FR9402799
CEA-CONF--11790

ENRICHMENT, AN OVERVIEW

INTRODUCTION

This general presentation on uranium enrichment will be followed by lectures on more specific topics including descriptions of enrichment processes and assessments of the prevailing commercial and industrial situations. I shall therefore avoid as much as possible duplications with these other lectures, and rather dwell on :

- some theorical aspects of enrichment in general, underlying the differences between statistical and selective processes,
- a review and comparison between enrichment processes,
- remarks of general order regarding applications,
- the proliferation potential of enrichment.

It is noteworthy that enrichment :

- may occur twice in the LWR fuel cycle : first by enriching natural uranium, second by reenriching uranium recovered from reprocessing,
- must meet LWR requirements, and in particular higher assays required by high burn up fuel elements.
- bears on the stucture of the entire front part of the fuel cycle, namely in the conversion/reconversion steps only involving UF_6 for the moment.

1) Theoritical aspects of enrichment applications

Enrichment processes may be broadly divided in two categories, i.e. statistical processes and selective processes :

a) *Statistical processes*

- A great variety of physical phenomena give way to isotopic effects. However, these effects are generally small since they appear as a function of mass differences between isotopes. In the case of heavy elements such as uranium, these differences become very small compared to the average mass of the element itself (lesss than 1 % when the element is under form of uranium hexafluoride : UF_6, a gaseous compound in which fortunately fluorine has no isotopes). Hence, elementary effects are small * .

approximatively . 1.002 in gaseous diffusion

1.03 in gaseous centrifuge (ampified to 1.3 for instance by means of a countercurrent)

and from 1.001 to 1.002 in chemical exchange.

- Elementary separation effects take place within separation elements which may be for example diffusion membranes assembled within a diffuser, or centrifuges or exchange columns.

* The elementary effect is measured by the separation factor defined as the abundance ratio N/(1-N) between product and feed. (N being the concentration in U235)

- Separation elements enable to separate feed in two fractions, one enriched, the other depleted (whereas mixing is the exact reverse). Since the isotopic effect is small, it has to be repeated a number of times, leading to the necessity to build separation cascades where each element is fed both by the enriched fraction of the previous element and by the depleted fraction of the next one. Mixing, which degrades enrichment, must be avoided as much as possible.

  Ideally if no mixing was to occur, cascade theory demonstrates that all stages should be different in size which condition is not practical from an industrial construction stand point. Hence the necessity to " square off" (i.e. approximize) ideal (non mixing) cascades by an assembly of square ones, thereby loosing a few points in overall efficiency.

- The work accomplished in separating isotopes is obviously proportional to the quantities of material processed, it is also a function of the assays attained. It can be demonstrated that separative work may be expressed under two equivalent forms, one obtained by summing up the separative work performed within each element, the other by taking into account the streams and assays of feeds product and waste. Time does not allow to enter calculations which are quite painstaking. Let it merely be said that the unit used to quantify the work accomplished in separation ΔU is called Separation Work Unit : SWU. It has the dimension of a mass and is generally expressed in kg. Enrichment plant capacities are expressed in kg/year. As an indication, one should have in mind tha the annual reloads of a 1 GWe LWR arise for approximately 100.000 SWUs.
- As in all calculations concerning costs of industrial products or services, there are two main items in the cost of a separative work unit :

one corresponds to the amortization of initial investment, i.e plant construction, material filling, start up etc

the second covers operating expenses such as manpower, energy consumption, maintenance etc.

This appears in the following formula :

$$c_\Delta = \tau\left[\frac{I}{\Delta U}\right] + c_E\left[\frac{E}{\Delta U}\right] + c_w\left[\frac{P}{\Delta U}\right] + \left[\frac{CR}{\Delta U}\right]$$

where

$C\Delta$ = cost of separative work unit
ΔU = plant capacity
I = total investment
E = plant energy consumption
P = personnel operating the plant
CR = repair and replacement costs

and

τ = Amortization factor i.e :
amortization period x amortization rate

C_E = Cost of kWh

C_w = Cost of wages, etc

It should be noted that in all cases, each economic item appears as the result of an intrinsic feature of the process (plant constuction, energy consumption, manpower required,...) multiplied by an external economic factor (costs of capital, energy, manpower , etc.) which means that the sensitivities of process features and background economics are the same. In other words, the competitivity of an enrichment plant depends as much on the process itself as on its economic surroundings

- The units cost of enrichment C_{Δ} is only one of the two main items (the other being the price of natural uranium C_F) which enter the cost of low enriched uranium C_p needed for the fabrication of fuel elements These two items may somewhat replace one another

For instance, a given quantity of product P at a given assay Np may either be obtained by spending much separative work ΔU and little natural material F, or spending little separative work and more material. In all cases :

$$P\,C_p = F\,C_F + \Delta U.C\Delta$$

$$C_p = \left[\ C_F\,\frac{F}{P}\left(N_F\,N_p.N_w\right) + \frac{C_\Delta}{C_F}\,\frac{\Delta U}{P}\left(N_F\,N_p.N_w\right)\ \right]$$

In other words,Optimal tail assay or $\dot{N}_{w}$ minimizing C_P depends on C_{Δ}/C_F

- Strictly speaking, other items of the front part of the cycle should also be taken into account This may become all the more pertinent as the cost of encrichment may decrease compared to that of conversion and reconversion.

b) selective processes

Whereas statistical processes involve " natural " physical phenomena such as the behaviour of a mixure of isotopes crossing a porous membrane or submitted to a high rotational field, other means of separation, far more efficient in principle, call upon " artificial " i.e. man made physical tools in order to achieve selective excitations and extractions of desired isotope. For example, photoselective irradiations by laser can be tuned to the specific frequencies of electron layers, or molecular structures, or chemical bonds of desired isotope.

There are two important aspects concerning isotope separation obtained by means of selective processes :

- one is the efficiency of excitation itself incurring a loss of photons and/or a loss of material
- the other is remixing which may occur in many ways such as exchange after excitation or mere pollution of the enriched fraction.

Experience shows that the processes outlined above behave as follows :

	AVLIS/SILVA (photoionization)	MLIS/SILMO (photodissociation)	CRISLA (photochemical excitation)	PSP plasma separation)
Efficiency	very high	medium	low	high
Remixing	high	low	likely	high

2) Review and comparison of enrichment processes

a) Review of processes

- aerodynamic processes. These include gaseous diffusion, with the largest industrial capacity presently on line in the world, as well as nozzle and vortex. Gaseous diffusion works on pure UF_6 and takes advantage of the sightly more numerous impacts of the lighter U 235 F6 on microporous membranes which enrich the mixture of isotopes by a factor of 1.002 or so. The United States and the Eurodif partners (France. Belgium. Italy and Spain) operate such plants which have long lifetimes but consume large amounts of electricity. The other two processes work on mixtures of UF_6 and hydrogen with an even greater consumption of energy. The nozzle process developped by Germany has never been successfully applied, wheras the Vortex process developped by South Africa has only been applied at small scale.

- Centrifugation has been widely studied with applications achieved at large scale in ex USSR and at smaller scale, by Urenco partners (Germany, Netherland and UK) and by Japan. Other countries, namely Australia, Brazil, France, Pakistan and the United States have also studied the process.
  Several versions of centrifuge machines have been designed :

  . minifuges in ex USSR (1 TO 2 $SWUs/_y$)
  . intermediate size machines in Urenco countries and Japan, (10 to 20 $SWUs/_y$)
  superfuges in the USA (100 to 200 $SWUs/_y$)

- Chemical exhange processes have been studied in France (Chemex) and Japan (Asahi), but are now abandoned.
- Selective processes, mainly laser, but also plasma separation, have been studied since roughly 15 years in the USA, 10 years in France, 5 years in Japan without giving way yet to industrial applications. Among the three laser processes, uranium vapour photoionization (AVLIS or SILVA) appears as the most promising compared to UF6 photodissociation (MLIS or SILMO) and much more so compared to chemical photo excitation (CRISLA)

b) Compared features of enrichment processes

	Gaseous diffusion	Centrifugation	Laser ionization
Industrial application	Yes(USA, Eurodif)	Yes (Russia, Urenco)	No
Modularity	No	Yes	Yes
Compacity	No	No	Yes
Energy consumption	High	Low	Low
Maintenance	Small	Small	High
Front cycle	UF_6	UF_6	Metallic uranium

c) Compared economics of enrichment processes

Cost items	Gaseous diffusion	Centrifugation	Laser ionization
Investment	High*	High	Low
Electricity	High	Low	Low
Maintenance & refurbishing	Low	Low	Sustantial

(*Totally amortized in the USA, partialy so in the case of Eurodif)

d) Conclusions

Whereas the general features of enrichment plants remain valid, the compared economics become more and more meaningless of the merits of the respective processes as the pricing policies concerning enrichment are less and less in relation with actual costs of the services. This tendancy appeared more than ten years ago with the birth of a secondary market resulting from nuclear power plant project shut downs and it has been amplified recently by russian offers of enrichment services or of low enriched material which are set to undercut all other offers. Only in the long run may intrinsic merits of processes come back to the forefront of the international enrichment scene.

3) Future prospects of enrichment

a) Remarks concerning the future demand in enrichment services

- Demand reflects primarily the tendancies observable in electronuclear capacity

This capacity should increase in South East Asia, i.e Japan, South Korea, Taiwan and possibly China.

In other industrialised areas such as Northen America and Western Europe, the lifetimes of power plants should yet increase before being replaced by new ones.

as for Eastern Europe and Russia, the energy needs are great but progression may be hampered for various reasons.

- second order effects will also appear with

the recycling of uranium and plutonium recovered from the reprocessing of spent fuels

the tendancy to increase burn ups

These will jointly reduce demand, may be up to 10 % in France by 2000.

b) State of the offer

- The US enrichment industry, both the oldest and still the most important in terms of capacity, is undergoing a radical change. The US-DOE who was the previous owner of the enrichment plants is presently handing business over to the US Enrichment Corporation which should attain full independancy within two years from now.
- Russian services or low enriched uranium (LEU) are being proposed by Tenex at prices well under western standards. Moreover, military uranium may also be converted into LEU in application of an agreement signed between the governments of the USA and of Russia.
- Japanese R&D teams are working on several processes including centrifugation, laser ionization and dissociation with the declared intent to cover part of its domestic needs.
- European producers : Eurodif and Urenco, remain active mostly inside Europe, but also abroad, in Asia for example.

c) The comparison between offer and demand reveals a worldwide overcapacity aggravated by the threat of transforming HEU of military origin into LEU. Except for the more stable european producers, deep changes may occur in the enrichment industry within the next years. Once this period is over, and in conjunction perhaps with a renewed growth of nuclear energy, large new enrichment capacities could be ordered and appear on the market.

4) Risks of proliferation related to enrichment

- Enriching natural uranium to assays above 90 % in isotope 235 is one of he two main routes leading to nuclear weapons, the other using plutonium produced by means of a reactor.

- Enrichment processes are more or less well adapted to reach high assays. History testifies that all five " nuclear powers " : USA, USSR, UK, China and France called on gaseous diffusion in order to achieve that goal. However, this occured between 50 and 30 years ago. Since then, other processes have been developped and offer similar if not better possibilities. Some aspects of the problem are the following :

  Technicological difficulties to overcome : microporous membranes, high resistance bowl material, high power electron guns, etc.

  possibility of hiding a small stand alone plant,

  possibility of converting a low enrichment plant into a high enrichment one,

  equilibrium times needed to reach high assays, etc.

- Ways to counter nuclear proliferation are, besides direct intelligence :

  . control of sensitive nuclear materials as applied by IAEA by means of containment and surveillance methods,

  control of sensitive equipment exports,

  . restriction of sensitive data.

- Of course, controls must be accepted in order to be efficient, which implies NPT acceptance and membership. Countries which have not signed the NPT are mainly found in South America, Northern Africa, the middle East and of course, India who made a nuclear weapon test some fiften years ago. The question will be raised on the occasion of the renewal of NPT scheduled in 1995.

BIBLIOGRAPHY

The following selection is proposed .

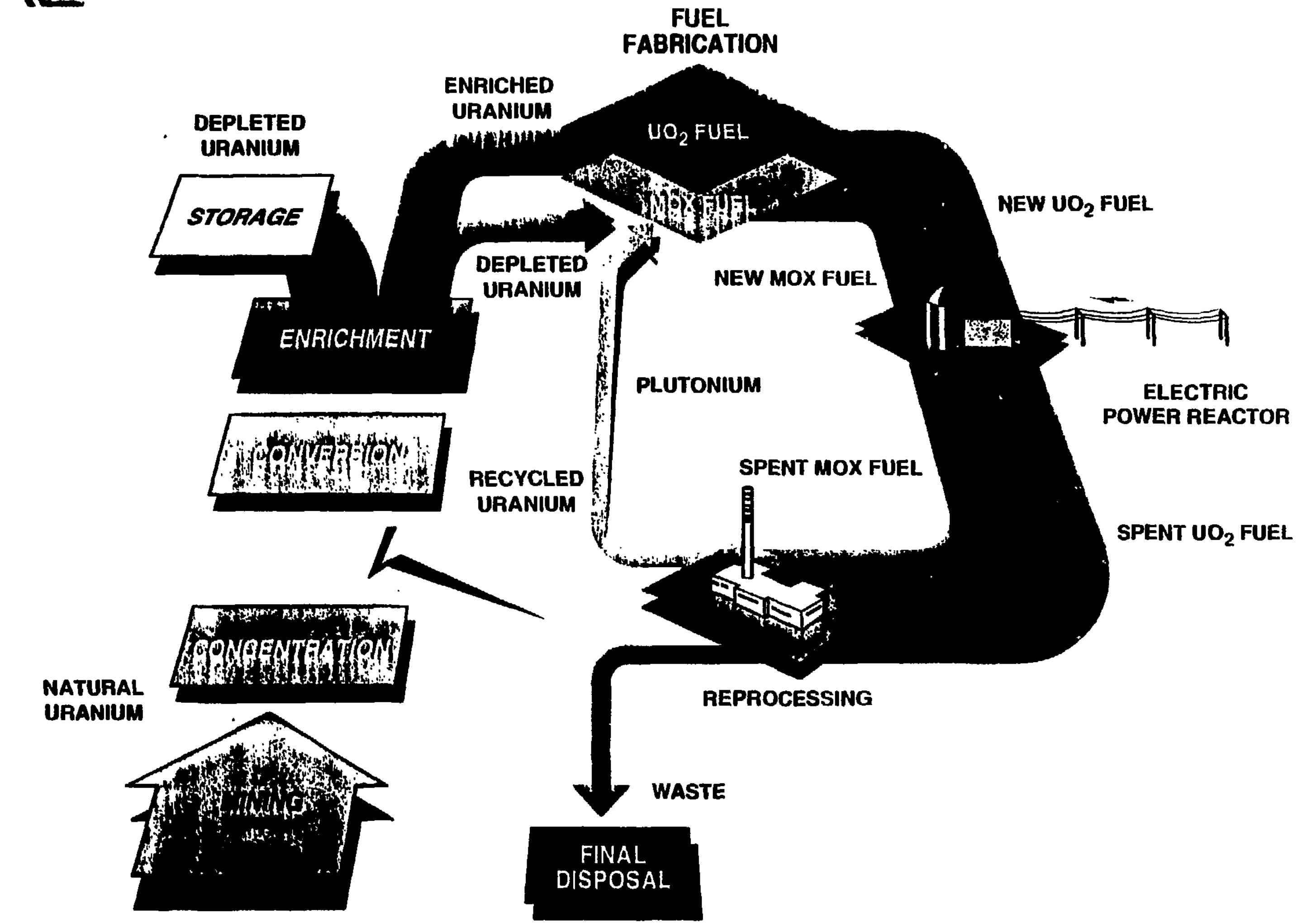
[1] The theory of isotope separation as applied to the large-scale production of U235 - Karl COHEN - Mc Graw-Hill Book Cy - 1951
(cascade theory for statistical processes).

[2] Uranium Enrichment - Stelio VILLANI and al - Springer - Verlag - 1979
(a review of enrichment processes as known in 1979).

[3] Advanced uranium enrichment processes - Michel CLERC and Pierre PLURIEN - Report EUR 10743 EN - Commission of the European Communities - 1986
(a comprehensive review of selective processes).

[4] Compared economic features of enrichment processes - Jean Hubet COATES - IEA - TECDOC - 555 - October 1988 - (economics of enrichment processes).

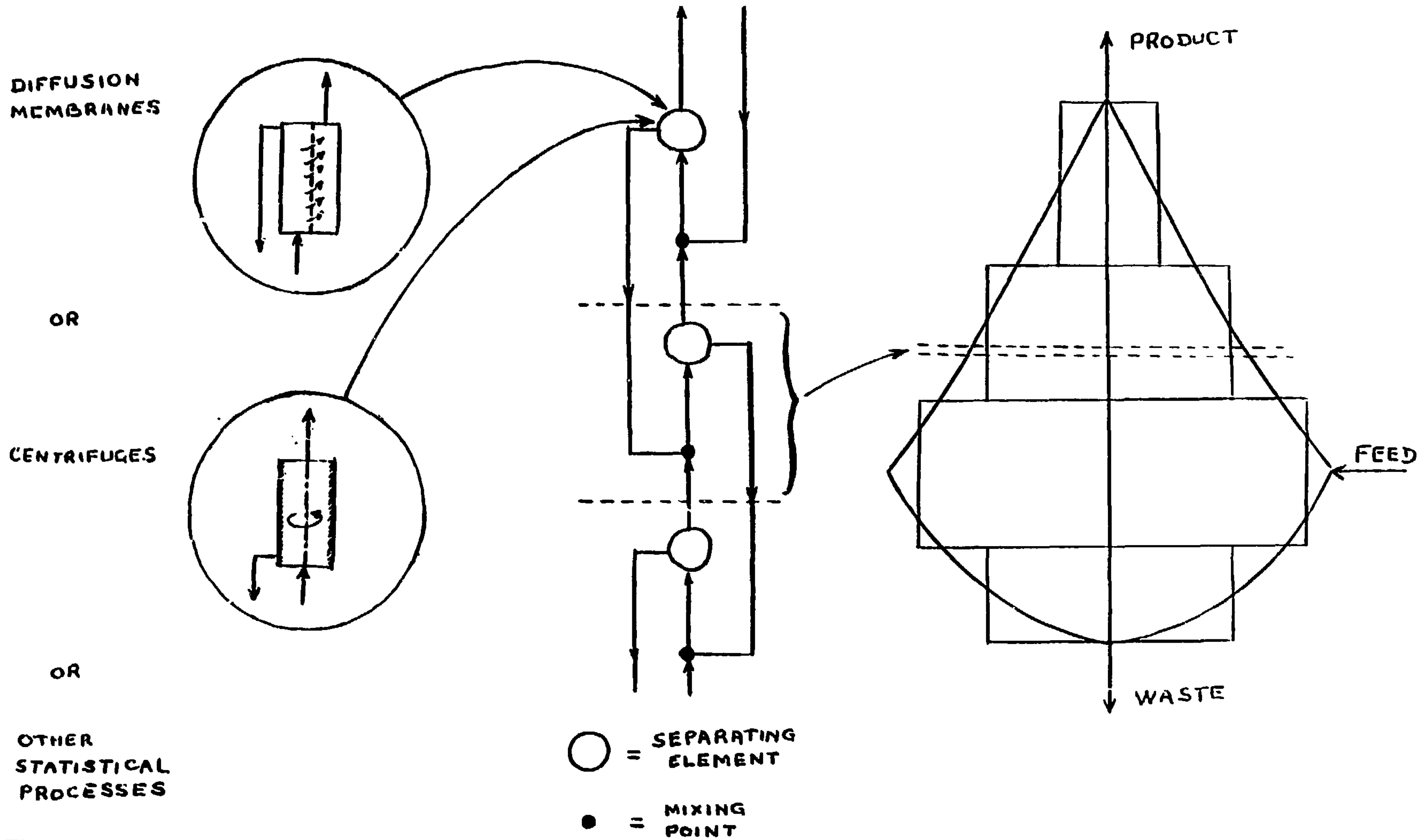
THE NUCLEAR FUEL CYCLE



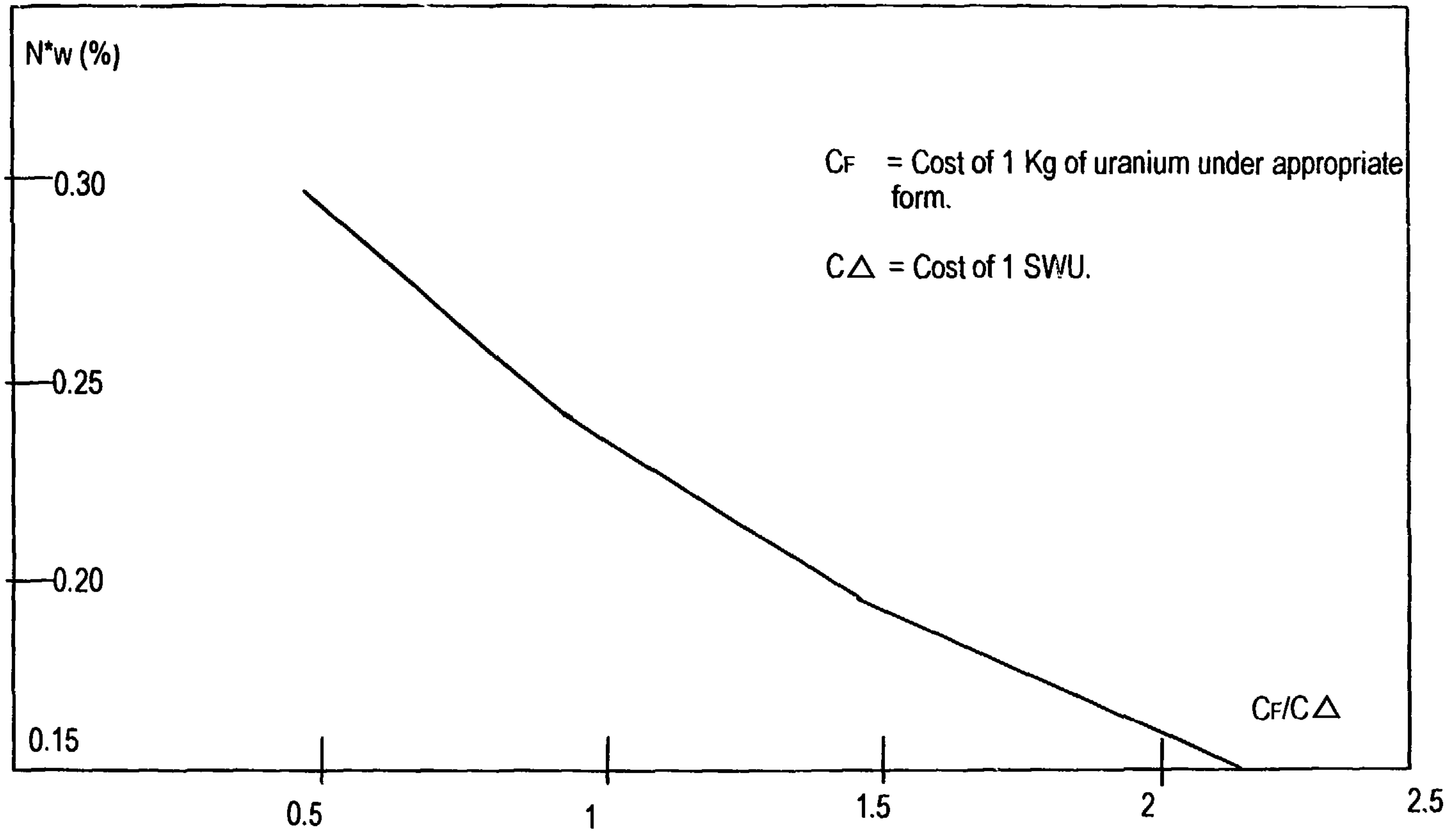
ISOTOPE SEPARATION FUNDAMENTALS

- NUMEROUS PHYSICAL PHENOMENA INDUCE ISOTOPIC EFFECTS DUE TO MASS DIFFERENCES BETWEEN ISOTOPES
- IN THE CASE OF HEAVY ELEMENTS SUCH AS URANIUM, MASS DIFFERENCES ARE SMALL COMPARED TO THAT OF THE ELEMENT ITSELF : 1 % OR SO
- HENCE, ELEMENTARY SEPARATION MUST BE REPEATED IN ORDER TO REACH REQUIRED ASSAYS
- REPETITION IS OBTAINED BY ASSEMBLING ELEMENTS INTO CASCADES, WHICH IS A TYPICAL CHARACTERISTIC OF SO CALLED "STATISTICAL PROCESSES"
- MORE SOPHISTICATED PROCESSES ENABLE TO EXCITE DISCRETE FEATURES OF DESIRED ISOTOPE, THEREBY OFFERING HIGH SELECTIVITY AND AVOIDING CASCADING. THESE ARE CALLED "SELECTIVE PROCESSES"

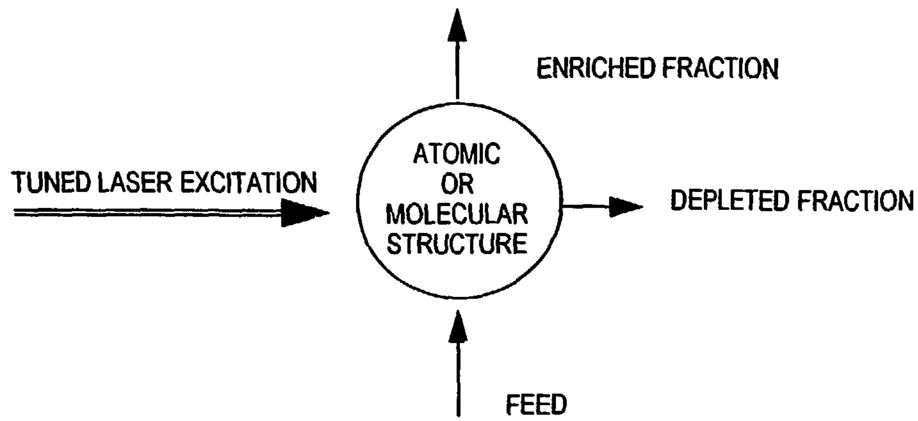
STATISTICAL PROCESSES



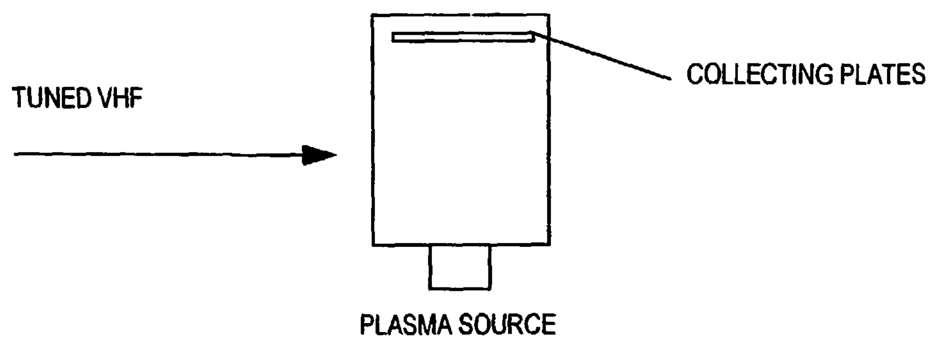
OPTIMAL TAIL ASSAY FOR STATISTICAL PROCESSES



SELECTIVE PROCESSES



TUNED ON ELECTRONIC ...	→	AVLIS OR SILVA
TUNED ON MOLECULE RESONANCE	→	MLIS OR SILMO
TUNED ON CHEMICAL BONDS	→	CRISLA



REVIEW OF ENRICHMENT PROCESSES

• ELECTROMAGNETIC		(USA)
• AERODYNAMIC	Gazeous Diffusion	(USA, USSR, UK, France, Argentine)
	Nozzle process	(Germany ⟹ Brasil)
	Vortex process	(Republic of South Africa)
• CENTRIFUGATION	Minifuges	(ex USSR ⟹ Russia)
	Intermediate	(Germany, Netherlands, Japan, UK, ...)
	Superfuges	(USA)
• CHEMICAL EXCHANGE	U4 / U6 ion exchange	(Japan)
	U3 / U4 liquid exchange	(France)
• LASER SEPARATION	Photoionisation : AVLIS / SILVA	(USA,France, Japan, UK, ...)
	Photodissociation : MLIS / SILMO	(USA, France, Germany, South Africa, Japan, ...)
	Chemical excitation : CRISLA	(North America)
• PLASMA SEPARATION		(USA, France, Russia)

COMPARISON OF MAIN ENRICHMENT PROCESSES

INDUSTRIAL FEATURES	GASEOUS DIFFUSION	CENTRIFUGATION	LASER PHOTOIDNIZATiON
PLANT APPLICATION	YES (USA, EURODIF)	YES (RUSSIA, URENCO))	NO
MODULARITY	NO	YES	YES
CASCADING	YES	YES	NO
COMPACITY	NO	NO	YES
ENERGY REQUIREMENTS	HIGH	LOW	LOW
MAINTENANCE	SMALL	SMALL	HIGH
FRONT CYCLE	UF6	UF6	METALLIC URANIUM
ECONOMIC FEATURE			
INVESTMENT	HIGH *	HIGH	LOW
ENERGY EXPENSES	HIGH	LOW	LOW
MAINTENANCE COSTS	LOW	LOW	SUBSTANTIAL

* TOTALLY AMORTIZED IN THE USA, PARTIALY SO IN THE CASE OF EURODIF

ENRICHMENT DEMAND (1)

- IT REFLECTS NUCLEAR POWER PLANT (NPP) NEEDS

  - INSTALLED NUCLEAR CAPACITY IS DUE TO INCREASE IN SOUTH EAST ASIA

  - NPPs SHOULD BE REPLACED IN WESTERN EUROPE, LESS CERTAIN IN THE USA

  - CAPACITY IN EX-EASTERN WORLD SHOULD RESUME GROWTH

- SECONDARY ASPECTS ARE

  - URANIUM AND PLUTONIUM RECYCLING

  - HIGH BURN UP FUEL

REDUCING DEMAND UP TO 10 % IN COUNTRIES LIKE FRANCE AND JAPAN, BY 2000

ENRICHMENT DEMAND (2)

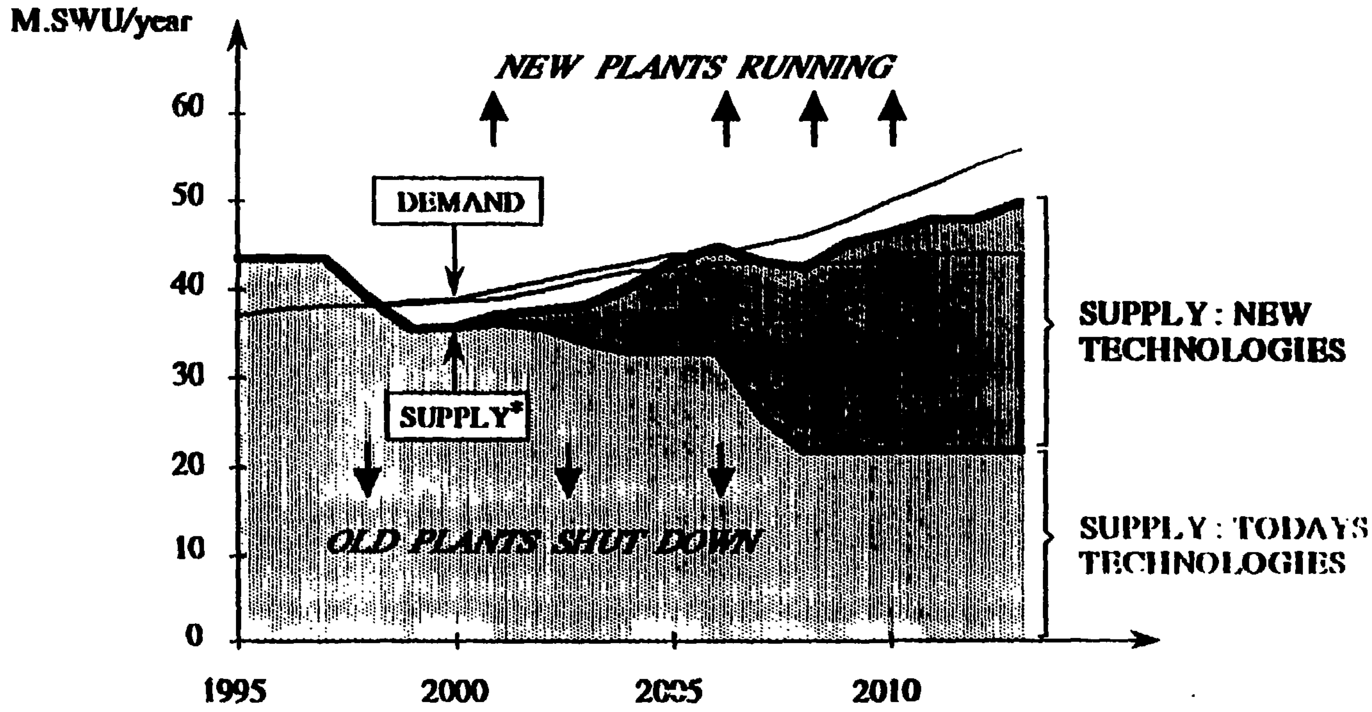
QUANTITATIVE FORECASTS	1990	1995	2000	2005
UNITED STATES	11.0	11.3	9.6	9.1
FRANCE + BELGIUM + SPAIN	6.7	6.6	6.6	6.9
JAPAN	3.9	4.7	5.1	6.7
FRG + NETHERLAND + UK	3.3	3.0	3.3	2.8
EASTERN EUROPE	6.7	7.5	8.5	9.0
OTHER COUNTRIES	3.5	3.6	3.9	4.2
TOTAL	35.1	36.7	37.0	38.7

ENRICHMENT OFFER *

SUPPLIER	PROCESS	CAPACITY (M.SWUs/YEAR)	REMARKS
USEC (USA)	GASEOUS DIFFUSION	19.2	TRANSITION BETWEEN PAST OWNER (US DOE) AND NEW ENTITY (USEC) PRESENTLY TAKING PLACE
EURODIF (EUROPE)	GASEOUS DIFFUSION	10.8	MAIN SHAREHOLDER IS COGEMA (FRANCE) WITH OTHER PARTICIPATIONS FROM BELGIUM, ITALY AND SPAIN
TENEX (RUSSIA)	CENTRIFUGATION	8 TO 14	
URENCO (EUROPE)	CENTRIFUGATION	2.7	SHAREHOLDERS FROM GERMANY, NETHERLANDS AND UK.
JNFL (JAPAN)	CENTRIFUGATION	0.3	
	TOTAL :	41 TO 47	

* WITHOUT TAKING INTO ACCOUNT THE POSSIBLE CONVERSION OF MILITARY HEU INTO LEU RESULTING IN SEVERAL MILLION SWUs PER YEAR EXTRA ENRICHMENT AVAILABILITY.

URANIUM ENRICHMENT
MARKET TRENDS



* Supply does not include diluted military stocks

PROLIFERATION HAZARDS

- TWO ROUTES TO PROLIFERATION :

  - ENRICHING NATURAL URANIUM TO HIGH ASSAYS IN U 235
  - EXTRACTING PLUTONIUM PRODUCED WITHIN A NUCLEAR REACTOR

- ALL NUCLEAR POWER COUNTRIES HAVE CALLED ON GASEOUS DIFFUSION, BUT OTHER PROCESSES ARE ALSO OF CONCERN

- DIFFICULTIES TO OVERCOME IN A PROLIFERATION VENTURE RELATE TO :

  - THE AVAILABILITY OF FEED MATERIAL
  - THE MASTERSHIP OF A PERFORMANT (AND PERFORMING) ENRICHMENT PROCESS
  - THE SECRECY OF THE OPERATION WHETHER
    . A DEDICATED FACILITY, OR,
    . CONVERSION OF A COMMERCIAL PLANT

MEASURES OPPOSING PROLIFERATION

- Control of sensitive nuclear materials
  (International or Multinational Safeguards)

- Control of sensitive equipment exports

- Restriction of sensitive data

◆◆◆◆◆

A key point however is acceptance of the Non ProliferationTreaty spirit and rules which have worked reasonably well until now.

An occasion to enforce such system will be offered in 1995 with the renewal of the Treaty.