SIGMA, THE NOVEL APPROACH OF A NEW NON-PROLIFERATING URANIUM ENRICHMENT TECHNOLOGY

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ABSTRACT

The SIGMA concept, under development by Argentina, represents the evolution of the Uranium Enrichment Gaseous Diffusion technology, updated to face the challenge of the new economic-based and competitive world frame. The Enrichment technology has been historically considered as a highly proliferating activity in the nuclear field, and central countries have limited the access of the developing countries to this technology. The SIGMA concept incorporates innovative proliferation resistant criteria at the beginning of the design process, and inherits all the non-proliferation features of the Gaseous Diffusion Plants (GDPs). The radical new proliferation resistant approach of the SIGMA technology, suggest a new kind of global control of the Uranium Enrichment Market, were some developing countries might access to an Enrichment plant without accessing to the technology itself. In this paper, we analyse the economy of the SIGMA plants, and the implications of this technology on the Uranium Global Market.

INTRODUCTION

Uranium Enrichment Technologies

Overview

As long as the main isotopic component found in the Natural Uranium is the U^{238} (a non-fissile isotope), the Natural Uranium must be processed to act as nuclear fuel, enriching its contain of U^{235} (the fissile isotope). The Uranium could be processed to different enrichment degrees, for being used in different processes.

The Enriched Uranium with more than 2% of U^{235} could be used in a Nuclear Power Plant (NPP), moderated and cooled by Light Water (PWR). The PWR Technology is the world dominant Nuclear Reactor design, for nuclear electric power plants (NPPs).

The Heavy Water Reactors (HWR) constitutes the other main Reactor Technology. Even though the HWR were designed to be fueled by Natural Uranium, it is a fact that the use of Slightly Enriched Uranium (SEU) improves the economical behavior of this kind of NPPs.

Thus the Uranium Enrichment Technology represents the basis of the civil nuclear industry, as the Enriched Uranium is the primary fuel virtually used in almost every nuclear reactor constructed in the world.

But the Enriched Uranium it is also used with military proposes, and historically this has been the driving force for the Enrichment technology development.

The use of Highly Enriched Uranium (HEU) in the nuclear devices is a conditioning fact, which has influenced the Uranium market in the world since the beginning.

The first method developed for Uranium Enrichment was made by the USA, in the Manhattan Project. The method was the Mass Spectrograph Isotope Separation Technology, based in an electromagnetic principle. This technique is simple and has a great separation factor, but uses a huge amount of expensive materials and electricity.

The Gaseous Diffusion Technology (GDT) was also developed within the frame of the Manhattan Project, surviving until our days. The GDT is the historically dominant technology in the Uranium Enrichment field, with more than a half of the Enriched Uranium produced in the whole Nuclear Industry history.

Nowadays, the Gaseous Diffusion Technology represents the 62% of the total installed capacity of enrichment services over the world.

Other technology that has reached industrial maturity is the Ultra Centrifugation Method (UCM). It was developed at first by the former Soviet Union, in the early 50's. This method represents the actual competitor for the GDT.

The UCM is less expensive at a lower scale of production. This economical behavior is a competitive advantage, especially in a competitive and non explosive-expanding market of enrichment. Even though, the UCM has a Separative Work Unit (SWU) cost distribution with a great component of capital investment.

Another methods have been also studied (chemicals, aerodynamical and LASER techniques), but none of them have reached industrial maturity and only work in a laboratory environment. Even more, some projects have been recently canceled (one of them is the Atomic Vapor Laser Isotope Separation, AVLIS). The AVLIS method was the hi-tech promise for an easy and cheaper enrichment technology, but it could not reach the industrial scale.

This technological status of the enrichment market leads in a world scenario where the actual production plants are in its end of life, and none of the technologies with industrial maturity reaches the economical and technical features required in this open and competitive world frame.

The replacement of the Enrichment plants imply investments in the order of 10 to 20 billions dollars in the next two decades, and the UCM is being take as the least bad option for the actual plants renovation.

Gaseous diffusions plants

The GDT stands on the statistical process of Uranium gas passing trough a porous membrane. The gas used for this process is the Uranium Hexafluoride (UF_6), because of its termophysical properties and the existence of only one isotope of Fluor. This gas is very toxic and corrosive.

Even though the GDT is not a complex technology, some main issues are not so easy to be developed. The mayor technological challenge of the GDT is the development of the porous membranes.

The corrosiveness and toxicity of the gas used generates some others technological problems to be also solved: materials, sealing junctures, security requirements, compressors, etc.

As the enrichment factor of the GDT is very low, is necessary to amplify the separative effect by connecting the diffusion stages in a cascade configuration. The GDP is then made-up of thousands of stages, each one having a diffusion unit (set of membranes), one or two compressors, and a heat exchanger.

The Figure 1 shows a typical cascade configuration. The construction of the GDPs started during World War II to produce enriched uranium for defense purposes. These plants were used primarily for this purpose through 1964. From 1959 through 1968, uranium enrichment production shifted primarily to supply the nuclear power industry. Nowadays, the GDPs produces the most part of the enriched uranium in the world. Increase in capital charge, electric power supply and interest rates, shifted competitiveness to centrifuge enrichment Plants.

This economic behavior is mainly produced by the component scale economy as compressor efficiency decrease at low flow stages. A GDP cascade has thousands of stages in series in which higher enrichments have lower mass flow. The smallest flow stages are the most expensive per SWU (higher component costs with less compressor efficiency). Thus a GDP will be competitive when the smallest stages are competitive, and this usually happens in GDP cascade configuration for a 3 MSWU/year capacity (Figure 2).

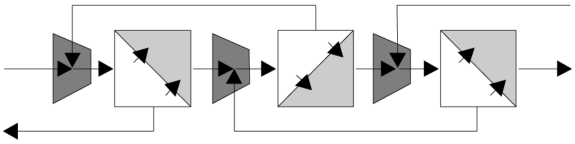

FIGURE 1. Process scheme of a GDP cascade

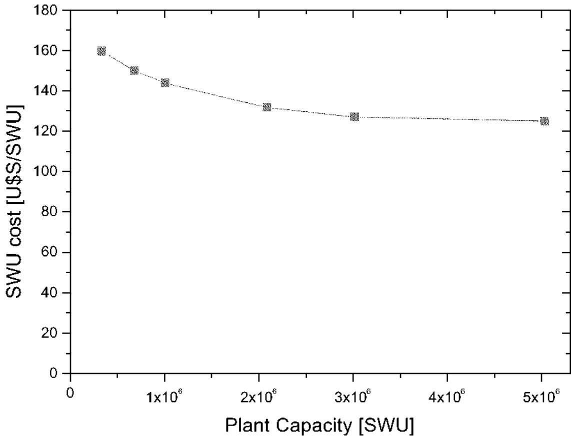

FIGURE 2. Gaseous Diffusion Technology Scale Economy: Cascade Paradigm

This behavior could be seen as a cascade paradigm, because is generated for the cascade concept itself, with small dependence on technology.

Argentinean Enrichment Project

Since the Atom for Peace meeting in 1948 until the India's nuclear explosion in 1964, Argentina received a wide technological cooperation from the developed countries in the nuclear field. With this international cooperation, Argentina could develop its own experimental and irradiation reactors, plants for Uranium concentration and could built the first NPP of Latin America: The Atucha I nuclear power plant.

With the India's explosion, all the technological assistance of the central countries was unilaterally canceled, even the contracts in force. All the nuclear installations were compelled to be under international safeguards, also those developed by the own country.

This change in the political rules, affected not only the technological assistance, but also the critical nuclear products supply. The new nuclear political order also introduced bigger restrictions in the development of critical processes by the non nuclear weapons possessor countries. For example it appeared restrictions in reprocessing and heavy water technologies. Even more, there were some new conditionings about what kind of nuclear fuel cycles should be used (no plutonium-based fuel cycles were contemplated as a valid option).

Due the development reached in the experimental reactor construction, Argentina contended for the first time in an international bid carried out by Peru, for a whole Atomic Center, with a nuclear reactor included.

In 1977, the Peruvian government selected Argentina for the construction. The Atomic Center was built in time, but the supply of the nuclear core could not be assured by Argentina, because of the negation of the western suppliers countries. In the same way as some European countries, Argentina found an alternative supplier in the former Soviet Union.

According to the new role of experimental nuclear reactors supplier, Argentina needed to be capable to offer all the fuel cycle stages.

That was the reason why Argentina started its own development of the enrichment technology (Castro Madero, 1990).

Up to that moment, the only proved technology reachable in the short term by Argentina was the GDT. The objective of the Argentinean Enrichment Uranium Project was to develop and construct a facility to obtain LEU for its own NPPs and 20% enriched Uranium for the future exportations of experimental nuclear reactors.

The project was top secret, and the international announce was made in 1983, when the pilot plant, sited in Pilcaniyeu, was finished.

Within the frame of this project, Argentina have developed not only the GDT itself, but also the related necessaries technologies, as the seals junctures, the special oils, the plant instrumentation, the UF_6 conversion plant, etc.

With the assurance of the whole fuel cycle, Argentina is now considered as a reliable nuclear supplier, and contends in the same hierarchy with the developed countries in the internationals bids, for the construction of experimental and irradiation nuclear reactors.

Since a few years ago, a new generation of Argentineans nuclear-related technology designers, have been working in a radical new improvement of the classical methods of enrichment, and has reached a new and innovative method for Uranium enrichment: The SIGMA concept.

SWU FUTURE MARKET AND ACCEPTANCE CRITERIA

Future Demand

Nowadays, an over-offer of enrichment services are available over the world, but a great percentage of the installed plants are just in its last operation years.

It can be estimated that the actual GDPs will be out of service in next two decades, beginning with the Americans, and followed by the Chinese and the Russian (2005-2010) and then the Europeans (2020). That leads in a fall of the enrichment services offer, that can not be alleviated with the enter of the HEU from the disarmed nuclear devices.

Comparing this situation with the Enriched Uranium demand, it can be see that the growing demand will overcome the offer between the years 2005 and 2010.

Figure 3 shows the projected development of the Uranium enrichment services offer and demand, according to a study made by IAEA (Wagner, 1997).

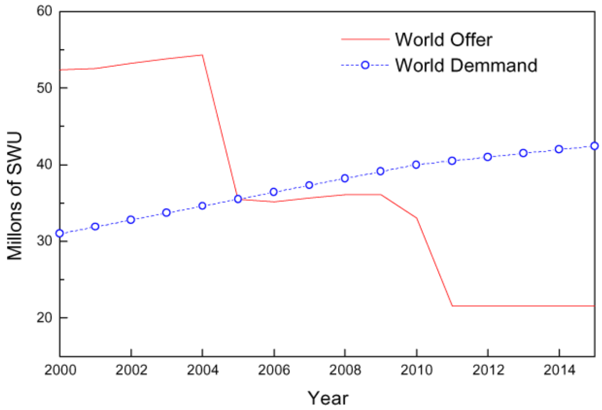

FIGURE 3. Projected offer and demand of SWU, for the next decades

Making a more detailed analysis, and grouping the demand in:

- Developed Countries.
- Eastern Europe Countries.
- Developing Countries.

It is not projected a significant increment in the SWU demand in the first two groups (Figure 4) for the period 2000-2050. On the other way, a great grown is visible in the developing country demand (China, Asiatic Southeast, Latin America, South and North Africa and Middle East).

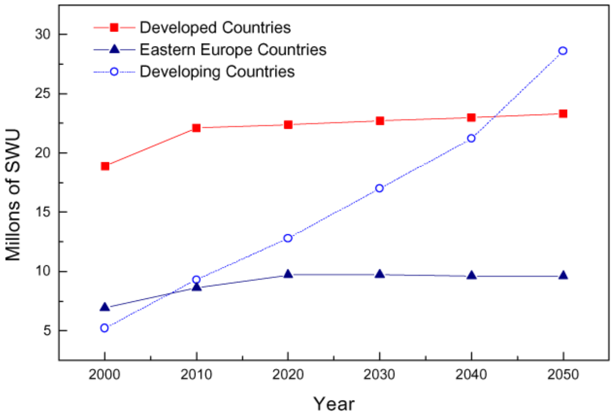

FIGURE 4. Projected demand of SWU, analyzed by groups of countries

Even more, this demand would overcome the developed countries demand, between 2040 and 2050.

The increment in demand of SWU is constant, and 4Millons of SWU are required every 10 years. This growing demand is equivalent to an inversion of 2.7 MU$S in the same period.

Nowadays, almost all the enrichment services are located in developed countries, and have been also used for military purposes. Even more, the central countries has constantly pressured to block the access of the developing countries to critical technologies, including the Uranium enrichment.

In the future, with the demand focused in developing countries, a serious problem will appear in central countries: Where will be the next generation of Enrichment plants? And who will pay the installations cost?

In this scenario, the market forces will interfere with the political constrains, related with the non-proliferation issues and commercial interests.

Even worst, the designers, trying to improve the economics for the new generation of enrichment technologies, looks to increase the separative factor and reduce the Uranium hold up, increasing the potential proliferation risk of all these new future technologies (Silvennoinen, 1986) (Ahmed, 1982).

Merits Factors for the next generation of Enrichment Plants

Having in mind the possible future scenario for the enrichment market, and analyzing the characteristics of the actual plants, it is easy to outline the main features that should an enrichment technology have to be considered as a replacement of the nowadays plants.

It is remarkable that all this conditions are determined by the competitors and the market itself but not by the designers. In the economical point of, and keeping in mind that the actual cost of the enrichment services is about U$S 120 per SWU, an enrichment technology should fulfill the following requirements:

- The total cost of the SWU should be less than the half of the present cost (less than 60 U$S/SWU).
- The highest cost for the electric consumption should be less than 30 U$S/SWU.
- The capital costs should be lower than 60 U$S/SWU.
- The O&M costs should be lower than 10 U$S/SWU:
- The availability factor should be greater than 95%.
- Economic plant capacity: less than 500,000 SWU.

On the other hand, non proliferation considerations should be included in the analysis. Since the nuclear devices constitute a global threat, if the market forces the installation of the plants in a non nuclear weapon owner country, this country should be controlled by the international community, with the natural repercussion of new political instabilities and consequences.

A new enrichment method, with intentions of being accepted as the next dominant technology for the future world market, should consider the non-proliferation problem as a key issue. In order to reduce the proliferation risk, some goods features are:

- High Uranium hold-up.
- Long time transients.
- Simple and useful safeguards methods for holdup control.

The NDA techniques assure the plant owner's confidentiality, and allow an actual control of the enriched Uranium hold-up.

SIGMA CONCEPT

Introduction to the SIGMA Technology

The gaseous diffusion technology developed by Argentina in the late 70’s operated successfully, but nowadays it cannot compete with the Ultra Centrifuge Plants (UCP).

The GDT presents a robust and simple operation, but it only reaches competitive prices at huge industrial sizes and relative high energy consumption. On the other way, The UCP reaches competence at a much lower scale, with modular plants and moderated investments.

This behavior is related with the cascade paradigm of the GDT: all the improvements that could be done in the classical GDT are marginal.

The new generation of Argentina's designers has found a new and revolutionary method for Uranium enrichment with gaseous diffusion. This method could reach, and it could even surpass, all the necessary requirements to be considered as the next generation of enrichment plants over the world.

The **SIGMA** (**S**eparaciyn **I**sotypica **G**aseosa por **M**йtodos **A**vanzados) concept represents the more drastic evolution of the GDT, adapted to the competitive world frame of the enrichment Uranium future market.

The SIGMA concept is focused in the reduction of the capital cost and the energy consumption, giving as a result, a small competitive production scale.

In the SIGMA concept, non proliferation is a central issue: the safeguards systems are included in the design itself, using all the non proliferation advantages of the GDT, multiplied by some innovative features that allows the use of NDA techniques for **on-line hold-up control**.

Some technical goals of the SIGMA concept are listed below:

- Reduced weight of main components.
- Low piping, joints and supporting materials.
- Low seal failure.
- Quick replacement of critical components.
- High compactness.
- High transportability of components.
- Reduced civil works.
- Modular design and construction.

- High overall energy efficiency.
- High separative factor by stage.

As long as the cascade paradigm of the GDT does not allow any significant changes in the plant economy, the SIGMA technology changed the cascade concept itself. This change opens a new design path and allows a new set of optimal design points, according with the restrictive requirements of future market.

The SIGMA concept includes a set of well known components, which are used in an innovative way, and allows the capitalization of all the operation experience obtained in the classical GDT.

The improvements made are significant, increasing the performance of the components and systems by a factor 2 to 30.

All the innovations in the SIGMA concept are proved, representing a low technological risk.

Economical behavior

The SIGMA technology overcomes the most of the economical objectives outlined, by reducing the number of components and civil works.

The new cascade scheme allows a drastic reduction of capital costs, and also reduces the O&M cost. The energy consumption is reduced practically up to its thermodynamic limit.

This new configuration opens new design paths, where the enrichment gain (separative factor) could be incremented in such a way, that enables to obtain different configurations of capital-energy costs, to satisfy the requirements of the plant owner and market border conditions.

The advance design membranes permits stretch the process parameters till its optimal operation points.

All this features working together achieves the historical great performance for industrial Enrichment plants.

Scale economy

A conservative first order economic analysis of the SIGMA characteristic has been made. The scale economy behavior of this technology could be compared with the conventional gaseous diffusion plants in Figure 5.

The cost of a SIGMA plant depends on some internal reconfiguration parameters, and the upper limit of Figure 5 has been estimated with a simple and non optimal SIGMA configuration.

It is remarkable that for optimal SIGMA configurations, the upper limit of this graph represents just a very conservative approximation of the economical potential of the SIGMA technology.

Non-proliferation characteristics

The SIGMA technology inherits all the proliferation resistant features from Gaseous Diffusion Technology, and incorporates some new features that results in a near zero risk of proliferation.

The SIGMA technology has:

- High inventory of process material.
- Long time characteristic times.
- Low cost NDA gamma-neutron probe, that allows on line control of the amount and enrichment of the Uranium being processed.
- Modular design that allows diffuser construction and reparation off site.

This last point, with a remote safeguard control system could enable the transference of the operation of the SIGMA plant to a country, without transferring the technology know-how itself.

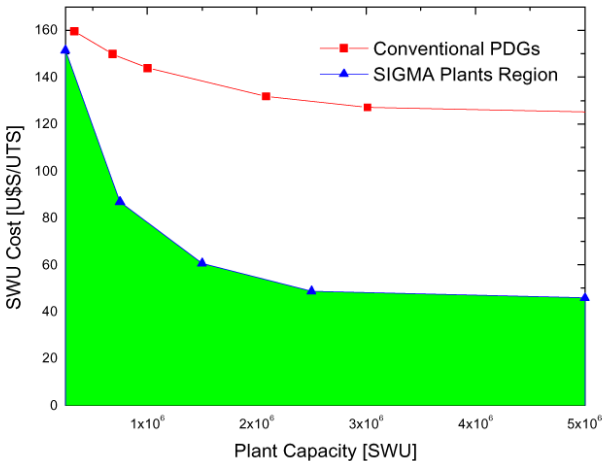

FIGURE 5. Comparison between Conventional GDPs and SIGMA plants scale economy

SIGMA Project

The SIGMA project represents the natural evolution of Argentina Enrichment development. There are several groups working in different areas of conventional gaseous diffusion technology, and in SIGMA specific areas.

A new generation of membranes has been developed. The new membranes have already reached industrial maturity. This membranes could be used so in conventional GDT as much as in a SIGMA module.

Design and economy groups are doing economical studies, in order to improve the main design characteristics of the SIGMA technology. Several numerical models have been developed since the project has begun. **Nowadays, the design group counts with a set of validated models in different areas**:

- Process and SIGMA cascade calculations.
- Membrane economical design and diffusion calculations.
- SIGMA Plant overall calculation.
- Physical model and economic behavior of each main SIGMA component.

Experimental groups are also working in validation of various models, membrane development, safeguard NDA probe design, and in the SIGMA pilot scale concept demonstration facility, which is built in The Pilcaniyeu Technological Installation.

Concept Demonstration Experimental Facility.

In order to study the design's feedbacks and some particular behaviors of the SIGMA technology, an experimental facility has been constructed, and is now being operated by a group of experimental engineers.

This facility is being used to prove the main innovative components incorporated to the design, as well as some minor engineering technical solutions.

An important set of parameters will be obtained as a result of the experiences with the concept demonstration facility, in order to improve the final commercial plant design with detailed engineering models.

Comparison between the different Enrichment Technologies

Keeping in mind the amount of time involved in design and construction of an enrichment plant, and the end of life of the actual plants, It is a fact that the new generation of enrichment plants should be chosen in the next few years.

The potential investor in a new enrichment facility will should make his decision based upon the economical, technical and political aspects of the available technologies and the market.

The economical aspects of the actual and future enrichment market were discussed earlier in this paper. The technical aspect changes continuously, and a new technological idea could appear in any moment, changing all the situation. In reference with the political aspects, it is unlikely that a mayor change occur, since the nuclear weapon situation is still a growing global threat.

Until now, the investor decision was unique. The only economically acceptable and technologically reasonable method for Uranium enrichment was the UCM.

The AVLIS method was considered as the “future technology” but it could not surpass the laboratory stage.

Even when the Gaseous Diffusion Plants were considered so simple, reliable and well known, its prohibitive economic size makes this technology an unacceptable choice.

As the demand was shifting to developing countries, the investor will should consider to install the plant in a non nuclear weapon owner country. Up today, making some punctual exceptions, this seems impossible, because of the implied proliferation risk.

If this next generation technology could offer a reliable and proliferation resistant method, perhaps what today seems impossible could be a reality tomorrow.

In the previous tables a comparison of the economical, technical and proliferation risk aspects of the different enrichment technologies in shown.

CONCLUSION

The future of the enrichment market outlines a without solution dilemma, using the up today available technologies.

Today’s plants are in its end of life, and none of the existent technologies are capable of offering the complete solution to the presented problem.

The new generation of enrichment plants should be economical, modular, with low investment rates, and low energy consumption. But also must be proliferation-resistant, and off course should be reliable, robust and with industrial maturity.

The SIGMA concept, an evolution of the GDT with some innovative components, overcomes all this requirements and it becomes the unique overall solution of the enrichment market dilemma.

ACKNOLEDGEMENTS

We want acknowledge to the authorities of the National Atomic Energy Commission the offered support and trust.

We also want to thank the authorities and the people of the Pilcaniyeu installations.

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TABLE 1. Comparison between the different economical and technical behaviors of the available enrichment technologies

Characteristic	Ultra Centrifuge	LASER Methods	Gaseous Diffusion	SIGMA
Operation Costs	High	Unknown	Moderate	Balanced
Energetic Costs	Low	Low	High	Balanced
Capital Costs	High	Unknown	Moderate	Balanced
Economical Size	Small	Unknown	Very Big	Low
Modular Design	No	No	No	Yes
Maturity	Commercial	Development	Commercial	Proved Changes
Future Expansion Potential	Good	Developing	Poor	Very Good

TABLE 2. Comparison between the proliferation risks of the available enrichment technologies

Characteristic	Ultra Centrifuge	LASER Methods	Gaseous Diffusion	SIGMA
Characteristic Times	Rapids	Rapids	Slow	Slow
Re-Configuration Risk	High	Very High	Low	Very Low
Hold up	Zero	Zero	High	High
HEU diversion capability	Medium	High	Low	Very Low
NDA techniques	Acceptable	Unknown	Acceptable	Excellent
On line analysis	No	No	No	Excellent
Overall Proliferation Risk	Medium	High	Moderated	Near Zero