



**THE ACTUAL AND POTENTIAL  
DEVELOPMENT  
OF NUCLEAR WEAPONS TECHNOLOGY  
IN THE  
AREA OF NORTH EAST ASIA  
(KOREAN PENINSULAR AND JAPAN)**

**CLIENT: GREENPEACE INTERNATIONAL**

**REF N° R3126-A1**

**JOHN H LARGE**

**LARGE & ASSOCIATES  
LONDON**

1 <sup>st</sup> Issue	Revisions	APPROVED	RESUBMISSION
15 March 2005	J.R2		<b>01 November 2016</b>

## DEVELOPMENT OF NUCLEAR WEAPONS TECHNOLOGY IN NORTH EAST ASIA

### SUMMARY

This Review examines the civil nuclear infrastructure of nuclear power reactors, fuel fabrication and reprocessing plants and, more generally, how the nuclear know-how might be deployed to procure sufficiently high quality materials to build up a nuclear weapons arsenal.

Applied to countries of the North East Asia region, the findings are that the present non-nuclear weapons states, the Republic of (South) Korea and, particularly, Japan are each capable of establishing an effective nuclear weapons arsenal on the basis of their technological know-how and high technology and industrial infrastructures. However, in terms of access to sufficient quantities of the specialised materials, especially the highly refined fissile highly enriched uranium (U-235) and plutonium (Pu-239), because of its broad ranging civil nuclear programme Japan has access to large quantities of these, albeit safeguarded by the International Atomic Energy Agency under the Non-Proliferation Treaty, whereas South Korea does not have any significant stocks of either fissile material because of the relatively narrow range of its civil nuclear programme confined, as it is, essentially to nuclear power electricity generation and the fabrication of unenriched nuclear fuel.

Comparisons are drawn with developments in the Democratic People's Republic of (North) Korea which is known to have extracted fissile plutonium from nuclear fuel irradiated in its Yongbyon reactor and, moreover, it has publicly declared its intention to procure, and may have already done so, a nuclear weapons arsenal. Indeed, at this present time the Yongbyon reactor is shut down, possibly for extraction of another batch of irradiated fuel for reprocessing into plutonium which, if correct, could become a regular procedure as North Korea regularly harvests plutonium with which to increase its nuclear weapons arsenal at a rate 1 to 3 atomic warheads (A-Bombs) per year.

Timescales to full development and possession of a nuclear arsenal are difficult to predict:

North Korea may have already developed and produced a viable fission device (A-Bomb), compact and robust enough to deploy against its near neighbour South Korea or further afield against Japan.

On its part, with its almost self-sufficient civil nuclear power and fuel industry, Japan should be recognised as a 'virtual' nuclear weapons country, with the practicable capability of bringing together within a few months the design and fabrication technologies to the nuclear materials that it already has in its possession. Such is Japan's high state of industrial development and prowess, it is more likely might capable of moving straight to the development of a thermonuclear (H-Bomb) warhead of much greater destructive yield than the A-Bomb design believed to have been developed by North Korea.

South Korea does not, at present, have (or so it declares) sufficient stockpiles of fissile material (either highly enriched uranium and/or plutonium) to move quickly to the nuclear weapon fabrication stage, although given the incentive it might be able to illegally procure these via the now established international trading nuclear materials network, thereafter becoming nuclear weapons capable in, say, six to nine months. If, at some time in the near or interim future, the North and South Korea were to unify, then access to the fissile materials known to be in the possession of North Korea which, when married to the high technological infrastructure of South Korea, might be expected to produce a number of nuclear devices within, like Japan, six to nine months. South Korea has a large quantity of fissile plutonium under store but laying dormant in its own nuclear reactor ponds, to release this plutonium South Korea would have to acquire fuel reprocessing technology and it would have to contravene the IAEA safeguards and the *prior consent rights* that the United States places over the most of the South Korean nuclear fuel.

Of course, to pose a nuclear weapons threat a means of delivery must also be developed. It is established that North Korea has proved missile systems that might provide suitable delivery platforms for nuclear warheads, striking into South Korea or beyond with its Taep'odong-1/2 vehicles to Japan. It is not known, although it is believed that Japan could adapt a variant of its M-5 vehicle to a ballistic delivery role although, that said, it might choose instead to depend upon the US Patriot PAC-3 missile defence system which should be fully operational in or about 2007. On its part, South Korea possesses somewhat limited range NHK-1/2 missiles capable of striking into but not completely covering North Korean territory, although the recent space programme involving satellite launch technology should be capable of technology transfer across to a medium range ballistic missile design.

So, with the continuing cross-border rivalry between South and North Korea, a sometimes bellicose North Korea articulating aggression to Japan, and wider regional security threats possible from either of or between the two established nuclear armed nations of China and the Russian Federation, the whole North East Asia region is and is likely to continue to be in a state of anxiety and instability. In response, it would not be unexpected for South Korea and Japan both, independently, to respond to this geo-political situation by striving to improve their readiness to acquire nuclear weapons should the need arise, a notion that no doubt, both governments will strenuously deny.

JOHN H LARGE  
LARGE & ASSOCIATES, LONDON

## DEVELOPMENT OF NUCLEAR WEAPONS TECHNOLOGY IN NORTH EAST ASIA

### NUCLEAR WEAPONS SAFEGUARDS AND CONTROLS

Nuclear weapons technology is an extremely sensitive subject. Not only is a veil of secrecy drawn across the technical details of nuclear weapons, the means of production, deployment and delivery, but there is much concealment about the nuclear ambitions and activities of individual countries, if and how these countries might be attempting to develop nuclear weapons and, indeed, if they already have a stockpile of nuclear weapons.

There are in place safeguards and international treaties to control the spread and technological know-how of nuclear weapons and the delivery systems. The mainstay of these is the International Atomic Energy Agency's (IAEA) role of monitoring the *Non-Proliferation Treaty* (NPT),<sup>1</sup> now strengthened by the *Additional Protocol*.<sup>2</sup>

However, even with these controls there are opportunities for a country determined to acquire nuclear weapons to do so, either openly along the route now being adopted by North Korea by serving notice and quitting the treaty or, in a clandestine fashion, by utilising the its civil nuclear industry in its dual capable role.

### NUCLEAR WEAPON TECHNOLOGY

A nuclear warhead is a complex, precision assembly comprising components of very high quality refined materials. In its simplest form, all of the nuclear materials required to build a nuclear warhead derive from natural uranium, either as highly enriched uranium or the transuranic by-product plutonium. The energy that produces the explosive yield is the culmination of the very rapid, near instantaneous, fissioning (breaking up of the atoms) of these materials.

An atomic or A-bomb<sup>3</sup> may be constructed using a few tens of kilograms of highly enriched fissile uranium in which fissioning is prompted by driving two sub-critical masses of HEU together at very high velocity to conjoin to a highly critical mass. This type of weapon configuration, comprising a length of barrel that projects a slug of HEU<sup>4</sup> into a static uranium target or doughnut, is referred to as 'gun' geometry. To increase the yield and reliability of yield of a gun type A-bomb, the enriched uranium fissile components can be replaced with a few kilograms of highly fissile plutonium assembled as a hollow shell that is crushed or imploded down to a critical mass by a conventional explosive wrap. This geometry, of the appearance and about the size of football, is called an 'implosive' device.

To advance the yield and reliability of an A-bomb, it is advantageous to boost the initial fissioning of the plutonium core. This is achieved by introducing a spurt of neutrons to the fissile heart of the warhead, either with a small pea-sized source of radioactive polonium combined with beryllium, or by creating neutrons from the fusing a few grams of radioactive tritium and deuterium. Both of these techniques require a nuclear reactor to generate the radioactive materials, and conventional chemical plants to isolate either the deuterium or beryllium, and to provide lithium as a source of tritium.

.....

The yield of the warhead can be increased if the atomic fission stage, the A-bomb, is used to trigger a second stage involving fusion - this is the basis of a thermonuclear or H-bomb. For this, the intense and almost instantaneous energy of the A-bomb is deployed to fuse a few kilograms of tritium and deuterium. The tritium is generated within the warhead from a fusion fuel of lithium-deuteride, a simple hydride of lithium metal and heavy water, produced by conventional chemical processes. Further increase in the nuclear yield is gained if the energy from the fusion stage is applied to fissioning a mantle of depleted uranium ( $U^{238}$ ).

## **NUCLEAR MATERIALS AND PRODUCTION FACILITIES INVOLVED**

As previously discussed, the fissile components of a nuclear warhead can be made up of either highly enriched uranium-235 or from a smaller quantity of plutonium (between 3 to 7 kg) which is rich in the plutonium-239 isotope. For both plutonium and uranium designs, a few kilograms of depleted uranium are required to contain the early stages of detonation, a few grams of tritium-deuterium or, alternatively, polonium to initiate the nuclear sequence, some conventional beryllium and high explosives and, if the warhead is to include a fusion stage, a fuel pack of lithium-deuteride, a few more kilograms of plutonium or enriched uranium, and a further 20kg of depleted uranium for the fusion-fission mantle.

These materials can be procured by dedicated military facilities, produced and extracted from dual capable civil nuclear plants, and/or by imports from overseas nations and organisations – see **APPENDIX I**.

## **PROCURING A NUCLEAR ARSENAL**

Setting aside the demanding technological know-how required for the design of a nuclear weapon, the technological and material production demands would seem to set back acquisition of practical nuclear weapons, of significant explosive yield, to sub-national and terrorist groups by several years or more into the future. Of course, this does not mean that such groups, in possession of even sub-grade nuclear materials and relatively primitive fabrication facilities, could not produce 'radiation' or 'dirty' bombs capable of a slight nuclear yield sufficient to disperse fission products and radioactive debris over a large area. This type of terrorist weapon would, no doubt, be more threatening and damaging, particularly in psychological and economic impacts, than the conventional explosive devices available today.

For countries determined to acquire a nuclear arsenal then a number of options or routes towards this goal are viable: i) an entirely separate military-industrial complex being established and devoted to weapons production, ii) an established civil nuclear power industry, with its power reactors, fuel manufacturing and fuel reprocessing facilities adapted to sideline the necessary nuclear materials streams, and/or iii) component parts, semi-finished materials, etc., be procured from other countries and/or commercial enterprises.

Past examples of these routes to establishing a nuclear weapons arsenal are i) the United States which, from the onset, established and dedicated a separate military-industrial complex (centred around Los Alamos) for its weapons development program, ii) the

United Kingdom with its use of civil, electricity generating nuclear power plants (Magnox plants) centred around spent fuel reprocessing (Sellafield),<sup>5</sup> and more recently iii) Pakistan and more specifically that of its chief weapons scientist, Abdul Qadeer Khan, by operating a clandestine network of countries and organisations trading in nuclear technology. The development time, from inception to nuclear test demonstration varies, depends obviously on the resources and urgency, but is relatively short, just a few years.<sup>6</sup>

## **NUCLEAR WEAPONS PROCUREMENT MODELS FOR NORTH EAST ASIA**

Setting aside China and the Russian Federation which are both declared nuclear weapons states, the development capacity for other states in the North East Asia region are:

### **JAPAN**

Supposedly, Japan had embarked upon its own nuclear weapons program during World War II, with part of this effort being located at Hungnam in North Korea, although there is little other than anecdotal surmise to substantiate the depth and achievement of this early nuclear weapons programme.

In Japan there are constitutional limitations on the development and research in nuclear activities other than for peaceful uses.<sup>7</sup> However, the Japanese government is pledged to maintaining energy security for which, because it lacks significant sources of fossil fuels (coal, oil and gas), it is strongly committed to nuclear power and the nuclear fuel cycle, generating about 40% of its total electricity needs by nuclear power.

Other than irradiated fuel reprocessing presently undertaken in the United Kingdom and France, Japan's civil nuclear sector is almost independent having capability to design, construct and operate a range of nuclear reactor types (light water thermal and prototype fast LMFR reactors), uranium enrichment and civil fuel fabrication facilities and, at Tokai, a low throughput (90 tonnes per year) fuel separation (reprocessing) plant. Presently undergoing commissioning, is a commercial-sized reprocessing plant at Rokkasho-Mura<sup>8</sup> with an annual throughput of 800 tonnes which will render Japan entirely self-sufficient in its civil nuclear activities from about 2006, or shortly thereafter.<sup>9</sup> Japan is also committed to a policy of nuclear fuel diversity and is presently adapting a number of its operational light water reactors to accept partial core loading of mixed oxide fuel (MOX).<sup>10,11</sup> To date approximately 5 tonnes of MOX fuel has been delivered to Japan from European-based fuel fabricators with a further 5 to 10 tonnes committed over the next 5 years from these sources.

Japan operates an extensive range of research reactors some of which are capable of producing the other nuclear materials/substances (polonium/tritium) required for a nuclear weapon development programme. As well as stocks of plutonium contained within the supplies of MOX fuel, Japan has considerable holdings of reactor grade plutonium, either located in Japan or held overseas on its behalf. The present (March 2004) stockpile of fissionable plutonium is 29 tonnes with a potential for further 76 tonnes contained within unprocessed irradiated fuel in storage,<sup>12</sup> the greater part of which is held in Japan.

.....

## NORTH KOREA

May 1992 North Korea reported to the IAEA that it had 90 grams of separated plutonium that was subject to safeguards from single batch reprocessing of defective fuel rods withdrawn from its 5MW<sub>e</sub> research reactor that had been operating since 1986 at Yongbyon. In its subsequent analysis the IAEA<sup>13</sup> became convinced it had been reprocessing small batches of irradiated fuel since 1989.<sup>14</sup>

Since that time and although it has become clear that North Korea has reprocessed a substantial number of irradiated fuel rods and extracted high grade plutonium, it has never been conclusively demonstrated that North Korea has an operational nuclear weapons arsenal. What is known is that North Korea has an active and ongoing nuclear weapons programme, it has admitted so, which initially centred around plutonium separation but later, according to United States intelligence, involved highly enriched uranium. Even whilst under inspection by the IAEA North Korea was able to extract plutonium, with estimates of the amount of plutonium held by North Korea prior to its expulsion of the IAEA inspectors in December 2002, ranging between 6 to 24kg. In the following January, North Korea served notice of its withdrawal from the NPT, it transferred the 8,000 or so irradiated fuel rods from the reactor spent fuel pond for reprocessing to yield, it is estimated, a further 20 to 30kg of plutonium.

Most recently, satellite images of the Yongbyon nuclear complex indicated that between the plutonium production reactor has ceased operating (7 April 2005) and that it may be being readied for discharging a batch of fuel for reprocessing. The potential capacity of North Korea's nuclear program is unsettling: The unfinished 200 MWt reactor at Yongbyon and the 700-800 MWt reactor at Taechon, if ever completed and commissioned, would generate about 275 kilograms of plutonium annually if operated at full capacity.<sup>15</sup> Moreover, the recent suggestion that North Korea has embarked upon a uranium enrichment programme suggests that it may be exploiting the limited quantity of plutonium by developing composite-core nuclear weapons which do not require particularly advanced nuclear weapons technology.<sup>16</sup>

## SOUTH KOREA

South Korea first became involved in nuclear technology in the 1950s but did not begin construction of its first power reactor until 1970.

There is firm evidence showing that South Korea embarked upon a nuclear weapon development programme in the early 1970s which included a bilateral agreement with France to supply a pilot fuel reprocessing plant, although under pressure from the United States, the programme seems to have been abandoned with South Korea ratifying its earlier signing of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) in April 1975 before producing any fissile material. Even following its commitment to the NPT, South Korea negotiated to purchase a CANDU-like NRX heavy water research reactor but this, together with its attempts to purchase a MOX fuel fabrication facility from Belgium, was withdrawn from, once again under US pressure.<sup>17,18</sup>

.....

In the 1990s South Korea expressed a strong interest in overseas fuel reprocessing for the return of MOX fuel, going so far as to negotiate with the COGEMA (France) for the French origin spent fuel irradiated at the PWR Ulchin site, because this fuel was exempt from the US prior consent rights.<sup>19</sup> More recently South Korea declared in 1991 that it would not “*manufacture, possess, store, deploy, or use nuclear weapons*”,<sup>20</sup> and late that year North and South Korea signed the *Joint Declaration on the Denuclearization of the Korean Peninsula*, although both sides have failed to implement its provision for a bilateral inspection regime.

South Korea’s nuclear power programme is dominated by light water reactors, with 16 pressurised water reactors (PWR) operational and a further 8 PWR units either on firm order or under construction. Interestingly, South Korea also operates 4 heavy water moderated CANDU reactors that are fuelled by natural uranium with on-load fuel loading and discharging.<sup>21</sup>

In 2004 when under pressure from the IAEA under its powers of the Additional Protocol,<sup>22</sup> South Korea publicly disclosed its past secret nuclear research activities, revealing that it had conducted chemical uranium enrichment from 1979 to 1981, separated small quantities of plutonium in 1982,<sup>23</sup> experimented with uranium enrichment in 2000,<sup>24</sup> and manufactured depleted uranium munitions from 1983 to 1987.

## **DUAL CAPABLE NUCLEAR FACILITIES – TECHNOLOGY TRANSFER**

The processes of manufacture, procuring, refining and enriching these materials are exactly the same for both military and civil needs. It is only the level of enrichment of uranium and degree of isotopic refinement of plutonium that distinguishes these materials between military and civil uses. This means that, essentially, the same plants can be used to isolate and process these two materials, it is only the extent of processing and the controls applied that distinguishes between military and civil grades of these materials.

Furthermore, as civil applications of nuclear power advance there is a wider crossover into the domain which has been until recent years almost exclusive to the military. This particularly applies to plutonium which had virtually no civil nuclear power application as a reactor fuel, other than in a few research and development fast reactors and for which there is little chance of commercial application in the near- and medium-term future. However, during the last decade plutonium has been adopted as a mixed oxide fuel (MOX) fuel for the relatively commonplace light water (PWR/BWR) civil power reactors. If the use of plutonium in civil nuclear power stations becomes established, the transfer and use of plutonium throughout the World could become relatively common currency. The emerging use of plutonium based MOX fuel in civil nuclear power plants adds a further element of concern with regard to the proliferation of nuclear weapons capability throughout the World.

Now, nuclear technology and the nature of industrialisation has changed, so much so that it is quite practical for relatively non-industrialised countries to complete nuclear materials supply and procurement in support of a civil nuclear power programme but which, by

intent or incidentally, provides capability and opportunity for nuclear weapons development.

A reliable indicator of the capability of a country to proceed along the nuclear warhead development route, that is if it has the intent, is the size and diversity of its activities in the civil nuclear power and research fields. Of course not all countries that develop their civil nuclear industry do so to acquire nuclear weapons capability, but the direction and scale of the nuclear activity can indicate the potential for such development. Also, some countries simply do not declare nuclear plants that are dedicated to military production.

The countries of North East Asia each have the following civil nuclear infrastructure:

**TABLE 1 NUCLEAR MATERIALS PRODUCTION AND POTENTIAL NUCLEAR WEAPONS CAPABILITY**

	URANIUM REFINING CONVERSION UO <sub>2</sub> t/Y	URANIUM ENRICHMENT Ut/Y	FUEL FABRICATION Ut/Y	MOX Ut/Y	D2	H3	REPROCESS Ut/Y	CIVIL NUCLEAR PLANTS N° - MW <sub>e</sub>	R& D REACTORS N°	WEAPONS STATUS OR PRODUCTION CAPABILITY
CHINA	\$	*400,000 diffusion/cen'fuge	\$	-	\$	\$	\$	3/2,100 6 units planned	7	YES – Arsenal of ~ 500
JAPAN	*120	*202,750	*1,565 U 60 MOX	\$	\$	°	*210 800	54/45,528	6	U+P+DT+H
SOUTH KOREA	*300	-	*550 PWR 700 CANDU	-	YES	YES	-	13/11,389	1	DT+H
NORTH KOREA	\$	\$	\$	-	\$	\$	\$	1/5	1	U+P+DT+H
TAIWAN	-	-	-	-	-	-	-	6/5,144	2	DT+H

.....  
For notes see Endnote 25.

## IAEA SAFEGUARDS - TECHNICAL SUPERVISION OF THE NPT

Over the last two decades nuclear technology and the nature of industrialisation has changed, so much so that it is quite practical for relatively non-industrialised countries to complete nuclear materials supply and procurement in support of a civil nuclear power programme but which, by intent or incidentally, provides capability and opportunity for nuclear weapons development.

The overlap of civil and military nuclear technologies increases as a result of the established nuclear nations providing advanced civil reactor and nuclear processes to countries that are stepping into nuclear power, and then by these countries themselves casting off dependence upon the established nations with the introduction of their own plants, particularly nuclear fuel cycle facilities including uranium enrichment and irradiated fuel reprocessing plants. These emerging nuclear countries have, in recent years, commenced nuclear trading in materials, technicians and technology, either directly between themselves (as allegedly between South Africa and Israel during the 1970-80s) or via an intermediaries in complex networks, as with Abdul Qadeer Khan's Pakistan-based nuclear trading web.

The outcome of these changes is that, whereas all of the key design and manufacturing technologies of nuclear weapons were controlled by and kept within the boundaries of a

few nations, now the technologies are dispersed over many countries for whom it is not necessary to trade only via a few industrialised, and often politicised nations such as the United States. This new freedom creates considerable difficulties for the International Atomic Energy Agency's (IAEA) in monitoring weapons development across the globe and, moreover, it frees up the additional controls, sanctions and embargoes that dominant countries, again principally the United States, were able to apply on nuclear technology, nuclear fuel and fissile materials.

These changes have introduced difficulties for and compromised the IAEA dual role of, on one hand, policing non-proliferation of nuclear weapons technology and materials and, on the other hand, encouraging the peaceful use of nuclear power. Maintaining the former role becomes more demanding as civil nuclear power plants advance, with the key technologies of nuclear power and nuclear munitions overlapping and becoming increasingly entwined.

The IAEA undertakes its function of maintaining the non-proliferation safeguards by monitoring the use and transfer of materials within and from nuclear installations - the keystone to this IAEA safeguard system is to control the availability and use of fissile materials, namely highly enriched uranium and plutonium. This requires the IAEA to have access to all parts of the nuclear fuel cycle, from uranium mining through to the production and post irradiation management of nuclear fuel, including monitoring of radioactive discharges and wastes. The introduction of the NPT *Additional Protocol* addresses some of the new challenges introduced by contemporary technology but it is, being primarily directed at the host country, somewhat cumbersome in routing out the intricacies of the Abdul Qadeer Khan-like networks.

Also, for effectiveness, the IAEA surveillance system requires that virtually all nuclear installations within any single state must be within the IAEA monitoring system - these monitored installations are referred to as 'safeguarded'. However, a number of states operate key installations that are 'unsafeguarded' and not open to IAEA monitoring; and certain states remain outside the Non-Proliferation Treaty for which signatory states accept (or pledge) that all nuclear installations might be considered to be safeguarded.

Even for safeguarded plants, particularly uranium enrichment and fuel reprocessing plants, the material throughput tonnages are so great that the quantities required to support a moderate nuclear warhead programme might be readily diverted undetected (*'be unaccounted for'*). In irradiated fuel reprocessing for plutonium extraction, which is completed in batches each taking a few days to process, not only does the reprocessing plant have to be continuously monitored but, also, the fuel core inventories of all of the supporting reactors (declared or otherwise) have to be logged on a very frequent basis.

If the conviction exists, an individual country can play a cat-and-mouse game within rules and safeguards of the Non-Proliferation Treaty. The country can advance its own civil nuclear power technology without constraint; it can establish independence for its own nuclear fuel supplies, including enrichment of uranium stocks and reprocessing of irradiated fuel; it can receive overseas technological assistance for civil nuclear projects; and it can conduct research and development in advanced nuclear techniques and processes, including fusion. In other words, a determined country can acquire the processes, physical

facilities, technological know-how and fissile materials required for nuclear munitions by proceeding along a quite legitimate civil nuclear power development route. Since the fundamental requirements of civil nuclear power and nuclear munitions share a great deal in common, an advanced civil nuclear power programme must have, by its very nature, a dual capability.

On its part, the IAEA can only inspect and monitor. It has to ensure that it has full access to all plants that might be involved, it has to physically measure and account all materials involved, wherever these might be located. In monitoring radioactive wastes and discharges from operational plants, it has to distinguish between quite legitimate civil and possible clandestine military applications, a differentiation which is now becoming increasingly more difficult as the two nuclear technologies merge.

## Appendix I

### MATERIAL STREAMS POSSIBLE FROM DUAL CAPABLE PLANTS AND FACILITIES

**Enriched Uranium – HEU:** For a high yield (10 to 20kt) nuclear detonation fuelled by uranium, the fissile mass at the heart of the warhead needs to comprise uranium metal enriched to a level in excess of 90%  $U^{235}$ . This applies to the 'gun' configuration, although with considerable loss of detonation efficiency, say perhaps achieving a 0.5 to 2-5kt yield, it is possible to construct a 'gun' configuration with fissile core components of about 70% to 80%  $U^{235}$  enrichment level.

The production of HEU requires an enrichment plant to raise the low content of the fissile isotope of uranium ( $U^{235}$  at 0.7%) existing naturally, to a very high level of concentration ( $> 90\%$  - HEU) by displacing the normally non-fissile isotope  $U^{238}$ . Large quantities of natural uranium, in the form of milled uranium, refined to yellowcake and then converted to uranium hexafluoride, are required for this process which centres around gaseous diffusion or centrifuge technology,<sup>26</sup> although the final stages of enrichment can be achieved by laser enrichment.<sup>27,28</sup>

**Plutonium:** Again for about a 20kt yield atomic warhead, a core containing between 3kg to 5kg of plutonium is required - for an implosion type warhead this would comprise a hollow plutonium sphere of about 80mm external diameter.

Ideally, the plutonium<sup>29</sup> required for a nuclear warhead should maximise the  $Pu^{239}$  content,<sup>30</sup> so subsequent fissioning of  $Pu^{239}$  has to be inhibited by either removing the plutonium yielding fuel from the reactor at a very low burn-up and/or by constraining this fission whilst the plutonium bearing fuel remains in the active core of the reactor.

For the first of these objectives, the ideal period for plutonium breeding in a relatively low power reactor core is between four to eight months. Accordingly, it would be very disruptive to have to close down the reactor for dismantling at this frequency so, for this reason, the large, high- powered light water reactors (PWR and BWR) are not well suited to plutonium production since these types of reactor require 6 to 8 weeks outage at each refuelling outage. Selective fuel channel withdrawal can be achieved by using reactors that are capable of refuelling whilst on load, such as the UK Magnox power station reactors that, in the past, contributed

.....

.....

Nevertheless, apart from the difficulties of scale of both the enrichment and the associated uranium hexafluoride feed plants, uranium enrichment to nuclear warhead levels is entirely practicable in plants designed to produce moderately low levels of enrichment for civil power station and R&D reactors (2% to 20%). Essentially, it is a matter of batching the process, by stretching and/or recycling,<sup>36</sup> at the penalty of rendering an already lengthy cycle even lengthier. For example, a civil gas diffusion type plant of 5,000 stages, capable of annually producing, say, 500kg of 20% enriched uranium for research reactor fuel, could be readily adapted to yield 25kg or so of 90% enriched uranium per year - this is sufficient for the manufacture of a single, enriched uranium A-bomb warhead per year.

In effect, all enrichment plants are dual capable in that low, moderate and highly enriched uranium can be produced for both civil and military applications.

**Depleted Uranium - DU:** Depleted uranium arises in very large quantities as a by-product of the enrichment process. All that is needed is to reduce uranium from the uranium hexafluoride to an oxide, and finish this in a metal plant.

Depleted uranium is a dual capable material.

## REFERENCES AND NOTES

<sup>1</sup> *Non-proliferation Treaty, NPT, 1967* in force 1970 – other international treaties and protocols, etc relating to nuclear weapons are:

<i>Partial Test Ban Treaty, PTBT</i> - Banning Nuclear Weapon Tests in the Atmosphere, In Outer Space and Under Water	1963
<i>Treaty of Tlatelolco</i> - Prohibition of Nuclear weapons in Latin America and the Caribbean, Amended in 1990,1991 &1992	1968
<i>Seabed Treaty</i> - Prohibition of the Emplacement of Nuclear and other Weapons of Mass Destruction on the Seabed and the Ocean Floor and in the Subsoil thereof	1972
<i>ABM Treaty</i> - Limitation of Anti-Ballistic Missiles ). (**In 1997 Russia, Belarus, Kazakhstan & Ukraine assumed the Treaty obligations.)	1972
<i>SALT I Agreement</i> - Interim Agreement on Certain Measures with Respect to the Limitation of Strategic Offensive Arms	1972 not in force
<i>SALT II Treaty</i> - Limitation of Strategic Offensive Arms	
<i>Threshold Test Ban Treaty, TTBT</i> - Limitation of Underground Nuclear Weapons States	1990
<i>Peaceful Nuclear explosions Treaty, PNET</i> - Underground Nuclear Explosions for Peaceful Purposes	1990
<i>INF Treaty</i> - Elimination of Intermediate - Range and Shorter-Range Missiles	1998
<i>Treaty of Bangkok</i> - Southeast Asia Nuclear Weapon-Free Zone	1996
<i>CTBT</i> - Comprehensive Nuclear Test-Ban Treaty	1996 not in force
<i>Joint Statement on Parameters on Future Reductions in Nuclear Forces</i>	1997

<sup>2</sup> IAEA Additional Protocol 1997 - The aim of the Additional Protocol of the NPT is to reshape the IAEA's safeguards regime from a quantitative system focused on accounting for known quantities of materials and monitoring declared activities to a qualitative system aimed at gathering a comprehensive picture of a state's nuclear and nuclear-related activities, including all nuclear-related imports and exports. The Additional Protocol also substantially expands the IAEA's ability to check for clandestine nuclear facilities by providing the agency with authority to visit any facility-declared or not-to investigate questions about or inconsistencies in a state's nuclear declarations. NP, although the IAEA is urging all to do so.

<sup>3</sup> This is, of course, a somewhat over simplified description since there are a number of considerable technical hurdles to be overcome. For example, the high explosive lens materials require considerable refinement, moving away from the neutron absorbing highly hydronated and nitrogen based explosives since these are effective neutron absorbers which would inhibit the fissile stage; the timing of the neutron injection is absolutely critical, requiring arrival at the compressing fissile mass just when it has reached supercriticality; and, for a thermonuclear device, there are some very significant synchronising problems to be mastered in progressing the 'spark plug' fissioning at a rate to match the fusioning of the lithium-deuteride charges.

<sup>4</sup> Of the two types of nuclear warhead configuration, the fissile material deployed in the 'gun' type is generally limited to enriched U- 235. This is because the small Pu-240 content of plutonium masses (even the limited fraction in 'weapons grade' plutonium) precludes its use because of its high spontaneous neutron emission rate pre- detonates, destroying the fissile mass geometry before a full fission reaction can occur. The higher content of Pu-240 in reactor grade plutonium makes a successful Pu gun geometry even more difficult and, indeed, applies quite severe limitations on the upper yield of implosion designs utilising reactor grade plutonium. The United States is believed to have developed small diameter atomic weapons, suited for artillery shell casings, by fashioning the plutonium fissile component as a collapsible tube.

<sup>5</sup> Initially, Britain's plutonium was produced in the two Windscale atomic piles(graphite moderated, air-cooled low temperature reactors) which operated from 1952 but which were abruptly closed down in 1957 following the Windscale Fire. The plutonium production was transferred to the four Magnox reactors at Calder Hall (also at Windscale) but to meet increasing demand for plutonium, a series of Magnox civil power stations were ordered in the late 1950s and brought into operation from 1962 at Bradwell, Berkeley, Hinkley Point, Dungeness, Hunterston and Trawsfynydd, in addition to another four dedicated military plutonium Magnox reactors at Chapelcross, commissioned in 1959. It has been acknowledged that plutonium recovered from the irradiated fuel of the civil power stations supplemented the military or 'unsafeguarded' plutonium stockpile certainly through the 1960s and, possibly, into the early 1970s.

In fact the roots of Britain's nuclear industry, much like that of France, stem from and have been very much determined by its nuclear military needs. The UK nuclear industry centred around plutonium breeding and reprocessing and, to offset the enormous cost of reprocessing, it has vigorously sought overseas fuel contracts for its reprocessing plants. In fact, the currently operational Magnox reprocessing plant at Sellafield (Windscale) is openly acknowledged to be a dual capable plant, reprocessing batches of 'civil' power station irradiated fuel in parallel to short-burn irradiated fuel from the Calder Hall and Chapelcross reactors which are dedicated to plutonium production.

<sup>6</sup> For example, the acknowledged nuclear weapons states that have tested (which excludes Israel) have incurred development times to demonstration as follows:

COUNTRY	PROGRAMME COMMENCED IN EARNEST	FIRST NUCLEAR TEST	DEMONSTRATION PERIOD - YEARS
United States	1942	1945	3
Russia (USSR)	1944	1949	5
United Kingdom	1948 (some prior US collaboration)	1952	4+
France	Mid 1950s	1960	~6
China Republic	1961 (some prior USSR collaboration)	1964	4+
India	1964	1974	10
Pakistan	1972	1998	<15

<sup>7</sup> Basic Atomic Energy Act 1956

<sup>8</sup> Large J H, Maginac Y *Submission to the Inquiry Committee on Rokkasho Reprocessing Plant Comprehensive Inspection* [Rokkasho Saishori Shisetsu Soutenken ni kansuru Kentoukai], Meeting of 28 February 2004

<sup>9</sup> The reprocessing plant at Tokai in Ibaragi has been reprocessing spent fuel since 1981, though its operation was temporarily halted by a fire and explosion in March 1997. The Recycle Equipment Test Facility [RETF] is designed to reprocess plutonium produced in Monju and Joyo, Japan's two fast breeder reactors.

<sup>10</sup> On February 4, 1997, the Japanese Government's Cabinet Consent stated that it was necessary for Japan to promptly start utilizing MOX fuel in its LWRs – the plan was to commence MOX utilization in three to four reactors by 2000, and to increase its use in more than 10 reactors by 2010 but this has been subsequently revised to 16 to 18 reactors being loaded with MOX by 2010. although delays in this have been experienced by local opposition in the prefectures and from quality control of the MX fuel supplied by British Nuclear Fuels and which was shipped back to the United Kingdom in 2002.

<sup>11</sup> **FISSILE PLUTONIUM - AMOUNT PRODUCED/ EXTRACTED AT 31 MARCH 2004<sup>1</sup>**

	IRRADIATED URANIUM FUEL HMU TONNES	POTENTIAL PLUTONIUM IN UNREPROCESSED SPENT FUEL <sup>3</sup> TONNES	EXTRACTED PLUTONIUM TONNES <sup>2</sup>
Spent Fuel Pond Storage – various sites in Japan	12,000	71	
Reprocessed extracted at Tokai, Japan			5 extracted
Spent Fuel already reprocessed overseas	6,800		27 extracted overseas
Total Spent Fuel sent overseas for reprocessing	7,100		
Amount remaining to be reprocessed overseas	300	5	

Total already extracted			32 tons
Amount already consumed			3 tons
Total Plutonium/Spent Fuel Stockpiles	12,300	76	29

- 1) Data for 2003 business year.
- 2) Tabulated tonnages of plutonium are for the fissile content only as against the total Pu content which is the reporting requirement to the IAEA – total all Pu isotopes tonnage is about x1.35 figures cited.
- 3) Estimated Pu yield based on fuel irradiation (burn-up).

Derived from the 6 July 2004 response to Diet Question by Hidekatsu Yoshii

- 13 North Korea signed the NPT in December 1985 but it announced in March 1993 that it intended to withdraw from the treaty. In June 1993, North Korea suspended the decision to withdraw, following negotiations with the United States in which it won considerable economic concessions from the US and South Korea under the Agreed Framework for which North Korea agreed to halt activities at its plutonium producing nuclear reactors in Pyongyang in exchange for a relaxation of economic sanctions, fuel oil deliveries, and construction of a light-water reactor to replace the graphite-moderated reactor shut down at Pyongyang. Upon completion of the light-water reactors, originally scheduled for 2003 but subsequently indefinitely delayed, North Korea was to dismantle its graphite reactors and ship its 8,000 remaining fuel rods out of the country.
- 14 The centre of North Korea's nuclear program is at Yongbyon, some 100km north of Pyongyang. In addition to a 20 MWt reactor, Yongbyon's major facilities include a chemical separation (reprocessing) plant and a fuel fabrication plant. The 1994 Agreed Framework with the United States halted the construction of a 200 MWt reactor in Yongbyon, as well as the construction of a 700-800 MWt reactor near Taechon and, although North Korea pulled out of the agreement, there is no evidence that it resumed construction of either plant. North Korea also operates uranium ore processing facilities at Pyongsan and Pakchon.
- 15 Even if North Korea resumed work at these unfinished reactors it would take several years to complete construction and more time to operate them and reprocess the fuel.
- 16 Perhaps the greatest danger of all would be North Korea selling its plutonium, highly enriched uranium, or finished weapons to other countries or terrorists. Its track record with ballistic missiles is not encouraging. It has sold missiles to Iran, Yemen, Syria, and Pakistan--lucrative sources of income to the impoverished country. Fissile material and nuclear weapons would be even more lucrative and would have a far larger impact on regional and international security.
- 17 The Canadian government withdrew from the heavy water CIRIUS reactor following knowledge that the Indian nuclear test explosion was with a device that had bred its plutonium in a NRX clone, the CIRIUS reactor, and the US intervened in other dual capable deals including that for the purchase of a series of radioactive handling cells, supposedly for the post irradiated inspection of fuel (PIE) which are presently in use for the so-called DUPIC fuel cycle development programme (ie reloading modified spent PWR fuel into the CANDU reactors).
- 18 Kang J et al, *South Korea's Shifting and Controversial Interest in Spent Fuel Reprocessing*, Non-Proliferation Review, Spring 2001
- 19 Hibbs, M *Reprocessing Bid Change after Change to Centre on Ulchin Spent Fuel*, Nuclear Fuel 24, April 1999
- 20 President Roh Tae Woo's statement of November 1991
- 21 Heavy water moderated, the natural uranium fuelled CANDU is an efficient plutonium breeder, particularly in that the fuel can be accessed whilst the reactor is on load – the reactor also requires a heavy water plant and it is a rich source of tritium which can be used in the initiator stage of a fission device.
- 22 South Korea signed the Additional Protocol on June 21, 1999, and it entered into force on February 19, 2004. Until then, South Korea's nuclear activities were regulated under the provisions of the NPT and the standard IAEA safeguards arrangements, as well as by bilateral agreements with suppliers, particularly the United States. Following the Gulf War of 1991, the IAEA acknowledged the standard agreements of the NPT to be weak and that a more intrusive and uninhibited inspection rights were required, especially the right to collect environmental samples that would enable forensic radiochemistry to be used to determine what radiochemical activities had been conducted and when, requirements that were incorporated into the IAEA's model Additional Protocol adopted in 1999.  
Once South Korea ratified the Additional Protocol, it had 180 days to submit a detailed report to the IAEA with additional information about South Korean nuclear fuel activities and sites. The Additional Protocol enables the IAEA to conduct environmental sampling and to demand access to undeclared locations. It also obligates states to facilitate access to locations other than those they have identified, if the agency has specific information or needs to implement specific technical measures such as environmental monitoring.
- 23 In 1981, a five-pin miniature fuel assembly was irradiated in the then operable TRIGA III reactor in Seoul, subsequently removed for laboratory scale reprocessing which yielded about 40 milligrams or less of plutonium.
- 24 South Korea has now admitted it conducted two enrichment activities separated by about 20 years. In October 2004, South Korea told the IAEA that it had conducted a chemical enrichment experiment in 1979-1981 that it had not previously declared as required under its safeguards agreement. According to South Korea's explanation, the experiment aimed to assess whether chemical exchange could be used to produce low-enriched uranium (3 percent uranium 235) for pressurized-water reactor fuel. Using an ion exchange column, scientists enriched 700 grams of natural uranium powder to 0.72 percent uranium 235. The activity ceased in 1981.  
A decade later, South Korea began to apply laser separation technology to uranium. This activity built on elementary laser research undertaken in the 1960s and molecular laser isotope separation technology development in the 1970s and 1980s, obtained with Russian and American technical assistance. In 1990, South Korea began to develop the AVLIS laser enrichment technology and, around that time,

research also began spectroscopic work with uranium. From 1993 to 2000 at least 10 AVLIS-related experiments involving depleted uranium or undeclared natural uranium were conducted.

25 Notes for **TABLE 1:**

GENERAL	Data entries refer to status in 1998 and exclude closed down civil plants - established nuclear military plants are not necessarily included.
	Where known, the total installed capacity of plants is given in tU/year (uranium tonnes), which also applies to the <u>feed</u> of irradiated fuel tonnage to reprocessing and heavy water t/year output for deuterium (D2) plants. For civil nuclear power stations number of reactors followed by total power capacity in MWe. Research (R& D) reactors under 0.25MW output are not included. Tritium (H3) plants exclude low activity sources.
*	means that facility is listed as a civil plant
-	nothing recorded, although undeclared plant may exist
§	such a plant most probably exists but not declared
°	OR technology and 'know how' readily available where trading of materials and/or known or alleged nuclear technology exchanged between countries, prefix indicates source or exporting country as listed, but incomplete and generally excludes trading between established nuclear nations
	POTENTIAL indicates potential of country to transfer civil technology, plants and materials to nuclear weapons manufacturer <u>if it had the intent</u> assuming technical 'know how' acquired: <b>U</b> enriched uranium A bomb, <b>P</b> plutonium fissile pit A bomb, <b>DT</b> fusion boosted atomic stage, <b>H</b> thermonuclear capacity.

26 All of these uranium enrichment techniques rely of the physical fact that the velocities of molecules of different mass differ and that, the minuscule difference between U-235 and U- 238, gives the U-235 a slightly higher velocity, kinetic energy and, hence, pressure - this is used to differentiate and separate molecules either by diffusing these through a membrane (diffusion), skimming the outer layer of a rapidly rotating mix (centrifuge and vortex), or by targeting the higher velocity molecules of a distended jet (jet and Calutron). Since the enrichment gain produced by a single separation is very slight, a very large number of separations (hundreds and thousands with, as a result, enrichment plants covering large area of factory building, easily detectable by size from satellite and by gas discharge) are necessary for substantial enrichment. This requires the separator stages to be cascaded with, at each separator, about one half the feed gas passing through, no w slightly enriched, to be passed to the next higher stage for a repetition of the cycle. The gas that does not pass through, slightly depleted, is returned to the previous lower stage for repetition. At each cascade of stages, compressors and heat exchangers are stationed to maintain the temperature and pressure conditions required, these are energy intensive processes. For gaseous enrichment processes a gas plant to produce the uranium hexafluoride (UF<sub>6</sub>) feedstock is required.

27 Laser enrichment processes are well advanced but have yet to reach commercial-scale production stage. In the United States development of the Atomic Vapour Laser Isotope Separation (AVLIS) and the French process known as SILVA began in the 1970s, although development work towards a commercial plant seems to have ceased in both the United States and France.

Atomic vapour processes work on the principle of photo-ionisation - a powerful laser ionises particular atoms present in a vapour of uranium metal with an electron being ejected by light of a certain frequency. The laser techniques for uranium use frequencies which are targeted to ionise a U-235 atom exclusively from U-238 atoms. The positively-charged U-235 ions are then attracted to a negatively-charged plate and collected. A variation of laser separation is the molecular process which also centres on photo-dissociation of UF<sub>6</sub> to solid UF<sub>3</sub>. The only remaining laser process on the world stage is SILEX, an Australian development which is molecular and utilises UF<sub>6</sub>. In 1996 USEC secured the rights to evaluate and develop SILEX for uranium (it is also useable for silicon and other elements) but relinquished these in 2003.

This laser separation technique is also applied to finishing or separating small quantities of plutonium isotopes.

28 The depleted uranium (U238) by-product of the enrichment process can be used as part of the fissile core of a nuclear warhead, first to contain the nuclear process and, instants later, contributing to the fission energy release.

29 Plutonium is produced in a nuclear reactor by the U<sup>238</sup> capture of a neutron. The nuclear sequence requires, first, a fission of U235 in the reactor fuel to release a neutron, capture by U238, and transformation of this through a short-lived decay chain to the relatively stable Pu239 with a half- life of 24,300 years. So long as fissile and fertile material (U235 and U238) are available in the core, any reactor will produce a proportion of plutonium integrated within the fuel matrix. Since Pu239 is a fissile material it, once established, will also be subject to fissioning, so under the right conditions the Pu239 also transmutes to Pu240 which will subsequently be available to fission to Pu241 and Pu242. This interplay between the uranium isotopes and fissioning of the plutonium produces an exponential relationship in the decay and growth of U235 and Pu239 respectively in the reactor core over time. Essentially, the aggregate increase of Pu239 reaches a saturation point as the fission rate of the Pu239 increases, this is accompanied by a greater content of the other plutonium isotopes, whilst the U235 decreases down to a level at which the reactor requires refuelling to maintain criticality.

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

So called 'weapons grade' plutonium normally contains 7% or less Pu-240 at the time of production, essentially no Pu-238 (0.07%), about 92% to 93.5% Pu-239, and about 0.5% to 0.7% Pu241. The short half-life of Pu-241 (some 13.5 years) means that stockpiles plutonium will develop a significant amount of Americium-241 (from Pu-241 decay), so that typically a 13-year old plutonium source (which is roughly the

age of the plutonium in US and UK warheads) the proportion of plutonium and americium will be approximately 0.07% Pu-238, 6% Pu-240, 0.35% Pu-241, 0.35% Am-241 and the remainder Pu-239. The radioactivity of such 'aged' weapons grade plutonium is 0.09Ci/g or 11.1 g/Ci, about x1.47 more hazardous to health than pure Pu-239 and about one-quarter as hazardous as 'reactor grade' plutonium.

The quality of the plutonium for nuclear warheads is important but not vital. In the mid-1960s the United States developed and successfully tested a plutonium warhead in which relatively impure (> 7% Pu-240) reactor grade plutonium was utilised - this plutonium was extracted from fuel irradiated in Britain's civil Magnox nuclear power stations, which suggests that the Pu-240 content was no more than 12% if the then current commercial power station burn-fuel was the source of the plutonium.

- <sup>31</sup> In reactors that are designed for power generation and plutonium breeding, the core may be divided into two regions, an inner fuelled power section and an outer blanket which contains the fertile material - some research reactors utilising enriched uranium fuel cores are configured in this way. Neutrons produced by fission diffuse into the blanket and are captured by the fertile U-238 to produce Pu-239 which can be extracted or further fissioned in-situ if required. Neutron capture in the moderator, structural core materials and leakage from the core has to be reduced to a minimum to maintain a high breeding ratio. Graphite and heavy water moderated cores have a low capture cross section, so neutron absorption is low, whereas water (light) moderation (as in a PWR) has a high capture cross section reducing the breeding ratio which, with the difficulties of arranging on-load refuelling for PWRs, further detracts from the use of PWR and BWR designs for the dual capable role.
- <sup>32</sup> Currently, MOX fuels contain no more than 7% plutonium and MOX fuel should not be greater than one-third of the entire reactor core, so the equivalent plutonium 'enrichment' in a fully integrated MOX fuel core is a little over 3%.
- <sup>33</sup> Metal finishing of plutonium involves a number of processes, including precipitating plutonium peroxide and conversion to plutonium tetrafluoride by anhydrous hydrogen fluoride, calcium and iodine added for reduction to metal buttons which are pickled in a dilute nitric acid to remove slag and these are cast into gallium alloyed ingots by gravity or pre-machining shapes (hemispheres) in rapidly rotating moulds, thereafter the final pit component (two hemispheres) are precisely machined by cutting, bead blasting and/or electrolytic reduction to the final components which are surface plated to inhibit oxidation.
- <sup>34</sup> There are claims that a nuclear weapon could be fabricated from MOX fuel oxide, without reduction to a metal form and need to separate out the U-235/238 components. The only stipulation being that the MOX plutonium concentration should exceed 4%. Just how a supercritical fissile mass could be achieved with such a voluminous and lightly fissile material is obscure and, even if it could, the amount of mixed oxide required would be enormous.
- <sup>35</sup> During the staging a small proportion the feedstock undergoes hydrolysis to form a solid uranyl fluoride compound, which depletes the enrichment, and, similarly, some of the uranium hexafluoride converts to uranium pentafluoride (by loss of an atom of fluorine), again depleting the enrichment particularly in the higher level stages. Also, a small amount of adsorption involving the deposit of uranium hexafluoride on the surfaces of the vessels and interconnecting piping occurs, which although small per unit area, totally it is a significant loss since the thousands of stages making up the plant represent many square kilometres of exposed surfaces.
- <sup>36</sup> There are two means of expediting uranium enrichment, these are 'stretching' and 'recycling', both of which break down the normally continuous process into batches. In stretching the cascade flow is 'blocked' by lowering the differential pressure over the stage, this increases the enrichment level of each stage but reduces the flow rate, thus lengthening the overall processing cycle time to obtain very small amount of enriched product. In recycling, the outputs of several cascades are reintroduced as feed to a single cascade, again this is time consuming and can create criticality problems.