696, 31 July 2006, www.un.org/News/Press/docs/2006/sc8792.doc.htm, para. 1. Almost identical wording also appears in UN Security Council Resolution 1737, 23 December 2006, www.un.org/News/Press/docs/2006/sc8928.doc.htm, para. 1 and UN Security Council Resolution 1747, 24 March 2007, www.un.org/News/Press/docs/2007/sc8980.doc.htm, para. 1.

5 UN Security Council Resolution 1696, para. 2; UN Security Council Resolution 1737, para. 2.

6 UN Security Council Resolution 1737, para. 2.

7 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement and relevant provisions of Security Council Resolution 1737 (2006) in the Islamic Republic of Iran', GOV/2007/8, 22 February 2007, www.iaea.org/Publications/Documents/Board/2007/gov2007-08.pdf, paras 4, 7, 9 and 13.

8 Before Iran was referred to the Security Council it indicated that it might be willing to accept additional safeguards in return for an early restart of its enrichment programme. According to press reports, at the meeting of the EU-Iran Steering Committee on 29 April 2005 Iran presented a proposed framework which included various transparency measures such as 'allowing continuous on-site presence of IAEA inspectors . . . at the UCF and Natanz'. See, for example, Jacqueline W. Shire, 'Iran seeks more centrifuges', ABC News Online, 3 May 2005, http://abcnews.go.com/International/Investigation/story?id=723794&page=1, which includes a link to the Iranian proposal.

9 See, for instance, the comments made by US Secretary of State Condoleezza Rice in 'Briefing en route Halifax Nova Scotia, Canada', 11 September 2006, www.state.gov/secretary/rm/2006/72040.htm.

10 Andreas Persbo, 'Thinking inside the box: exploring legal approaches to confidence building in the case of Iran's nuclear programme', *Verification Matters: VERTIC Research Reports* no. 7, Verification Research, Training and Information Centre (VERTIC), London, May 2007.

11 Treaty on the Non-Proliferation of Nuclear Weapons, 1968, article III.1.

12 For a list of states and other parties that have signed or ratified additional protocols see the IAEA website, www.iaea.org/OurWork/SV/Safeguards/sg_protocol.html.

13 Jozef Goldblat (ed) with David Fischer and Paul Szasz, Stockholm International Peace Research Institute, *Safeguarding the Atom: A Critical Appraisal,* Taylor & Francis, London, 1985, p. 33, footnote 16.

14 Contained in International Atomic Energy Agency, 'The text of the agreement between Iran and the Agency for the application of safeguards in connection with the Treaty on the Non-Proliferatio [*sic*] of Nuclear Weapons', INFCIRC/214, 13 December 1974, www.iaea.org/Publications/Documents/Infcircs/Others/infcirc214.pdf.

15 This figure refers only to the mass of uranium. For example, for uranium in the form of UF_6, a flow of 100 tU/yr translates into a flow of 147 t/yr of UF_6.

16 Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD NEA) and the International Atomic Energy Agency (IAEA), *Uranium 2005: Resources, Production and Demand,* Organisation for Economic Co-operation and Development, Paris, 2005, p. 206.

17 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2004/83, 15 November 2003, www.iaea.org/Publications/Documents/Board/2004/gov2004-83.pdf, paras 4–6.

18 GOV/2004/83, para. 4.

19 Mohammad Saeidi, 'Nuclear fuel cycle activities in Iran', World Nuclear Association Annual Symposium, London, 7–9 September 2005, www.world-nuclear.org/sym/2005/pdf/Saeidi.pdf, pp. 4–8; GOV/2004/83, para. 19; International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2003/75, 10 November 2003, www.iaea.org/Publications/Documents/Board/2003/gov2003-75.pdf, Annex 1, paras 1–4.

20 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2006/64, 14 November 2006, www.iaea.org/Publications/Documents/Board/2006/gov2006-64.pdf, para. 2.

21 GOV/2007/8, para. 9.

22 Brian Ross and Christopher Isham, 'Iran nuclear bomb could be possible by 2009', ABC News Online, 2 April 2007, http://blogs.abcnews.com/theblotter/2007/04/exclusive_iran_.html.

23 Saeidi; GOV/2004/83, paras 60–63.

24 'Arak heavy water plant launched', MehrNews.com, 26 August 2006, www.mehrnews.com/en/NewsDetail.aspx?NewsID=371762.

25 GOV/2007/8, para. 13.

26 Paul Brannan and David Albright, *ISIS Imagery Brief: Update on Construction Activities at Arak 40 MW Heavy Water Reactor,* Institute for Science and International Security, 21 April 2006, www.isis-online.org/publications/iran/arakupdate.pdf.

27 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2003/40, 6 June 2003, www.iaea.org/Publications/Documents/Board/2003/gov2003-40.pdf, para.30; GOV/2004/83, para. 65; Brannan and Albright.

28 Brannan and Albright.

29 GOV/2006/64, para. 7.

30 For a full list of facilities in Iran subject to safeguards see GOV/2004/83, Annex 1.

31 Thomas B. Cochran and Christopher E. Payne, *The Amount of Plutonium and Highly-enriched Uranium Needed for Pure Fission Weapons,* Natural Resources Defense Council, Washington, DC, 13 April 1995, www.nrdc.org/nuclear/fissionw/fissionweapons.pdf. Cochran and Payne argue that the value for a significant quantity should be set to 3 kg^{235}U for HEU. This is unrealistically low for a nation making its first weapon and here 10–20 kg^{235}U is used as a more reasonable but still conservative estimate.

32 This assumes that Iran's centrifuges are capable of producing 1.5 kgSWU/yr. For the most authoritative estimate currently available in the public domain see David Albright, 'Iran's nuclear program: production and potential', Statement before the Senate Foreign Relations Committee, 17 May 2006, www.senate.gov/~foreign/testimony/2006/AlbrightTestimony060517.pdf. A P1 centrifuge can, in theory, produce up to 3 kgSWU/yr. If Iran's centrifuges are capable of doing this the throughput of the PFEP would be doubled—but this would not alter any of the conclusions reached in this paper.

33 This fear is more relevant to reprocessing than reactor technology since it is much harder to hide a reactor than a reprocessing plant.

34 See, for example, J. Carson Mark, Frank von Hippel and Edwin Lyman, 'Explosive properties of reactor-grade plutonium', *Science & Global Security,* vol. 4, no. 1, 1993, www.princeton.edu/~globsec/publications/pdf/4_1Mark.pdf, pp. 111–128; and Bruno Pellaud, 'Proliferation aspects of plutonium recycling', *Comptes Rendus Physique,* vol. 3, nos 7–8, 2002, pp. 1067–1079.

35 It is standard practice to remove a fraction of the initial core of a reactor after only one year, rather than three. This fuel would be exactly of the low burn-up type that would be ideal for weapons manufacture.

36 International Institute for Strategic Studies, 'Iran's strategic weapons programmes: a net assessment', *Strategic Dossier*, Routledge, London, 2005, table 1A, p. 54.

37 David Albright and Jacqueline Shire, *Better Carrots, not Centrifuges: Why Iran Must Halt Enrichment and how the US can make it Happen*', International Institute for Science and International Security (ISIS), 10 July 2006, www.isis-online.org/publications/iran/iranissuebrief.pdf.

38 This can be inferred from recent IAEA reports. GOV/2004/83, para.10 reports that in August to October 2004 Iran converted 22.5 t of U_3O_8 (containing 19 tU) into 2 t of UF_4 (containing 1.5 tU) and 17.5 tU of other products. The loss for this campaign was therefore less than 0.5 tU or about three per cent. International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2006/38, 8 June 2006, www.iaea.org/Publications/Documents/Board/2006/gov2006-38.pdf, para.11, reports that from August 2005 to April 2006 Iran produced 118 t of UF_6 at the UCF. This translates to about 120 tU per annum.

39 Mark Hibbs, 'Intelligence estimates vary widely on Iran's timeline to purify UF_6', *Nuclear Fuels,* vol. 30, no. 18, 29 August 2005, p. 1.

40 Michael Adler, 'Iran using Chinese-made feedstock for enriched uranium: diplomats', Agence France-Presse, 18 May 2006, www.petroleumworld.com/storyt06051901.htm; Jonathan Marcus, 'Iran enrichment: A Chinese puzzle?', BBC News Website, 18 May 2006, http://news.bbc.co.uk/1/hi/world/middle_east/4995350.stm.

41 Albright.

42 Paul Kerr, 'IAEA investigation makes little headway', *Arms Control Today,* vol. 36, no. 6, July/August 2006, www.armscontrol.org/act/200607-08.

43 Hibbs; Richard Stone, 'Iran's trouble with molybdenum may give diplomacy a second chance', *Science,* vol. 311, no. 5758, 13 January 2006, www.sciencemag.org/cgi/reprint/311/5758/158.pdf, p. 158.

44 Robert J. Einhorn, 'The Iran nuclear issue', Statement before the Senate Foreign Relations Committee, 17 May 2006, www.senate.gov/~foreign/testimony/2006/EinhornTestimony060517.pdf; William J. Broad and David E. Sanger, 'Iran's drive to nuclear fuel has slowed, diplomats say', *New York Times,* 29 May 2006, http://select.nytimes.com/gst/abstract.html?res=F50A10FE345A0C7A8EDDAC0894DE404482.

45 GOV/2007/8 para. 4; see also GOV/2006/64, para. 2.

46 Einhorn.

47 GOV/2006/64, para. 2.

48 Albright.

49 Albright.

50 Jill N. Cooley, 'Integrated nuclear safeguards: genesis and evolution', *Verification Yearbook 2003,* Verification Research, Training and Information Centre (VERTIC), London, 2003, www.vertic.org/assets/YB03/VY03_Cooley.pdf.

51 International Atomic Energy Agency, '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, June 1972, www.iaea.org/Publications/Documents/Infcircs/Others/infcirc153.pdf, para.19.

52 International Atomic Energy Agency, 'Model protocol additional to the agreement(s) between state(s) and the International Atomic Energy Agency for the application of safeguards', INFCIRC/540 (Corrected), September 1997, www.iaea.org/Publications/Documents/Infcircs/1998/infcirc540corrected.pdf, article 2.(a).(v).

53 V. Bragin, J. Carlson and R. Leslie, 'Implementation of the additional protocol: Verification activities at uranium mines and mills', IAEA-SM-367/6/01/P, 2001; R. Leslie, P. Riggs, V. Bragin, Q. S. Bob Truong, R. Neville and K. Staenz, 'Satellite imagery for safeguards purposes: Utility of panchromatic and multispectral imagery for verification of remote uranium mines', Annual Meeting of the Institute of Nuclear Materials Management, Orlando, 23–27 June 2002, www.asno.dfat.gov.au/publications/02satimg.pdf.

54 GOV/2004/83, paras. 6.

55 Bragin, Carlson and Leslie.

56 'Statement of the DDG-SG [Deputy Director General for Safeguards] on 16 June 2005 at the IAEA Board of Governors meeting', June 2005, www.fas.org/nuke/guide/iran/nuke/iaea0605.pdf.

57 R. Scott Kemp, 'On the feasibility of safeguarding uranium mines', *Non-proliferation Review,* vol. 13, no. 2, July 2006.

58 OECD NEA and IAEA, *Uranium 2005: Resources, Production and Demand,* p. 206.

59 OECD NEA and IAEA, *Uranium 2005: Resources, Production and Demand,* p. 206.

60 H. Aigner et al., 'International target values 2000 for measurement uncertainties in safeguarding nuclear materials', *ESARDA Bulletin,* no. 31, April 2002, http://esarda2.jrc.it/bulletin/bulletin_31/08.pdf.

61 Assuming that the probability of a false alarm is set at 5 per cent.

62 More specifically, it would be necessary to take a number of samples each day which is large compared to $(\sigma_0 / \mu_0)^2$, where the mean uranium content for the material mined over the course of a day is expressed as μ_0 and its standard deviation as σ_0.

63 Almost all the uncertainty in the MUF measurement for a mill would come from the uncertainty in the flow of uranium into the facility, X; hence $\sigma(MUF) \approx \sigma(X)$, which is smaller by a factor of $\sqrt{2}$ than the corresponding expression for a mine (see appendix I for details).

64 Kemp.

65 Italics in the original.

66 Saeidi, pp. 5–6.

67 International Atomic Energy Agency, 'Policy paper 18: Safeguards measures applicable in conversion plants processing natural uranium' in International Atomic Energy Agency, *Safeguards Manual* (SMR 2.18), para. 14.

68 SMR 2.18, para. 10.

69 Interestingly, the IAEA's complementary access rights at conversion facilities can be derived from two articles: 5.a.(i), since a conversion facility is necessarily located on a site, and article 5.a.(ii), which permits the IAEA to inspect any location identified by a state pursuant to its declaration under article 2.a.(vi).(a). Iran would be required to declare the UCF under this article because it contains more than 10 t of natural uranium.

70 SMR 2.18, paras 3 and 21.

71 Treaty establishing the European Atomic Energy Community, 1957 (amended 1992), http://eur-lex.europa.eu/en/treaties/dat/12006A/12006A.htm, article 77.

72 Aigner et al.

73 With these values for detection probability and false alarm rate D=2.9σ(MUF). See appendix 1 for details.

74 International Atomic Energy Agency, *IAEA Safeguards Glossary,* International Nuclear Verification Series no. 2, International Atomic Energy Agency, Vienna, 2002, www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_prn.pdf, table III.

75 International Atomic Energy Agency, *IAEA Safeguards Glossary,* table III.

76 In some circumstances the IAEA may be able to ascertain when a diversion took place. For example, if nuclear material is removed from IAEA containment and surveillance and at the next PIV it is discovered that there has been a diversion, it would be very likely that it occurred while the material was outside IAEA control. Indeed, on one occasion the IAEA did lose continuity of knowledge of a 48X UF_6 cylinder in Iran (see GOV/2006/53, para. 19), although there is no evidence that a diversion took place on that occasion. There is, however, an important difference between ascertaining when a diversion took place and providing timely warning of the fact.

77 GOV/2007/8, para. 5.

78 Enriching uranium would be, by far, the most time-consuming step for a proliferator that had already manufactured all of the non-nuclear components of a weapon and had also acquired the technology necessary for fabricating its pit. A clandestine enrichment facility capable of producing 6000 kgSWU/yr with a tail assay of 0.3 per cent could produce 20 kg ^{235}U of 93 per cent enriched HEU in about 260 days. This is a 'worst case' estimate but not an unreasonable one. This time would shorten to about 90 days by using 3.5 per cent enriched LEU (i.e. material from the PFEP). This is, however, not really a plausible diversion scenario (provided that Iran is not permitted to build up an LEU stockpile) because it would require almost 5 t of $LEUF_6$ (six or seven times the annual production capacity of the PFEP).

79 Or, to be absolutely correct, its estimate of σ(MUF-D) would be reduced. See appendix 1.

80 International Atomic Energy Agency, *IAEA Safeguards Glossary,* para. 10.6. For a description of the procedure for calculating the required number of items for verification see *IAEA Safeguards Glossary,* para. 10.8.

81 Russell Leslie, Annette Berriman and John Carlson, 'Are randomized inspections at Pu or HEU storage facilities sufficiently effective under integrated safeguards?', Annual Meeting of the Institute of Nuclear Materials Management, Phoenix, July 2005, www.asno.dfat.gov.au/publications/inmm2005_udu_and_snri.pdf. Although this paper discusses SNRIs in the context of unirradiated direct use material storage facilities, the principles it outlines are more generally applicable.

82 See footnote 8.

83 An enrichment facility with a capacity of 2,000,000 kgSWU/yr can produce about 530,000 t of 3.5 per cent enriched UF_6 per year with the tail assay set to 0.2 per cent.

84 Hexapartite Safeguards are designed to provide greater assurance about the operation of GCEPs than INFCIRC/153 would do alone while ensuring that commercially sensitive information is respected. Their central feature is that they permit inspections in the cascade hall under an arrangement known as limited frequency unannounced access (LFUA). Following an LFUA request, inspectors must be granted access into the cascade hall within two hours. During an inspection they are escorted and walk along predetermined paths. In order to ensure that the cascade has not been reconfigured to produce HEU, they may compare the cascade configuration to photographs, take environmental samples and verify enrichment levels by using a hand-held monitor. Australia, Japan, the US, Euratom, Urenco and the IAEA were participants in the project. Ultimately, however, only Urenco and Japan built GCEPs. The US and France are now in the process of following suit. K. Naito, 'The Hexapartite Safeguards Project: a retrospective', Symposium on international safeguards: Addressing verification challenges, Vienna, IAEA-CN-148/97, 16–20 October 2005; US Office of Technology Assessment, *Nuclear Safeguards and the International Atomic Energy Agency,* OTA-ISS-615, US Government Printing Office, Washington, DC, April 1995, www.wws.princeton.edu/ota/disk1/1995/9530/9530.PDF, pp. 71–72.

85 W. Bush, D. Langlands, N. Tuley and J. Cooley, 'Model safeguards approach for gas centrifuge enrichment plants', Symposium on international safeguards: Addressing verification challenges, Vienna, IAEA-CN-148/98, 16–20 October 2005.

86 See footnote 85.

87 Just as it is possible to account for all the material flowing through an enrichment facility by performing a material balance, so all the separative work units produced by a GCEP can, in theory, be accounted for by performing a SWU balance.

88 This is a plausible scenario because, although LEU is not directly usable in weapons, using it as feedstock for an enrichment plant significantly shortens the time required to produce HEU. See footnote 78.

89 GOV/2006/53, para. 6.

90 GOV/2007/8, para. 4.

91 Bush, Langlands, Tuley and Cooley.

92 LFUA and the use of visual observation to verify that GCEPs have not been reconfigured are starting to go out of fashion because of the complexity of many modern facilities (plants with a capacity of 4,000,000 kgSWU/yr are currently planned in France and the US). However, both the FEP and PFEP are so small by this standard that visual observations should still be effective.

93 GOV/2007/8, paras. 7–9.

94 UN Security Council Resolution 1737, para. 8.

95 Victor Bragin, John Carlson and Russell Leslie, 'Integrated safeguards: Status and trends', *Nonproliferation Review,* vol. 8, no. 2, 2001, www.cns.miis.edu/pubs/npr/vol08/82/82bragin.pdf, pp. 102–110.

96 John Carlson and Russell Leslie, 'Special inspections revisited', Annual Meeting of the Institute of Nuclear Materials Management, Phoenix, 10–14 July 2005, www.asno.dfat.gov.au/publications/inmm2005_special_inspections.pdf.

97 David Fischer, *History of the International Atomic Energy Agency,* International Atomic Energy Agency, Vienna, 1997, pp. 288–294.

98 Bragin, Carlson and Leslie, 'Integrated safeguards: Status and trends'.

99 Bragin, Carlson and Leslie, 'Implementation of the additional protocol: Verification activities at uranium mines and mills'. This point is discussed above with reference to the relevance of the additional protocol to undeclared mining and milling.

100 Hassan Rohani, 'Beyond the challenges facing Iran and the IAEA concerning the nuclear dossier', undated remarks, [30 September 2005], www.armscontrolwonk.com/file_download/30.

101 Mark Hibbs, 'US briefed suppliers group in October on suspected Iranian enrichment plant', *Nuclear Fuel,* vol. 27, no. 26, 23 December 2002, p. 1.

102 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2003/63, 26 August 2003, www.iaea.org/Publications/Documents/Board/2003/gov2003-63.pdf, para. 18; GOV/2003/75, para. 32.

103 International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/2006/15, 27 February 2006, www.iaea.org/Publications/Documents/Board/2006/gov2006-15.pdf, para. 38.

104 K. Chitumbo, S. Robb and J. Hilliard, 'Use of commercial satellite imagery in strengthening IAEA safeguards' in Bhupendra Jasani and Gotthard Stein (eds), *Commercial Satellite Imagery: A Tactic in Nuclear Weapon Deterrence,* Springer-Verlag, Berlin, 2002, p. 41.

105 Leslie, Riggs, Bragin, Bob Truong, Neville and Staenz.

106 See, for example, OECD NEA and the IAEA, *Uranium 2005: Resources, Production and Demand,* p. 206.

107 Chitumbo, Robb and Hilliard.

108 Chitumbo, Robb and Hilliard, pp. 41–42.

109 To the best of our knowledge, there has not been any discussion in the open source literature about the use of environmental sampling to detect uranium mines. Presumably the reason for this is that unenriched uranium—the most obvious indicator of a uranium mine—is, in general, not a good indicator of nuclear activity (since the uranium background is high and variable). However, there are reasons to suppose that detecting uranium mines via environmental sampling might be feasible. Emissions from a uranium mine will be much larger than from any other kind of nuclear facility. Environmental uranium levels around a mine might, therefore, be *much* higher than the background level. Moreover, emissions from a mine will also include other non-nuclear chemicals used in the mining and milling process. These materials might also be detectable and could provide corroborating evidence. Developing a WAEM system to detect uranium mines, if it is feasible, is likely to take considerable time and is therefore not considered further in this paper.

110 R. Scott Kemp, 'Initial analysis of the detectability of UO_2F_2 aerosols produced by UF_6 released from clandestine uranium conversion plants', preprint, 23 August 2006, www.princeton.edu/~rskemp/KEMP-Detection_Clandestine_Enrichment_Conversion.pdf.

111 Kemp, 'Initial analysis of the detectability of UO_2F_2 aerosols produced by UF_6 released from clandestine uranium conversion plants'.

112 Chitumbo, Robb and Hilliard, pp. 43–44.

113 Chitumbo, Robb and Hilliard, p. 43.

114 Kenneth W. Nicholson, 'Practical application of wide area environmental sampling for the detection of undeclared nuclear activities', 22nd ESARDA Annual Meeting, Dresden, 8–12 May 2000, http://esarda2.jrc.it/db_proceeding/mfile/P_2000_Dresden_8-6.pdf.

115 Hui Zhang, 'Uses of commercial satellite imagery in FMCT verification', *Nonproliferation Review,* vol. 7, no. 2, www.cns.miis.edu/pubs/npr/vol07/72/72zhang.pdf, pp. 120–135.

116 Chitumbo, Robb and Hilliard, p. 45.

117 N. A. Wogman, R. W. Perkins and G. R. Holden, 'Environmental sampling and analysis as a safeguards tool', International Safeguards Meeting, Vienna, March 1994, www.osti.gov/bridge/servlets/purl/139483-66lWO7/139483.PDF.

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119 D.W. Swindle, R.L. Pearson, N.A. Wogman and P.W. Krey, 'Screening of potential sites for undeclared nuclear facilities in environmental monitoring for nuclear proliferation', *Journal of Radioanalytical and Nuclear Chemistry,* vol. 248, no. 3, pp. 599–604.

120 International Atomic Energy Agency, 'Strengthening the effectiveness and improving the efficiency of the safeguards system', GOV/2784, 21 February 1995, para. 54.

121 INFCIRC/540 (Corrected), article 9.

122 For a review of the field see, for example, V.M. Piksaikin, G.M. Pshakin and V.A. Roshchenko, 'Review of methods and instruments for determining undeclared nuclear materials and activities', *Science and Global Security,* vol. 14, no. 1, 2006, www.princeton.edu/~globsec/publications/SciGloSec.shtml, pp. 49–72; Nicholson, 'Practical application of wide area environmental sampling for the detection of undeclared nuclear activities'; David W. Swindle, 'Wide area environmental sampling: Results from an international evaluation on potential applications in international safeguards', 22nd ESARDA Annual Meeting, Dresden, 8–12 May 2000, http://esarda2.jrc.it/db_proceeding/mfile/P_2000_Dresden_8-5.pdf.

123 International Atomic Energy Agency, 'Use of wide area environmental sampling in the detection of undeclared nuclear activities', STR-321, 1999.

124 Garry Dillon, *Wide Area Environmental Sampling in Iran,* The Nonproliferation Policy Education Centre, 2006, www.npec-web.org/Essays/WideAreaEnvironmentalSampling.pdf.

125 This figure is obtained by dividing the 'detection area' of each sampler (given by pi multiplied by its radius squared) by the land area of Iran. In fact, the detection area is kite shaped rather than circular but that is a subtlety which can be ignored in obtaining an order of magnitude estimate such as ours. See Nicholson, 'Practical application of wide area environmental sampling for the detection of undeclared nuclear activities'.

126 Dillon.

127 Ken W. Nicholson, 'Technical solutions and directions: Wide area monitoring', ESARDA/INMM workshop on 'Safeguards perspectives for a future nuclear environment', Como, 14–16 October 2003, http://esarda2.jrc.it/db_proceeding/mfile/P_2003_Como_3-6-nicholson-040206.pdf.

128 Dillon.

129 T. Valmari and R. Rosenberg, 'Wide area environmental monitoring', 24th ESARDA Annual Meeting, Luxembourg, 28–30 May 2002, http://esarda2.jrc.it/db_proceeding/mfile/P_2002_Luxembourg_g1-02-valmari-rosenberg-ed.pdf.

130 Dillon.

131 Hartwig Spitzer, 'The improvement of satellite capabilities and its implications for the open skies regime' in Pál Dunay, Márton Krasznai, Hartwig Spitzer, Rafael Wiemker and William Wynne, *Open Skies: A Cooperative Approach to Military Transparency and Confidence Building*, United Nations Institute for Disarmament Research (UNIDIR), Geneva, 2004.

132 For a survey of commercial satellite capabilities see B. Jasani and Gotthard Stein, 'Introduction' in Bhupendra Jasani and Gotthard Stein (eds) *Commercial Satellite Imagery: A Tactic in Nuclear Weapon Deterrence,* Springer-Verlag, Berlin, 2002, p. 8. The figure of 0.3 m for aircraft imagery is the maximum permissible resolution under the Open Skies Treaty (see below).

133 Leslie, Riggs, Bragin, Bob Truong, Neville and Staenz.

134 US Office of Technology Assessment, *Environmental Monitoring for Nuclear Safeguards*, OTA-BP-ISS-168, US Government Printing Office, Washington, DC, 1995, www.wws.princeton.edu/cgi-bin/byteserv.prl/~ota/disk1/1995/9518/9518.PDF, p. 42.

135 Procedures to be followed in the event of a disagreement are also laid down in paragraphs 18, 21 and 22.

136 Emphasis added.

137 An excellent summary of CWC challenge inspections can be found in US Office of Technology Assessment, *Nuclear Safeguards and the International Atomic Energy Agency,* pp. 61–62.

138 Convention on the Prohibition of the Development, Production, Stockpiling and Use of Chemical Weapons and on their Destruction (Chemical Weapons Convention), 1993, Annex on implementation and verification (Verification Annex), Part X, para. 29.

139 Chemical Weapons Convention, Verification Annex, Part X, para. 41.

140 Chemical Weapons Convention, Verification Annex, Part X, para. 41.

141 Chemical Weapons Convention, Verification Annex, Part X, para. 48.

142 John R. Walker, 'Chemical weapons verification: the UK's practice challenge inspections programme at government facilities', *Verification Report 1991,* Verification Research, Training and Information Centre (VERTIC), London, 1991; United Kingdom, 'Verification of nuclear disarmament: Second interim report on studies into the verification of nuclear warheads and their components', Working paper submitted to the Preparatory Committee for the 2005 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons, NPT/CONF.2005/PC.III/WP.3, 8 April 2004, www.reachingcriticalwill.org/legal/npt/prepcom04/papers/UKwp3.pdf.

143 International Institute of Strategic Studies, 'Iran's strategic weapons programmes: A net assessment', p. 46.

144 GOV/2003/75, para. 32.

145 This is what happened at Lavisan-Shian, a military facility which, it has been alleged, was part of Iran's clandestine nuclear programme.

The facility was razed to the ground and the topsoil removed in late 2003, a result Iran claimed of a planning dispute between the Municipality of Tehran and the Ministry of Defence. Information provided by Iran to back-up this claim 'appeared to be coherent and consistent with its explanation', International Atomic Energy Agency, 'Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran', GOV/ 2005/67, 2 September 2005, www.iaea.org/Publications/Documents/Board/2005/gov2005-67.pdf, para. 39. Environmental samples were taken at Lavisan-Shian in June 2004 and no evidence of undeclared nuclear material was found. Iran states that this was because 'no nuclear material and nuclear activities related to the fuel cycle were carried out at Lavisan-Shian', GOV/ 2004/83, para. 100.

146 UN Security Council Resolution 1696, para 1; UN Security Council Resolution 1737, para 1.

147 INFCIRC/540 (Corrected), article 2.a.(i). Italics in the original.

148 INFCIRC/540 (Corrected), article 2.a.(iv).

149 INFCIRC/540 (Corrected), Annex I, para. (i). Italics in the original.

150 International Atomic Energy Agency, 'Communications received from certain member states regarding guidelines for transfers of nuclear-related dual-use equipment, materials, software and related technology', INFCIRC/254/Rev.7/Part 2, 20 March 2006, www.nuclearsuppliersgroup.org/PDF/infcirc254r7p2-060320.pdf. The Nuclear Suppliers Group is a group of states with advanced nuclear industries that aims to control the export of fuel cycle technology in order to prevent the proliferation of nuclear weapons.

151 British American Security Information Council (BASIC), 'A constructive EU-US approach to the Iran nuclear dispute', 6 December 2005, www.basicint.org/countries/iran/statement.htm.

152 If Iran had a clandestine nuclear programme, it would not risk military action by announcing its intention to proliferate by leaving the NPT. It would manufacture its first nuclear weapon in secret and renounce the NPT only after it had done so.

153 Producing 20 kg^{235}U of 93 per cent enriched uranium from NUF$_6$ feedstock requires 4300 kgSWU (with a tail assay of 0.3 per cent). This would require a 1,000-machine cascade consisting of centrifuges with a separative capacity of 2 kgSWU/yr (higher than Iran's centrifuges have achieved so far) to operate for 2 years, 2 months.

154 Using the same assumptions as listed in footnote 153 except for 3.5 per cent enriched feedstock.

155 Persbo.

156 International Institute of Strategic Studies, 'Iran's strategic weapons programmes: A net assessment', pp. 18–27.

157 For the text of the June 2006 offer see www.diplomatie.gouv.fr/en/article-imprim.php3?id_article=5314.

158 M. Ghannadi-Maragheh, 'Iranian nuclear fuel cycle experience', World Nuclear Association Annual Symposium, London, 3–5 September 2005, www.world-nuclear.org/sym/2003/ghannadi.htm; OECD NEA and IAEA, *Uranium 2005: Resources, Production and Demand,* p. 209.

159 Albright.

160 Oliver Meier, 'News analysis: The growing nuclear fuel-cycle debate', *Arms Control Today*, vol. 39, no. 9, 2006, www.armscontrol.org/act/2006_11/NAFuel.asp; Pierre Goldschmidt, 'Mechanisms to increase nuclear fuel supply guarantees', Carnegie International Non-Proliferation Conference, Washington, DC, 7–8 November 2005.

161 Goldschmidt.

162 Goldschmidt.

163 Goldschmidt.

164 For a list of the states that have ratified the Open Skies Treaty see the website of the Canadian Defence Forces, www.dnd.ca/site/newsroom/view_news_e.asp?id=982.

165 Jozef Goldblat, *Arms Control: The New Guide to Negotiations and Agreements*, 2nd edn, Sage Publications, London, 2002, p. 266.

166 Iran, 'Complementary information and clarification on the report of the Director General to the Board of Governors on implementation of safeguards in the Islamic Republic of Iran (GOV/2006/15)' in International Atomic Energy Agency, 'Communication dated 7 March 2006 received from the permanent mission of the Islamic Republic of Iran to the Agency', INFCIRC/672, 8 March 2006, www.iaea.org/Publications/Documents/Infcircs/2006/infcirc672.pdf.

167 Pursuant to article IV.1, four types of sensor may be used: optical panoramic and framing cameras, video cameras with real-time display, infra-red line-scanning devices and sideways looking synthetic aperture radar.

168 1992 Treaty on Open Skies, article X.2, www.osce.org/documents/doclib/1992/03/13764_en.pdf.

169 Goldblat, p. 11. Examples of this include the 1990 Vienna Confidence and Security Building Measures Document and the 1995 Santiago Declaration.

170 See for instance the comments by John Redick, Julio Carasales and Marco Marzo at the conference 'Argentina and Brazil: The Latin American nuclear rapprochement', Nahel Soreq, 1996. The transcript is available at www.isis-online.org/publications/israel96/isr_toc.html.

171 Persbo.

172 For an excellent overview see Goldblat (ed) with Fischer and Szasz, chapter 2.

173 International Atomic Energy Agency, *IAEA Safeguards Glossary,* para. 3.20.

174 International Atomic Energy Agency, *IAEA Safeguards Glossary,* para. 3.14. See also table II.

175 International Atomic Energy Agency, *IAEA Safeguards Glossary,* para. 6.43.

176 In fact, the same measurement errors that make MUF inevitable also result in slight differences between the IAEA's measurements and those of the operator. There is therefore likely to be a difference, D, between the IAEA's estimate of MUF, MUF', and that of the operator: MUF' = MUF - D. It is therefore σ(MUF') not σ(MUF) that is important in interpreting the results of inspections, but the difference is rarely important. See International Atomic Energy Agency, *IAEA Safeguards Glossary,* para. 10.2.

177 US Office of Technology Assessment, *Nuclear Safeguards and the International Atomic Energy Agency*, pp. 46–48.

178 Aigner et al. The figure in table 3 for the uncertainty in sampling from dirty uranium scrap has been taken as the value for δ_s assuming that the random error, which has not yet been defined, is equal to the systematic error.

179 Aigner et al.