Beyond A.Q. Khan

The Gas Centrifuge, Nuclear Weapon Proliferation, and the NPT Regime

■ Alexander Glaser

The recent exposure of an operating supplier network around the Pakistani scientist A.Q. Khan has propelled the front-end of the nuclear fuel cycle back into the center of the non-proliferation debate. The ongoing debate is focused upon measures that emphasize export controls and technology denial as a primary means to halt nuclear proliferation.[1] These are insufficient or even inadequate proposals because they address only part of the problem. The gas centrifuge for uranium enrichment is a highly proliferation-prone technology. Nonetheless, its large-scale commercial use has never been seriously discouraged. Indeed, the centrifuge plays an increasing role in the enrichment industry and all facilities recently built, under construction, or planned are based on centrifuge technology. In 2001, for the first time, a larger enrichment capacity was provided by centrifuges than by the gaseous diffusion process.

As will be argued below, the fact that advanced centrifuge technology has been developed and deployed in various regions of the world without having a competitive technological alternative to it, may become a central dilemma for future nuclear energy use – unless an internationally acceptable and non-discriminatory supply system can be devised and agreed upon.

Centrifuge Technology

The development of centrifuges for isotope separation began in the 1930s and had already been considered for uranium enrichment during the Manhattan project. In the early days, the technology was not competitive with alternative enrichment processes, because huge facilities based on the gaseous diffusion process were already under construction or operational and no further capacities were needed. Nonetheless, development of the gas centrifuge continued after World War II, especially in the Soviet Union, but later also in Western Europe and the U.S. With the installation of significant capacities in the U.K., the Netherlands, and Germany since the 1970s and the technological advances that came along with the associated research and development programs, the modern gas centrifuge gradually became the workhorse of the international enrichment industry. Table 1 lists centrifuge facilities worldwide and their respective operational status.[2]

In essence, the gas centrifuge is a rapidly rotating, vertically oriented rotor, into which a uranium-containing gas (UF_6) is injected. Once following the motion of the wall, the gas molecules experience an enormous centrifugal force and accumulate on the inner surface of the rotor. Based on an elementary physical effect, the relative abundance of the lighter uranium-235-containing molecules increases with distance from the wall due to the mass difference of the two relevant uranium isotopes. This effect can be used to extract a product from the machine that is slightly enriched in the desired isotope.[3] In practice, several thousand machines have to be connected in parallel to generate significant uranium throughput and connected in series to achieve adequate enrichment of the product – a configuration called cascade.[4]

The Safeguards Approach to Centrifuge Facilities

The first enrichment facilities in the world were built for military purposes and, hence, designed and used for HEU production. These facilities were unsafeguarded then and usually still are so today. Until the mid-1970s, supply of enrichment services for

Country	Location/Name	Status	Start-Up	Capacity
Brazil	BRN Aramar	Operational	1992	5 tSWU/y
	BRF Aramar	Operational	1998	4 tSWU/y
	Resende	Under Construction	2004	120 tSWU/y
China	Shaanxi	Operational	1997	200 tSWU/y
	Lanzhou 2	Under Construction	2005	500 tSWU/y
France	GBII Tricastin	Planned	?	7,500 tSWU/y
Germany	Jülich	Operational	1964	Laboratory
	Gronau	Operational	1985	1,800 tSWU/y
India	Rattehalli	Operational	1990	3—10 tSWU/y
Iran	Natanz	Under Construction	?	?
Iraq	Al Furat	Destroyed in 1991	—	—
Israel (unconfirmed)	Dimona	Operational	1980	Pilot scale
Japan	Ningyo-Toge	Shutdown in 2004	1979	75 tSWU/y
	Ningyo-Toge	Shutdown in 2004	1989	200 tSWU/y
	Rokkasho	Operational	1992	1,050 tSWU/y
Libya	?	Abandoned in 2004		
Netherlands	Almelo	Operational	1973	2,200 tSWU/y
North Korea	?	Under Construction	?	
Pakistan	Kahuta	Operational	1984	5 tSWU/y
Russia	Sverdlovsk	Operational	1949	7,000 tSWU/y
	Seversk	Operational	1950	4,000 tSWU/y
	Angarsk	Operational	1954	1,000 tSWU/y
	Krasnoyarsk	Operational	1984	3,000 tSWU/y
U.K.	Capenhurst	Operational	1972	2,300 tSWU/y
US	Portsmouth	Awaiting license	?	Pilot scale
	?	Planned	?	?

Total centrifuge capacity operational in 2004	~ 23,000 tSWU/y
Total enrichment capacity available in 2004 (all processes)	~ 53,500 tSWU/y
Total enrichment capacity required in 2004	~ 35,000 tSWU/y

Table 1: Centrifuge enrichment facilities of the world.

commercial purposes was monopolized by a few nuclear-weapon states. Only then it became obvious that non-nuclear-weapon states, namely some Western European countries with advanced nuclear programs, would aspire and acquire independent enrichment capacities, which would be placed under safeguards.

For these reasons, work on safeguards procedures on enrichment facilities started relatively late and was then focused on centrifuge facilities, the main candidate to be covered by safeguards. Furthermore, studies carried out under the auspices of the IAEA in the 1970s revealed that no simple safeguards concept existed that would be adequate for centrifuge enrichment facilities.[6] This is mainly due to the fact that centrifuge facilities show a high degree of operational flexibility, which complicates safeguards procedures in general. At the same time, they do also involve sensitive technologies, which is why technology holders have been generally concerned that design information might be compromised by visual access to the machines. Unsurprisingly, the question of whether or not inspectors would have access to the cascade halls at all was subject of considerable debate during negotiations on safeguards concepts for centrifuge facilities. The original safeguards concept developed specifically for centrifuge facilities under an INFCIRC/153-type agreement emerged from the discussion and analysis of the Hexapartite Safeguards Project (HSP) that convened from 1980 to 1983. In essence, the HSP approach, which became the *de facto* standard for centrifuge facilities since then, envisions two conceptually different activities:

- Activities outside the cascade halls are primarily based on "conventional" safeguards practices and are focused on material accountancy to deter or detect diversion of declared material.
- Activities inside the cascade halls are used to verify that no material beyond the declared enrichment level, and in particular no HEU, is being produced. Access to the cascade areas is governed by the so-called Limited Frequency Unannounced Access (LFUA) concept, which regulates delay and maximum duration of the visits, as well as permitted activities of the inspectors.

More recently, safeguards techniques applied in centrifuge facilities have been extended by Environmental Sampling (ES) or High Precision Trace Analysis (HPTA). Approved by the IAEA in 1995 and used on a routine basis since then, the method consists in the collection of deposited particles with swipe samples, usually taken during inspections of the cascade areas along the agreed access routes. Subsequently, these samples are analyzed off-site allowing extremely accurate determination of the composition of the feed and product material. This method is a formidable tool to identify traces of HEU in general and has been extremely successful so far. As a result, clandestine production of HEU in a safeguarded declared facility has become an extremely risky undertaking for a potential proliferator as it is effectively doomed to be uncovered sooner or later.

Proliferation Challenges

Uranium enrichment technology has always been recognized as a highly sensitive technology.[7] Indeed, it is the only technology used in the civilian nuclear fuel cycle whose technicalities were not shared within the Atoms for Peace program – contrary to the details of plutonium reprocessing. While some enrichment processes are more proliferation-prone than others, the main barrier preventing a faster spread in the past was the difficulty to master enrichment technologies, a feature inherent to all known processes. Possible proliferation risks associated with enrichment technologies in general, and with centrifuge technology in particular, are listed in Table 2.

Only one category of proliferation and diversion scenarios for enriched uranium are addressed by traditional safeguards measures applied in declared facilities under an INFCIRC/153-type agreement. Current safeguards standards are very effective in verifying that no declared material has been diverted and that no HEU has been or is being produced in the facility – the latter aspect strongly benefitting from the environmental sampling techniques introduced in the 1990s and supplementing the somewhat limited LFUA concept.

However, current safeguards procedures are based on the fundamental assumption that no undeclared material is processed in the facility – and they are not designed to detect such an activity. To address this issue, one could require additional surveillance in the facility or install instruments monitoring uranium flow and enrichment on a continuous basis.[8] Such a strengthened safeguards approach would require revision and a negotiated upgrade of the existing one.

Detection of Undeclared Facilities

With covert HEU production in a safeguarded facility becoming more difficult to conceal effectively, the construction of undeclared facilities ironically becomes more attractive or "inevitable" for a potential proliferator. Clearly, detectability of such facilities would be highly desirable – but the experience made recently in Iran points in a different direction.

The main concerns specific to centrifuges relevant in this context are their low energy consumption and the small process area compared to alter-

	Declared Facility	Undeclared Facility
Covert (operation as declared)	Diversion of LEU (abrupt or protracted)	Production of HEU (possibly using LEU feed)
Covert (with modifications)	Excess LEU production (or production of HEU)	
Overt	Break-out scenario	

Table 2: Proliferation scenarios associated with enrichment technology

native processes in use today, namely gaseous diffusion: the footprint of a centrifuge facility large enough to produce 25 kg of HEU annually is about 600 square meters and its energy consumption would be less than 100 kW.[9] Both numbers indicate that detection by satellite remote-sensing techniques is virtually impossible. Another option to detect an undeclared nuclear facility would be to use wide area environmental monitoring (WAEM) to collect characteristic particle samples emitted by the plant. Note, however, that an enrichment facility based on the centrifuge process uses equipment operated under high-vacuum conditions. Leaks primarily lead to an inflow of air into the centrifuge equipment, not to a significant release of gas molecules from the system. Even though the presence of uranium-containing particles in any operational or previously operational facility can be detected inside the building with the above-mentioned sampling techniques, for plausible reasons, a centrifuge facility is no major emitter of characteristic signatures that would be readily detectable via WAEM.

Again, safeguards are obviously not designed for this category of proliferation scenarios. The provisions in the IAEA Additional Protocol do however facilitate detection of undeclared facilities substantially, although not necessarily in a timely manner.

Breakout Scenario

Finally, an existing and declared enrichment facility may be used for overt HEU production in a breakout scenario. The use of nuclear technologies under national control for this proliferation path can never be excluded once a political decision has been taken to violate a safeguards agreement or related international treaties, to which the country is a party. Nonetheless, contrary to other enrichment processes, a centrifuge facility can be reconfigured and used to produce HEU without delay – a fact that is obviously of serious concern in the present context.

Due to the high separation factor of a modern gas centrifuge, only a small number of stages is required to enrich uranium to significant uranium-235 fractions. The hold-up time of the material in each stage reportedly is in the order of 10-20 seconds and, as a consequence, the total mass of uranium (as UF_6 gas) present in the cascade is extremely low, typically between several 100 grams and one kilogram.[10] A low inventory is equivalent to a short period required to achieve a new enrichment level, which typically is in the order of one hour. It should be emphasized that alternative enrichment processes, like the gaseous diffusion process or the chemical exchange process – the latter studied in the 1980s – have equilibrium times in the order of several months or even years, which makes facilities based on these processes rather unattractive assets to rely upon in a breakout-scenario compared to the alternative plutonium-extraction route.

What Can Be Done About It? Moving Beyond Traditional Frameworks

For the above reasons, in many circumstances, even a comprehensive safeguards approach may be considered inadequate to address all proliferation risks associated centrifuge technology. As a remedy, the idea of multinational operation of sensitive nuclear facilities – or even of an internationalized nuclear fuel cycle – comes to mind. This idea is not new. In fact, the concept was invoked in the earliest days of post-war organization of atomic energy.

To begin with, it is worthwhile to examine existing arrangements and assess their non-proliferation impact. Both existing multinational arrangements for uranium enrichment, Urenco and Eurodif,[11] were not designed with non-proliferation criteria in mind, but mainly to minimize and share economic risks involved in developing enrichment technologies able to compete with existing U.S. supplies. It is not surprising, therefore, that these arrangements do not hold out very well against an analysis of non-proliferation criteria. Table 3 compares both arrangements with respect to their non-proliferation attributes using a set of criteria based on an earlier analysis.[12]

A detailed discussion of multinational concepts is beyond the scope of this article,[13] but the single most important criterion from the non-proliferation perspective is the requirement that multinationally operated fuel cycle facilities have to be a substitute of, rather than an addition to, corresponding facilities under national control. Otherwise, the virtues of multinational operation are almost entirely lost. This is obviously the most fundamental flaw of the Urenco arrangement since each participant carries out national centrifuge research and development – and each partner ultimately built its own enrichment facility.[14]

Nonetheless, multinational facilities, even "poorly" designed arrangements, have indisputable and important virtues – and even though they are no stand-alone solution to address emerging proliferation concerns, they may represent the only approach capable of minimizing proliferation risks in the long-term, especially if the criteria of Table 3 are applied when such arrangements are set up.

Urgent Action Needed

Any future energy scenario partially based upon nuclear energy will require large-scale operation of enrichment facilities. As shown above, the modern gas centrifuge, which is the favored enrichment technology today and already dominates the market, is highly proliferation-prone and difficult to safeguard and detect.

Nonetheless, the U.S., France, and China are gradually abandoning their gaseous diffusion plants and plan to replace them with centrifuge facilities. Capacities in the original Urenco countries are being expanded and additional countries, often without significant domestic nuclear programs (like Brazil or Iran), are independently pursuing centrifuge development. It is therefore likely that a growing number of countries will have access to centrifuge technology in the near future. Unfortunately, no alternative enrichment processes with more favorable non-proliferation characteristics have been seriously considered since the

1970s and, hence, no alternative technology can compete economically with the gas centrifuge today. Finally, we might also witness an erosion of the technological barriers that slowed down the spread of centrifuge technology in the past.

The response to this dilemma has to be manifold – envisioning both short-term and long-term strategies. First, in addition to measures that are taken as a response to the exposure of the A.Q. Khan network, the current safeguards standards should be revised and substantially upgraded. Reluctance of those already operating safeguarded facilities to do so is predictable, but it will be key to convince all parties involved that the objectives are of utmost importance – and also in their own best interest.

France and the U.S., both planning to build new enrichment facilities based on the centrifuge process, must set positive examples in this respect and design their facilities safeguards-friendly from the ground up.

In the longer term, these measures alone will not be sufficient. With centrifuge technology in widespread use, we are apparently reaching a limit where national control plus international safeguards becomes an unacceptable compromise. The Director General of the IAEA, M. ElBaradei, in his Statement to the Fifty-Eighth Regular Session of the United Nations General Assembly on November 3, 2003, emphasized this important aspect: "In light of the increasing threat of proliferation, both by States and by terrorists, one idea that may now be worth serious consideration is the advisability of limiting the processing of weapon-usable material (separated plutonium and high enriched uranium) in civilian nuclear programmes – as well as the production of new material through reprocessing and enrichment – by agreeing to restrict these operations exclusively to facilities under multinational control. These limitations would naturally need to be accompanied by appropriate rules of assurance of supply for would-be users."

Are such proposals realistic? – Most think that they are not. Nonetheless, previous fruitless discussions of multinational or international fuel cycle arrangements were focused on reprocessing facilities, including plutonium and waste storage. Especially, the Western European countries were suspicious about such initiatives in the 1970s and 1980s, at a time when they were expanding their nuclear programs or exports.[15]

	Urenco	Eurodif
Only NPT parties	Yes	Yes (was: No)
Governmental participation	Yes	No
International safeguards	Yes	Yes (was: No)
Withdrawal exclusion	No	No
Prohibition of national control	No	No
Multinational R&D only	No	No
One facility	No	Yes
Prohibition of technology transfer	No	No
Exclusion of internal technology sharing	No	Yes (in theory)
HEU production exclusion	No	No
Proliferation-resistant process	No	No (was: Yes)

Table 3: Non-proliferation criteria applied to the Urenco and Eurodif frameworks

Today, there is certainly a higher level of convergence of international nuclear fuel cycle policies, less economic competition on the international export market for nuclear technologies, and broader acceptance of nuclear supplier guidelines. More generally, in the political arena, there is now nearly universal support of the NPT and a strong sense of urgency that the regime has to be strengthened. If the A.Q. Khan incident served as a wake-up call for the international community to get such a discussion started, something useful could ultimately emerge from the current crisis of the NPT regime.

The prospects of internationalization and progress in nuclear disarmament are closely related. The recent renewed interest of the U.S. in new nuclear weapons, the possibility of resumed nuclear testing, and the new nuclear posture are undermining any possible progress in the area of reducing the military relevance of nuclear weapons – and hence also, of a more internationalized structure of the nuclear fuel cycle.

1 This strategy is exemplified in U.S. President G.W. Bush's speech given at the National Defense University on February 11, 2004, articulated in the following excerpt: "The world's leading nuclear exporters should ensure that states have reliable access at reasonable cost to fuel for civilian reactors, so long as those states renounce enrichment and reprocessing. Enrichment and reprocessing are not necessary for nations seeking to harness nuclear energy for peaceful purposes. The 40 nations of the Nuclear Suppliers Group should refuse to sell enrichment and reprocessing equipment and technologies to any state that does not already possess full-scale functioning enrichment and reprocessing plants."

2 Data for centrifuge facilities retrieved from IAEA Integrated Nuclear Fuel Cycle Information System (iNFCIS) in March 2004, except for the case of India and the unconfirmed case of Israel.

3 In addition to the radial effect, an axial flow of the gas along the rotor is established, which substantially increases the separative power of the centrifuge and also allows for convenient extraction of product and waste at the ends of the rotor.

4 There exists an extensive literature on isotope separation and cascade theory, cf. for instance: D. G. Avery and E. Davis, *Uranium Enrichment by Gas Centrifuge,* Mills & Boon Limited, London, 1973; or S. Villani, *Isotope Separation,* American Nuclear Society, 1976.

5 See footnote 2.

6 For a discussion, see: A. von Baeckmann, *Implementation of IAEA Safeguards in Centrifuge Enrichment Plants,* Proceedings of the Fourth International Conference on Facility Operations-Safeguards Interface, September 29 – October 4, 1991, Albuquerque, New Mexico, pp. 185-190.

7 A. S. Krass, P. Boskma, B. Elzen, and W. A. Smit, *Uranium and Nuclear Weapon Proliferation,* Stockholm International Peace Research Institute (SIPRI), Taylor & Francis

Ltd, London and New York, 1983. For a comparison of different enrichment processes, see p. 19, Table 2.1.

8 For instance, flow rates and enrichment levels are monitored in the Chinese Shaanxi enrichment facility, which uses Russian centrifuge technology. For a detailed discussion, see: A. Panasyuk, et al., *Tripartite Enrichment Project: Safeguards at Enrichment Plants Equipped With Russian Centrifuges,* IAEA-SM-367/8/02, 2001.

9 About 6000 separative work units (SWU) are needed to produce 25 kg of weapon-grade HEU from natural uranium. As can be inferred from aerial views of existing centrifuge facilities, the specific capacity of typical plants is 10-20 SWU/yr per square meter of the facility's total footprint. Urenco quotes 40-50 kWh per SWU for its advanced technology.

10 See Krass, op. cit., p. 45 and p. 133 (Table 6.2), for exemplary numerical data.

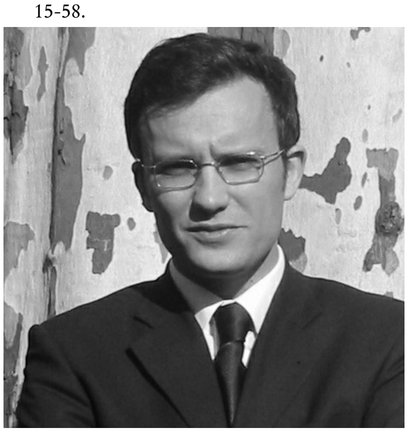
11 The Urenco and Eurodif frameworks are discussed in: L. Scheinman, *Multinational Alternatives and Nuclear Nonproliferation,* International Organization, Vol. 35, No. 1, *Nuclear Proliferation: Breaking the Chain,* Winter 1981, pp. 77-102.

12 Krass, op. cit., p. 71 (Table 3.1).

13 See for instance Scheinman, op. cit., for an excellent discussion of virtues and limits of multinational frameworks.

14 The concept did not solve the problem of dissemination of centrifuge design information. Urenco involuntarily became a source of centrifuge technology for proliferating states, namely directly in the cases of Pakistan and Iraq – and from Pakistan to some other countries.

15 For a contemporary discussion, see: J. S. Nye, *Maintaining a Nonproliferation Regime;* and P. Lellouche, *Breaking the Rules Without Quite Stopping the Bomb: European Views.* Both in International Organization, Vol. 35, No. 1, *Nuclear Proliferation: Breaking the Chain,* Winter 1981, pp. 15-58.



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