Assessment of Aerodynamic Separation Process and regulation by Nuclear Supplier Group

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Abstract

Nuclear Suppliers Group recognises that in many cases, plants, equipment, and technology for uranium isotope separation have a tight relationship to plants, equipment, and technology for isotope separation of “other elements”. These controls on facilities and equipment for "other element" isotope separation are in addition to controls on plants and equipment specifically constructed or equipped for the processing, use, or production of special fissionable material covered by the Trigger List.

Due to the close and complementary relationship, controls of Trigger List items are employed during the regulation of plants, equipment, and technology for isotope separation of “other elements”. However, these isotope separation plants, equipment, and technology of “other elements” do not meet the *Especially Designed or Prepared* applicable to the Trigger List. Furthermore, although the Trigger List item would trigger safeguards, the regulation of some of these plants, equipment, and technology for isotope separation of “other elements” can only be covered under the Section 2(b) of the Additional Protocol, which unlike the IAEA Safeguards, is not condition of supply.

Currently, South Africa hosts a company, which uses Aerodynamic Separation Process (ASP) to separate lighter elements such as Si-28 and O-18, however, it has not been proven to separate fissile elements. Such has been the difficulty regulating the technology in South Africa, that the export and import of this company’s plants, equipment and technology are controlled via the Non-Proliferation of Weapons of Mass Destruction Act, No. 87 of 1993 whilst the safeguards implementation is through the Nuclear Energy Act, No. 46 of 1999.

However, the preceding aerodynamic technologies, i.e. the Becker process and the UCOR process, were only used for the separation of Uranium, which made them to be regarded as trigger list items. The purpose of this study was to understand the similarities and differences between the current ASP technology and UCOR process and assess the control thereof domestically in South Africa and by the NSG.

It has been found out that despite the difference in the layout of the front end of the ASP plant for separation of other elements, compared to the architect of the preceding aerodynamic technologies, such as autoclave, or the lack of carrier gas in the case of natural gas separation, the controls are still the same. This means that ASP plant for

separation of other elements and natural gas is still subjected to the same controls despite that fact that either it cannot be efficient for fissile material in the case of other elements, or it is not applicable in the case of natural gas.

It has also been found that both the Nuclear Energy Act, No. 46 of 1999, and its Government Notice 207 of 3 February 2009 would need to be amended to standardize the control of this technology with the NSG prescripts. Similarly, the Government Notice No. 493 of 29 March 2019 would need to be repealed to ensure alignment with the NSG.

The survey conducted showed lack of understanding of the non-proliferation controls by academic researchers and some officials in the nuclear safety regulation. Therefore, there is a need to increase outreach and consolidation of the non-proliferation regulatory framework to be at a single body.

NSG's regulation of plants, equipment, and technology for isotope separation of "other elements" is correct, based on the responses of the technical expert industry, as they are closely related to regulation of plants, equipment, and technology for isotope separation of fissile materials, but exempted for natural gas is necessary.

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ASP	Aerodynamic Separation Process
AP	Protocol Additional to Safeguards Agreement
CARST	Centre for Applied Radiation Science and Technology
EDP	Especially Designed or Prepared
CSA	Comprehensive Safeguards Agreement
IAEA	International Atomic Energy Agency
NSG	Nuclear Suppliers Group
NECSA	Nuclear Energy Corporation of South Africa
PLC	Process Logical Control
SCADA	Supervisory Control and Data Acquisition
UCOR	Uranium Enrichment Corporation of South Africa
ZC	Zangger Committee

CHAPTER 1: INTRODUCTION AND PROBLEM STATEMENT

1.1 Background literature

Mining has been the bedrock of South Africa’s economy for more than a century. Although gold was and still is the element of choice, other minerals such as platinum, uranium, chrome, etc., grew in value as the economy diversified and in certain instances other parameters such as, technology, politics, energy security, etc. dictated. Processing of these minerals further created economic value chain and also other industrial applications whose products precipitated into security and other civil/consumer applications. Late in the 1800s, information on the presence of uranium in South Africa was first discovered when the gold ores in Witwatersrand yielded mic roscopic diamonds with green fluorescence caused by radioactivity. Few years later, Uraninite was revealed in heavy mineral concentrates from the City Deep Gold Mine, but there was minimal interest due to its low commercial worth (Brynard & Ainslie, 1990; Kemp et al., 1992).

South Africa’s uranium mining industry started from the local availability of large uranium deposits, which were coveted from 1945 by the United States of America and the United Kingdom for use in the Manhattan Project during World War II and in the subsequent Cold War period. Figure 1.1 indicates production estimates supporting the results of the survey undertaken on the instruction of the then South African Prime Minister Jan Christian Smuts. South African uranium was sold to the Combined Development Agency, which was essentially a uranium procurement agency established co-operatively between Washington and London with the goal of securing uranium supplies for, *inter alia*, their nuclear weapons programs (Cochran, 1993; Brynard & Ainslie, 1990). The mining industry quickly built uranium plants, with the first one opening in October 1952 at West Rand Consolidated Mines. By March 1955, 16 mines had been granted uranium production permits. Production increased fast until 1959, when 26 mines fed 17 facilities, resulting in a total output of 4 954 tonnes. South Africa's entire output was dedicated to providing the Western World's nuclear armaments program in the early years. After 1959, these programs' requirements decreased, and South African uranium production fell to a low of 2 262 tonnes U in 1965 (Brynard & Ainslie, 1990; Heald, 2010; Onwumechili et al., 1981).

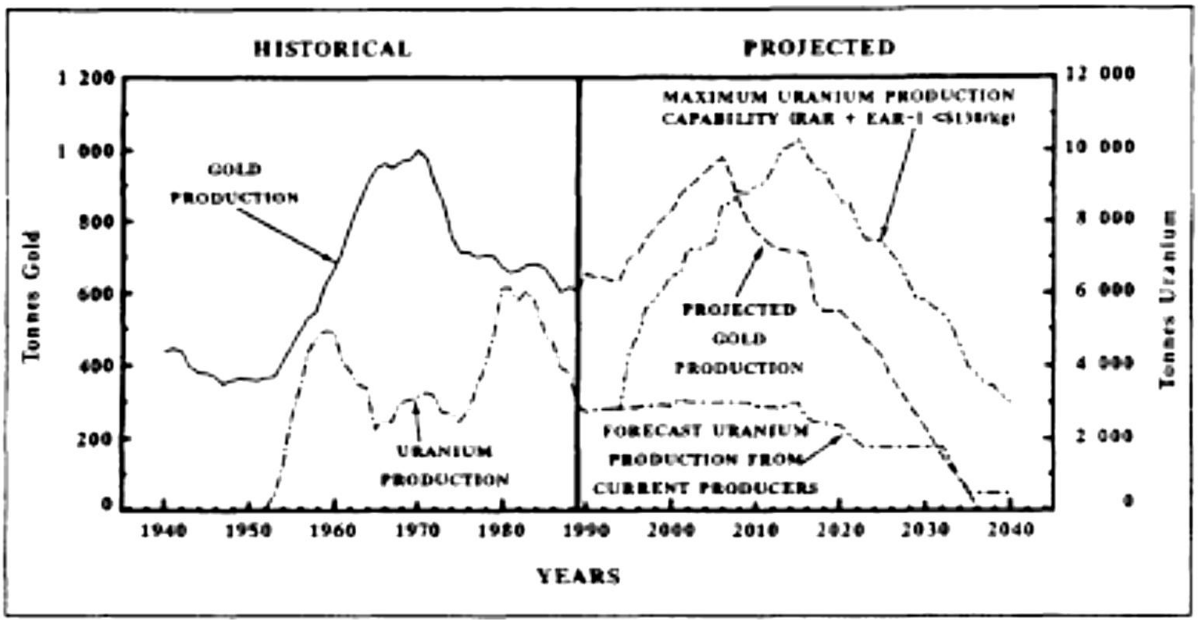


Figure 1.1 Historical and projected uranium and gold production for South Africa (Brynard and Ainslie, 1990).

Energy production has become the most crucial aspect of every country's economic development. Although coal, gas and oil reserves are still available, in addition to newly discovered sources such as solar and wind, the production of power from controlled nuclear fission of heavy elements is still the most important technical application of nuclear reactions, aside from nuclear medicine applications. The world's reserves of energy in nuclear fuels uranium and thorium exceed the world's reserves of coal, oil, and gas because the energy of nuclear fuels is far more intense and concentrated than that of conventional fuels, while the production costs in many countries would be the same over the entire life cycle of both plants. (Benedict et al, 1981).

The development of nuclear power industries based on fission reactors necessitates the production of a wide range of materials with varying commercial importance, thereby developing various economic value chains. The use of uranium, thorium, zirconium, and heavy water in fission-based energy processes, supplemented by the development of different chemical engineering processes to isolate these isotopes, including isotope separation, solvent extraction, as well as large-scale separation and purification of highly radioactive materials, further gave emphasis to the importance of nuclear in the development of humankind. Isolation and enrichment of these isotopes requires a myriad of techniques developed through the years. Whereas there are commercial benefits in isotope enrichment, there is also a possibility to develop weapons of mass destruction, which in the case of uranium and plutonium would be nuclear weapons and /or explosives. Whereas ^{239}Pu is manmade isotope through the reprocessing of nuclear fuel waste, ^{235}U is attained through separation and enrichment of natural uranium.

Table 1.1 Methods for enriching ^{235}U (Benedict et al., 1981; Krass et al., 1983)

Method	**Status**
Gaseous diffusion of UF_6	Three large plants operating in the United States of America; large plants operating in the Russian Federation and People's Republic of China; smaller plants operating in the United Kingdom and France
Centrifugation of UF_6	Large pilot plants operating and commercial plants under construction in the United Kingdom and the Netherlands; large plant to be built in the United States of America
Thermal diffusion of UF_6	Small amount of slightly enriched UF_6 produced in the United States of America; process abandoned
Electromagnetic separation of UCl_4	Used in the United States of America in 1945 for first large-scale production of highly enriched ^{235}U; process abandoned in 1946
Separation nozzle process	Process demonstrated on large pilot-plant scale at Karlsruhe, Germany; semi commercial plant built in Brazil
UCOR process	Process demonstrated in pilot-plant at Valindaba, Republic of South Africa; commercial plant built and both plants decommissioned
Chemical-exchange	Pilot plants envisaged in Japan and France, process still at research stage in the United States of America.
Laser-based process	Neither technology has been deployed on a production scale; however, several atomic uranium vapor-based demonstration facilities were built and operated in the 1980s and 1990s and a molecular vapour-based method is currently being investigated in the United States of America. Many countries have hosted research projects on laser isotope separation (LIS) of uranium, plutonium, and other elements, and a few projects currently exist to investigate enriching isotopes useful in medical and industrial applications.

1.1.1 Development of nuclear non-proliferation regulations

Nuclear has become synonymous with destruction in relation to the use of nuclear weapons during the World War II. It has however, developed to be an innovation that can be used in human development to advance technology mainly in power generation. In order to promote peaceful nuclear applications, countries that provide technology recognized the obligation to ensure that international trade and cooperation does not aid in the spread of nuclear weapons (IAEA, 2019). The adoption of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) was a milestone by the United Nations to cull the possibilities of nuclear arms race.

Shortly after entry into force of the NPT in 1970, multilateral consultations on nuclear export controls led to the establishment of two separate mechanisms for dealing with nuclear exports: (1) the Zangger Committee, in 1971, when major nuclear suppliers regularly involved in nuclear trade met to reach common understandings on how to implement Article III.2 of the NPT in order to facilitate a consistent interpretation of the obligations arising from that Article, and (2) in 1975, when the Nuclear Suppliers Group was formed. The NSG and the Zangger Committee differ slightly in the scope of their trigger lists of *especially designed or prepared* (EDP) items and in the export conditions and guidelines for items on those lists (IAEA, 2019).

Whereas there is acceptable understanding of both what qualifies an item (both tangible and intangible) to be on the trigger and dual use lists, both the “especially designed or prepared” and “dual use” terms are not specially defined by the regimes (NSG). It thus probable that with development of technology, especially evolving from technology previously associated exclusively with nuclear fuel cycle applications that did categorization of new technologies would not fit the criterion specified for both terms, despite their proliferation credentials (NSG).

This was acknowledged by the NSG when it resolved that plants, equipment, and technology for isotope separation of uranium have a close relationship, in many cases to plants, equipment, and technology for isotope separation of “other elements”. In particular cases, the controls for plants for the separation of isotopes of natural uranium, depleted uranium or special fissionable material and equipment also apply to plants and equipment that are intended for isotope separation of “other elements”. These plants and equipment controls for isotope separation of “other elements” are corresponding to regulations on plants and equipment, which have been especially designed or prepared for the processing, use or production of special fissionable material covered by the trigger list (IAEA-1, 2019).

A similar control mechanism is adopted by the Zangger Committee, albeit for stable isotopes than other elements (ZC, 2017). Whereas these controls were not practiced prior to 2007 when the NSG adopted the control text, the changes affect the use of similar processes in separating other elements. Although it is justifiable and legally permissible through Article III.2 of the NPT, for fissile isotopes and Hydrogen, the use of similar processes to separate other elements is still subject to interpretation even-though the text to control them is provided for by the NSG and Zangger Committee. Such does leave suppliers with a regulation conundrum of whether to apply controls meant for especially designed and prepared uranium separation processes on similar isotope separation techniques of “other elements” verbatim. The NSG in its Section 5 Introductory Note states that the controls ought to equally apply (IAEA-1, 2019).

1.1.2 South Africa and nuclear non-proliferation controls

South Africa as a host of Aerodynamic Separation Process (ASP) developed by the private company Klydon, is also affected by the conundrum. The technology carries similar traits as the German jet nozzle technology (Becker process) and the Uranium Enrichment Corporation of South Africa (UCOR) method named *the advanced vortex tube process* was developed from genesis technology that was first detailed in the scientific media in the mid-1970s (Ronander et al., 2012). Whilst the jet nozzle technology and advanced vortex tube process were developed and commercialized for uranium enrichment, the ASP has not been proven to separate uranium but optimized to separate other elements or stable isotopes.

South Africa as a member of both the NSG and Zangger Committee, complies with obligations of both regimes and has domesticated the legislative requirements thereof through the Nuclear Energy Act, No. 46 of 1999 and the Non-Proliferation of Weapons of Mass Destruction Act, No. 87 of 1993 with implementing departments as Mineral Resources and Energy, and Trade, Industry and Competition respectively. The Ministry of Mineral Resources and Energy oversees the implementation of trigger list obligations whilst the Ministry of Trade, Industry and Competition has control over the dual use list. However, both departments are affected by controls over the ASP as the Mineral Resources and Energy Ministry oversees the safeguards implementation.

Nuclear currently forms only 5% of the national electricity generation mix in South Africa, with the majority being coal based. An additional 40 GWe electrical power needs to be added to the current electricity supply system, of which amount 50% was planned to be nuclear (Bredell, 2008). (Currently, South Africa is considering preparations for a nuclear construction program with a capacity of 2 500 MWe (DMRE-1, 2019).

In line with the Nuclear Energy Policy which defines the role of South African Nuclear Energy Corporation (NECSA) as the agent acting on behalf of government to investigate, develop, establish, support and/or participate in uranium mining and milling, uranium conversion, uranium enrichment, fuel fabrication, spent fuel management, reprocessing and radioactive waste management, NECSA decided to create a nuclear fuel cycle department in 2007 to investigate the feasibility of re-establishing the nuclear fuel cycle or aspects thereof in South Africa (DMRE, 2008 & Bredell, 2008). Similarly, Klydon was considering ASP application in uranium enrichment in October 2011 (Ronander et al., 2012). This would have tested the regulation of ASP as a proven uranium enrichment technique compared to the other technologies that were initially and purposefully developed to enrich uranium.

1.2 Motivation and problem statement

The ASP carries similar traits as UCOR and Becker process through the stationary wall design (Strydom et al., 2016; Ronander et al., 2012). However, although the ASP was never used in uranium enrichment (Ronander et al., 2012), the NSG has used previous knowledge that similar aerodynamic processes (UCOR and Becker process) have enriched uranium, and without listing ASP as a trigger list item, imposed similar controls thereof (IAEA-1, 2019).

This has been adopted by NSG participating governments and adherence countries as a method to regulate isotope separation technologies (including aerodynamic technologies which have not been proven to enrich uranium) of other elements. With the control language mainly meant for the trigger list uranium enrichment technologies, this Research was intended to assess the current language and its applicability to the plant, equipment and technology for the isotope separation of ″other elements″ (All elements except for hydrogen, uranium and plutonium).

Non-proliferation studies in South Africa are not entrenched academically, with a lot of research done by regulatory bodies themselves for their continued day-to-day operations. Although such studies by regulatory bodies ensures that South Africa keeps abreast with all the non-proliferation developments worldwide, there are certain aspects that can be dealt with academically that South Africa can still contribute.

Additionally, the South African non-proliferation regulatory bodies are bound by the confidentiality in the execution of their tasks which is a drawback in making the non-proliferation and safeguards a common subject. Therefore, the South African Council for the Non-Proliferation of Weapons of Mass Destruction and the Ministry of Mineral Resources and Energy keep content of non-proliferation within the affected industry and not publicise it.

This study endeavored to review the scientific aspect and regulation of the ASP technology and its applications relative to the UCOR and Becker processes and conduct a survey to different role players that are directly/indirectly involved in the regulatory framework, within which the activities of Klydon fall, in the nuclear industry. This would include assessing the proposed criterion by the NSG and Zangger Committee, the implementation of obligations by South Africa.

The resultant assessment could either confirm similarities or show differences between the genesis technologies (UCOR and Becker process) and the ASP, understanding of and also propose the amendment of regulation language by both the NSG and South Africa, if necessary.

It should be noted that due to the proliferation and controlled nature of the information dealt with in the study, there are no recent publications that can be cited hence mostly old and limited publications are referenced.

1.3 Aim and objectives of the study

The purpose of this research was to review the Aerodynamic Separation Process (ASP) relative to the genesis technologies, especially the UCOR Stationary Wall Centrifuge and the Becker Jet Nozzle technique and to consider the Nuclear Suppliers

Group's determination on the regulation of the ASP technology relative to the South African legislation.

The objectives of the research were to:

- Review South Africa's history in the advancement of separation or enrichment technology and the evolution of the Aerodynamic Separation Process (ASP) from enrichment genesis technologies,
- Empirically determine the perceptions of relevant stakeholders regarding
  a) the Nuclear Suppliers Group's determination on the regulation of the ASP technology,
  b) their understanding of UCOR and ASP technology, and
  c) the regulation of ASP through South Africa's non-proliferation legislation,
- Suggest recommendations of on how the South African Government can enhance its regulation of the ASP technology.

1.4 Chapter summary

Chapter 1 contains the history of South Africa's discovery of Uranium and nuclear technology came through the advance world nuclear weapons programme. It further demonstrates development of nuclear non-proliferation regulations internationally and domestically, the problem statement, motivation, aims and objective of this research. Chapter 2 contains the literature review of the separation techniques and the nuclear non-proliferation regime.

CHAPTER 2: LITERATURE REVIEW

2.1 Isotope separation

Despite the chemical characteristics of an element's isotopes being relatively similar, they behave as wholly distinct entities in nuclear processes. Because their chemical characteristics are similar but their physical qualities are vastly different, their separation is extremely challenging, necessitating the creation of concepts and procedures tailored to a specific purpose (Benedict et al., 1981). Isotope separation and enrichment are used interchangeably because, while isotope separation is the process of separating individual isotopes from isotope mixtures, enrichment is the act of increasing the proportion of a desired isotope in an element.

Table 2.1 Isotope separation methods (Benedict et al., 1981).

Method	**Applied to**
Electromagnetic	^{235}U, all others
Electrolysis	^{2}H, Li
Distillation	^{2}H, ^{10}B, ^{13}C, ^{15}N, ^{18}O
Chemical-exchange	^{2}H, Li, ^{10}B, ^{13}C, ^{15}N, ^{18}O
Ion migration	Li
Diffusion methods	^{235}U
Gas centrifuge	^{235}U
Aerodynamic methods	^{235}U

Uranium enrichment is a subset of the much broader problem of isotope separation. Since the number of neutrons in a nucleus has only minute effects on the chemistry of an atom, the separation of isotopes cannot be accomplished by the use of chemical techniques of the kind normally used to purify substances (von Wielligh, 2015). The separation must take advantage of those properties of the nucleus which are affected by the number of neutrons: its mass, size and shape, magnetic moment, or angular momentum. By far the most important of these is the difference in mass, which is utilized in all of the proven enrichment processes and all but one of the advanced methods currently under development (Krass et al., 1983).

The impacts of uranium isotope mass discrepancies may be divided into two categories. The first is based on variations in average speed of atoms or molecules of various weights in thermal equilibrium. This is true for gaseous diffusion, centrifugation, and aerodynamic processes like jet nozzles and vortex tubes. The second takes use of various masses' inertias, or resistance to acceleration, when applied to the same force. Lighter atoms or molecules move quicker on average than heavier ones in mixtures at a given temperature, and lighter molecules respond more readily (i.e., accelerate faster) than heavier ones when a force is applied to them (Krass et al., 1983).

Table 2.2 Techniques for enriching uranium based on physical principles and mechanisms (Krass et al., 1983).

Property of isotope	**Physical principle**	**Physical mechanism**	**Separation process**
Nuclear mass	Newton's law of acceleration	Acceleration by electromagnetic forces	Calutron Plasma centrifuge Ion cyclotron Resonance
	Quantum theory of molecular bonds	Shift in chemical equilibrium	Chemical Exchange
		Selective absorption of infra-red light	Molecular laser isotope separation (MLIS)
	Equipartition of energy	Flow through porous barrier	Gaseous Diffusion
		Diffusion against pressure gradient	Centrifuge Jet nozzle Vortex tube
Nuclear size, shape, spin, magnetism	Quantum theory of atomic structure	Selective absorption of visible or ultraviolet light	Atomic vapour laser isotope separation (AVLIS)

Gas molecules are in constant motion and continuously collide with each other irrespective of temperature, thereby constantly caring equal kinetic energy among themselves. However, if the two particles are of different molecular mass, the lighter particle would have a larger velocity (Benedict et al., 1981; Krass et al., 1983). In gaseous diffusion, the particles are also continuously striking a wall, and if the wall has holes the lighter particle, which strikes the wall more frequently, gains advantage to permeate than larger particle. In such instances, if the holes are large enough to permeate, without allowing a flow of gas as a continuous fluid, the concentration of the smaller particles would be higher than the larger particles (Benedict et al., 1981).

Diffusion is used in the centrifuge and aerodynamic processes, although significant accelerations are added to accentuate the impact. The gas is propelled into fast rotation in all of these ways, generating a centrifugal force field in the gas that drives particles towards the circle's periphery. This force behaves similarly to gravity in that it accelerates particles at a constant pace regardless of their mass. However, centrifugal force cannot effect isotope separation on its own. All it does is cause a pressure variation in the gas, which causes particles of varying masses to diffuse at different rates. The centrifuge, nozzle, and vortex tube techniques are based on differential diffusion against a pressure gradient (Krass et al., 1983).

2.2 Separation principles and methods

2.2.1 Cascade structure and nomenclature

2.2.1.1 Separating element

Separating unit/element is the smallest part of an isotope separation plant that effects some separation of the process material. During separation, material of a certain isotopic composition flows into the element and then out as two flow streams, one stream contains a higher percentage of the desired isotope than the feed stream, while the other contains a lower percentage of the desired isotope than the feed stream. The material with the higher percentage is referred to as 'product,' while the material with the lower percentage is referred to as 'waste' or 'tails' (Benedict et al., 1981; Villani et al., 1979; Krass et al., 1983).

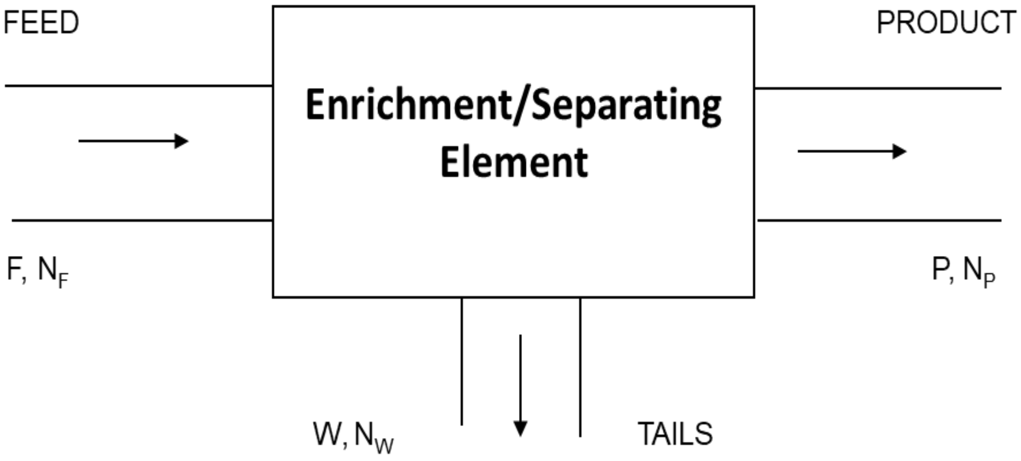


Figure 2.1 Schematic representation of an enrichment element showing the input (feed = F) and outputs (product = P, tails = W). NF, NP, NW denote the fraction of ^{235}U present in each stream (Krass et al., 1983).

where N_F, N_P, N_W denotes the percentage composition in numbers of molecules of the desired isotope (i.e., ^{235}U) in the respective flow stream, if the mixture contains only two isotopes, then the fraction of isotopes which are of the undesired type (^{238}U) will be (1-N). Thus, when a mixture contains only two isotopes, the 'relative isotopic abundance' is defined as

$$R = \mathrm{N}/(1 - \mathrm{N}) \qquad (1)$$

which is equivalent to the ratio of the number of molecules in the mixture of the two isotopes. The single-stage separation factor, q, which determines the concentration change across each stage, is given by the ratio between the relative abundance in the head and in the tail streams as

$$q = \frac{Rp}{Rw} = Np(1 - Nw)/Nw(1 - Np) \qquad (2)$$

However, because each discrete separative element enriches the material only slightly, and the single-stage separation factor is often close to unity despite being always slightly larger than one in many enrichment processes, it is best to deal with a smaller value to quantify the enrichment between separative elements. The separation gain g (also called the simple process difference) gives a distinct enrichment difference between elements through equation.

$$g = q - 1 \tag{3}$$

The single-stage separation factor is always smaller for heavier isotopes than for lighter isotopes, hence U enrichment requires interconnected separative elements.

2.2.1.2 Stage

A stage is a set of separating components that are linked in parallel, all fed with material of the same isotopic content, and produce partially separated product streams of the same composition. Even though an individual element has a relatively modest capacity, large volumes of material can be processed in a given stage by grouping multiple parts in parallel. This indicates that the cascade's 'width,' defined as the number of components in a given stage, is proportional to the overall rate of material flow through that stage. Although a single separating unit can act as a stage, numerous units are employed in parallel in enrichment procedures where the product gained each stage is minimal (Benedict et al., 1981; Villani et al., 1979).

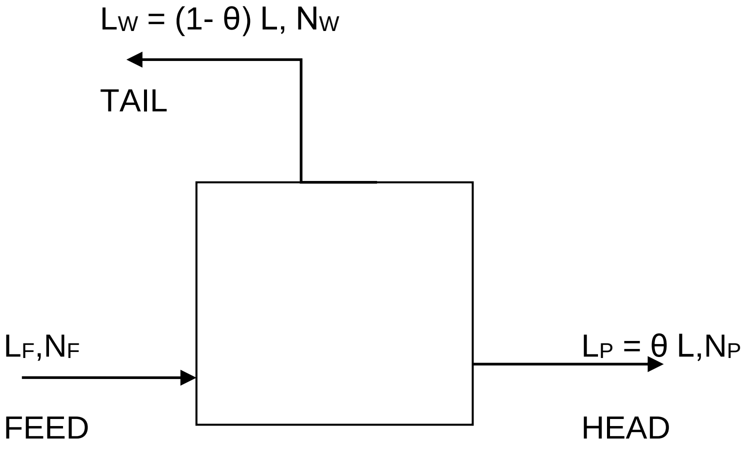


Figure 2.2 Generic stage of a cascade (feed = F, product = P, tails = W) (Villani et al., 1979).

The generic stage shows a steady state conditions of flow rates and compositions. The feed, with molar flow rate L_F and composition N_F, is separated in a head fraction $L_P = \theta L_F$ with composition $N_P > N_F$ and a tail fraction $L_W = (1-\theta) L_F$ with composition $N_W < N_F$ being θ the "cut" of the stage (Villani et al., 1979). Simply put, cut (θ) is the product flow to feed flow ratio (Krass et al., 1983).

$$\theta = P/F \tag{4}$$

2.2.1.3 Cascade

In case where the amount of separation accomplished by a single stage is less than the degree of separation desired between product and waste, the stages are connected in series pattern. Such a group of stages is called a cascade (Benedict et al., 1981). The various stages are linked in series, which means that each stage receives input from the previous one and passes it on to the next stage. The width of the stages, in general, is not constant, implying that the amount of material processed at each stage varies with stage number (Krass et al., 1983). The number of separating units in most uranium enrichment cascades decreases with each stage towards the product and waste ends and this is known as a tapered cascade. Conversely, a cascade with the same number of units (i.e., the same capacity) known as a squared off cascade, occurs at all stages of a group, as depicted in Figure 2.3.

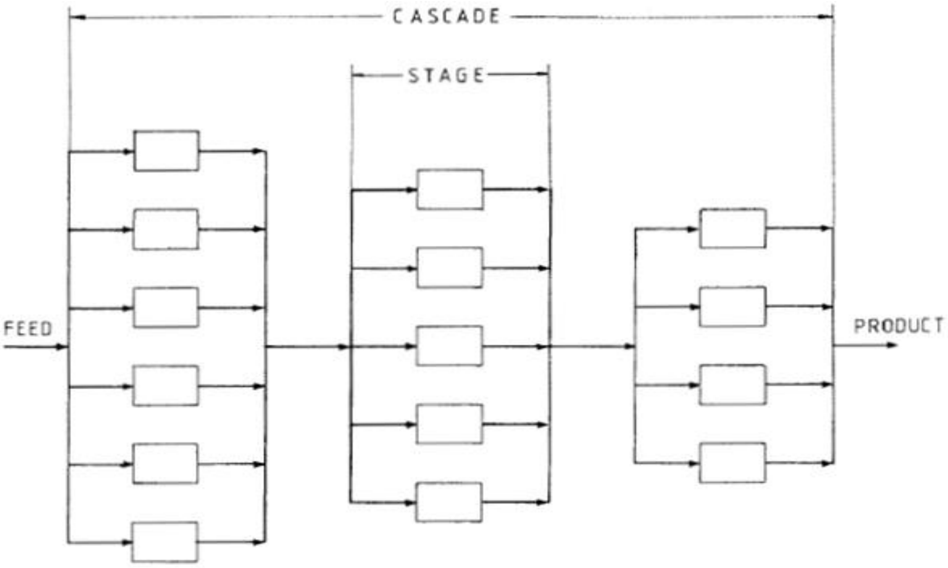


Figure 2.3 Arrangements of separating elements in stages and of stages in a tapered cascade. As this is a simple cascade, the tails are not shown (Villani et al., 1979).

In a simple cascade, the head fraction (product) of a particular stage feeds the next stage in line with the series connection of the stages, whilst the tail fractions (waste) leaving the stage is not reprocessed. This is not a viable or efficient way of isotope enrichment hence the separation plants adopt a counter-current scheme cascade where the yield is increased by further fractionation of each stage, in the next lower stage, of the tail fraction (Villani et al., 1979).

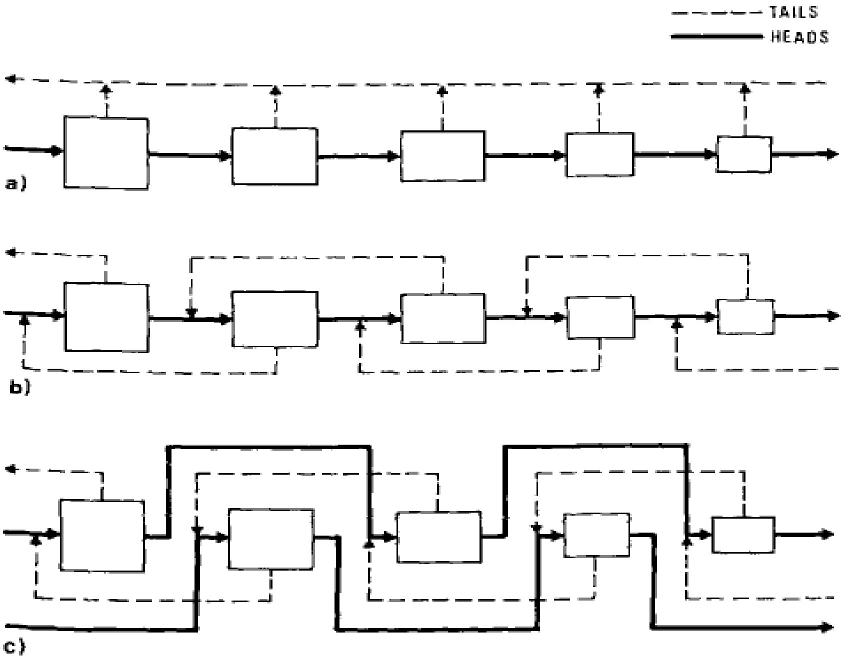


Figure 2.4 Examples of cascades; (a) simple cascade; (b) counter-current symmetric cascade; (c) counter-current asymmetric cascade with feed two stage downstream (Villani et al., 1979).

A counter-current scheme cascade can be symmetric or asymmetric. When the head stream of one stage feeds the next upper level, while the tail stream is recycled at the entrance of the next lower stage, it is said to be symmetric. In an asymmetrical counter-current scheme cascade, both head and tail streams are sent to different numbers of stages forward or backward, respectively, and the cascade design becomes considerably more complex (Villani et al., 1979; Krass et al., 1983). This is because whilst the symmetric counter-current cascade has a constant $\theta = \frac{1}{2}$, the asymmetric counter-current cascade, in some isotope separation processes, can't operate a stage at a cut of $\theta = \frac{1}{2}$ due to mechanical, or hydraulic reasons, or because the stage has a higher separative capacity (Benedict et al., 1981). The aerodynamic methods mostly employ such type of cascades where the amount of separation achieved in a stage varies depending on how the feeding stream is shared between the head and tail streams, leading to the “two-up, one-down” cascade depending on the process.

In cases where the feed is very valuable, it is vital to “clean” the first stage’s tail stream in a cascade, which depletes the above material, reducing the feeding flow rate per unit of product. This creates the enriching section, a cascade portion between the feed point and product end, and the stripping section, a cascade portion between the feed point and the waste end. The enriching section makes material of product composition and is essential during the making of desired isotope from feed. The stripping section increases the recovery of the desired isotope from feed through reducing the amount of feed required to make a given amount of product (Benedict et al., 1981).

Because cascades have an enriching section above the feed point and a 'stripping' section below the feed point, the number of stages required in each section is determined independently by the desired product and tails assays, and the widths of the stages in each section are determined by the flow rates of enriched and depleted materials, with an enriching section above the feed point and a 'stripping' section below the feed point. This small collection of parameters is sufficient to completely establish the geometry of a 'ideal' cascade, which optimizes the ratio of separative labor to product generated by guaranteeing that streams of varying concentrations are never mixed together. In an ideal cascade, the isotope ratios of each phase and the preceding and next stages are inextricably linked. If n denotes the number of stages and Rn denotes the relative isotopic abundance of material entering that stage, then

$$R_{n+1} = \propto R_n \tag{5}$$

$$R_{n-1} = \frac{1}{\propto} R_n \tag{6}$$

where α is referred to as a stage's 'enrichment factor' (Krass et al., 1983).

2.2.1.4 Value function and Separative Work Unit

Entropy is the fundamental property that is altered by the separation process. Entropy is a measure of a system's disorder, and the product and tails from a separative element are a slightly less disordered system than the incoming feed material (Krass et al., 1983). In other words, the isotopes have been partially separated and are on their way to a more orderly state of total separation. According to the second law of thermodynamics, any decrease in a system's entropy can only be accomplished through the expenditure of energy. In this case (during enrichment) the separative element is seen as absorbing energy. Thus, if separation was reversible, one would be able to calculate the energy absorbed by an element and equate to production cost (Villani et al., 1979; Krass et al., 1983). Additionally, feed material composition in a cascade also adds to uncertainty because a given element will cause different entropy changes at different points in a cascade. Due to this, concept of 'separative work' or 'separative power' was invented to have a quantity that could be assigned to a separative element regardless of its position in a cascade and was roughly proportional to the element's rate of energy consumption.

Hence, instead of entropy of a mixture, the value function of a mixture is given by

$$V(x) = (2x-1)\ln(\frac{x}{1-x}) \tag{7}$$

Such value function feeds into the calculation of the Separative Work Unit (SWU), which is a measure of Separative Work (denoted by *ΔU*). SWU is the standard measure of enrichment services. The effort expended in separating a mass F of feed of assay x_f into a mass P of product assay x_p and waste of mass W and assay x_w is expressed in terms of the number of separative work units needed, given by equation,

$$SWU = WV(x_w) + PV\left(x_p\right) - FV(x_f) \tag{8}$$

where V(x) is the "value function" (Whitaker, 2019).

2.2.2 Separation and enrichment methods

Different types of uranium enrichment processes that have been developed or are in the process of being developed, with only few techniques having shown some success and even a lesser number commercialised. Post the Manhattan project, whose motivation was military application, progress from research to commercialising of uranium enrichment techniques has been influenced by different factors, *viz*, production costs, operational costs and efficiency, marketability, proliferation risks, etc. Certain techniques have proven to be more viable and hence more common whilst others such as the aerodynamic process became unique to certain countries and shrouded in secrecy, as a result, the descriptions that follow must concentrate on the features that can be deduced from a basic physical understanding of the process without detailed engineering data.

2.2.2.1 Gaseous diffusion

Basic principles: Gaseous diffusion method is based on the so-called 'equipartition principle' of statistical mechanics. This principle states that in a gas consisting of several types of molecules, each type will have the same average energy of motion (kinetic energy, $E_{\mathrm{k}} = {}^{1}/_{2}\, mv^{2}$). This equality of average energies is attained and preserved by the enormous number of collisions between molecules which are taking place at all times in the gas. These collisions ensure that any excess energy which may have been associated with one component will rapidly be shared equally with all the others. This equal sharing is called thermal equilibrium (Krass et al., 1983). With kinetic energy, E_k, of a molecule of mass m related to its velocity v, molecules with the same average kinetic energy will have average velocities, which differ in inverse proportion to the square roots of their masses.

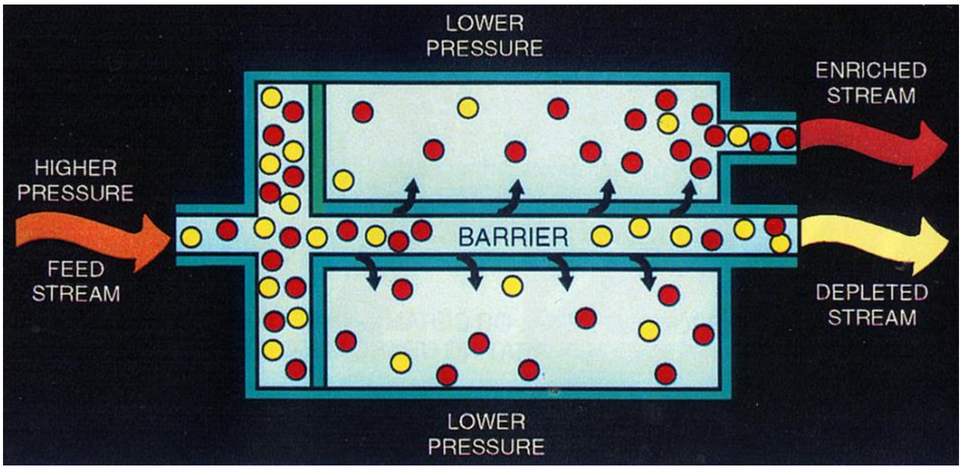


Figure 2.5 Illustration of the gaseous diffusion principle. The enriched stream has a higher ^{235}U concentration than the feed stream, which has a higher concentration than the depleted stream (Whitaker, 2019).

Process: During the process, the stage feed gas UF_6 flows past a diffusion barrier made of sintered powdered nickel material with very fine holes, i.e. smaller than the mean free path of the UF_6 molecules. About half of the feed gas flows through the barrier to a lower-pressure region. The gas passing through the barrier is slightly richer in ^{235}U than the gas remaining on the high-pressure side, because the mean speed of $^{235}UF_6$ molecules is slightly higher than that of $^{238}UF_6$ molecules. These mean speeds are in the inverse ratio of the square roots of the molecular weights of the two molecules. With uranium hexafluoride gas comprising of $^{235}UF_6$ and $^{238}UF_6$ and their respective molecular masses of 349 and 352, and under operating conditions, the ratio of $^{235}UF_6$ atoms and $^{238}UF_6$ atoms in the enriched UF_6 fraction passing through the barrier, $y/(1-y)$, to the corresponding ratio in the depleted UF_6 fraction remaining behind, $x/(1-x)$, is in the ratio of their mean speeds (Benedict et al, 1981; Ragheb, 2019):

$$\propto \equiv \frac{y/(1-y)}{x/(1-x)} = \sqrt{\frac{m_{238UF6}}{m_{235UF6}}} = \sqrt{\frac{352}{349}} = 1.00429 \tag{9}$$

The ratio $\left(\frac{y/(1-y)}{x/(1-x)}\right)$ is called the stage enrichment factor and is denoted by $\propto$, as described under section 2.2.1.3. The single stage separation/enrichment factor for a gaseous diffusion is close to unity thereby depicting small separation efficiency. It is thus important to use multiple counter-current cascades to achieve desirable enrichment levels.

2.2.2.2 Gas centrifuge

Basic principles: Under gas centrifuge, the movement of the gas molecules are guided by the potential energy ($E_\mathrm{p} = mgh$) of the molecules where m is the molecule's mass and g is the acceleration due to gravity, equal to 9.8 m/s^2. The UF_6 gas rotating inside the rapidly rotating cylindrical bowl is subjected to centrifugal accelerations thousands of times greater than gravity. This makes the pressure at the outer radius of the bowl millions of times greater than at the axis and causes the concentration of $^{238}UF_6$ relative to $^{235}UF_6$ to be higher at the outer radius than at the axis.

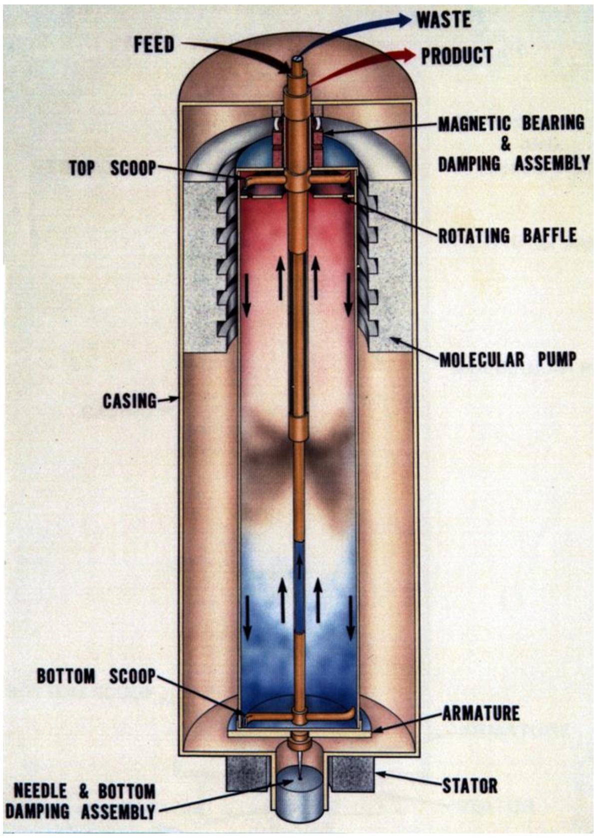


Figure 2.6 A gas centrifuge is depicted schematically; the feed, product, and waste lines are all stationary. Because of centrifugal force, the heavier $^{238}UF_6$ molecules preferentially travel to the rotor's periphery, resulting in partial separation of molecules containing ^{235}U and ^{238}U. The axial counter-current movement of the gas within the centrifuge enhances this action (Whitaker, 2019).

Process: The UF_6 gas, a mixture of $^{235}UF_6$ and $^{238}UF_6$, is fed to the top of the centrifuge casing through a pipe that feeds a stationary column located at the centre of the rotor. Openings in the column admit feed gas to the interior of the spinning rotor. Centrifuges can be of varying height and diameter. High-speed rotation produces centrifugal forces that create a concentration gradient in the UF_6 gas contained within the rotor tube. The heavier $^{238}UF_6$ concentrates near the rotor wall, while gas closer to the axis of rotation (further away from the wall) is relatively rich in $^{235}UF_6$, the lighter constituent of the UF_6 gas. A counter-current flow parallel to the axis of rotation enhances the centrifugal separation effect and makes it possible to withdraw product through a stationary scoop at one end of the rotor and waste through a second static scoop at the other end of the rotor. Because the product stream has a higher ^{235}U concentration than the feed stream, it is said to be enriched in ^{235}U relative to the feed. The waste stream is depleted in ^{235}U relative to the feed. By making the bowl longer, the concentration difference between the top and bottom can be made to be many times greater than the between the centre and outside speeds (Benedict et al., 1981).

2.2.2.3 Chemical exchange methods

Basic principles: The chemical-exchange method of isotope separation depends on the very small tendency of different isotopes of an element to concentrate in different molecules when there is an opportunity for exchange between the molecules, leading to an equilibrium with reversible reaction capabilities. Thus, when compounds XU and ZU are mixed, the reversible reaction equation $X^{238}U + Z^{235}U \rightleftharpoons X^{235}U + Z^{238}U$ eventually comes to an equilibrium with equilibrium constant $= \frac{[X^{235}U][Z^{238}U]}{[X^{238}U][Z^{235}U]}$. (10)

The chemical equation is written in such a way that K is greater than one, implying that in equilibrium, the product of concentrations with ^{235}U in X and ^{238}U in Z is greater than the product containing the traded ^{238}U and ^{235}U. As a result, if the two compounds XU and ZU initially have identical isotopic ratios, after the equilibrium is established, compound X will be slightly enriched and compound Z will be slightly depleted in ^{235}U (Krass et al., 1983).

Process: The slight difference in mass between uranium isotopes causes small changes in chemical reaction equilibria, which can be used to separate the isotopes. Two processes have been developed with great success: liquid-liquid chemical exchange and solid-liquid ion exchange.

Immiscible liquid phases (aqueous and organic) are counter-currently contacted in the liquid-liquid chemical exchange process, resulting in a cascading effect of thousands of separation stages (Krass et al., 1983). The aqueous phase contains uranium chloride in a hydrochloric acid solution, whereas the organic phase contains an extractant containing uranium chloride in an organic solvent. In the separation cascade, liquid-liquid exchange columns (such as pulsed columns with sieve plates) or liquid centrifugal contactors can be utilized. To meet the reflux criteria at each end of the separation cascade, chemical changes (oxidation and reduction) are necessary. A major design concern is to avoid contamination of the process streams with certain metal ions. Plastic, plastic-lined (including use of fluorocarbon polymers) and/or glass-lined columns and piping are therefore used (Krass et al., 1983).

In the solid-liquid ion-exchange process, enrichment is accomplished by uranium adsorption/desorption on a special, very fast-acting, ion-exchange resin or adsorbent. A solution of uranium in hydrochloric acid and other chemical agents is passed through cylindrical enrichment columns containing packed beds of the adsorbent. For a continuous process, a reflux system is necessary to release the uranium from the adsorbent back into the liquid flow so that ‘product’ and ‘tails’ can be collected. This is accomplished with the use of suitable reduction/oxidation chemical agents that are fully regenerated in separate external circuits and that may be partially regenerated within the isotopic separation columns themselves. The presence of hot concentrated hydrochloric acid solutions in the process requires that the equipment be made of or protected by special corrosion-resistant materials (Krass et al., 1983).

2.2.2.4 Laser isotope separation

Basic principles: Uranium enrichment processes using lasers take advantage of the different photon absorption properties of uranium isotopes. If the quantum levels of the particles differ, certain particles (of interest) can selectively and exclusively be excited by monochromatic (single wavelength) laser (Kemp et al., 1992). Using laser photons for separating isotopes is attractive because the frequency differences or “isotope-shifts” of isotopes such as ^{235}U and ^{238}U, or compounds like $^{235}UF_6$ and $^{238}UF_6$, far exceed the narrow linewidths of laser emission lines. Thus, if the laser frequency is tuned to the frequency of the absorption peak of one isotope, it is possible to have a gaseous species of this isotope absorb most laser energy, provided isotope overlap from broadening effects is small (Krass et al., 1983).

Process: Although there are various laser isotope separation techniques that have been researched, the description below will be limited to Molecular Laser Isotope Separation (MLIS) and Atomic Vapour Laser Isotope Separation (AVLIS).

MLIS: This uses selective photodissociation of molecules into stable fragments. UF_6 plus a carrier gas is flow-cooled via adiabatic expansion through a narrow slit. At 100 Kelvin, approximately 30% of the ground state is populated, where isotope differences in absorption spectra can be used for selective excitation of the ^{235}U isotope containing UF_6 molecules. $^{235}UF_6$ is selectively excited by tuneable 16 µm laser energy obtained from a Raman shifted CO_2 laser (Kemp et al., 1992).

$$^{235}UF_6 + {}^{238}UF_6 + \text{carrier gas} \longrightarrow_{16\mu m}\longrightarrow {}^{235}UF^*_6 + {}^{238}UF_6 \tag{11}$$

The excited species is further excited by a second 16 µm laser and finally dissociated by either a 10.6 µm CO_2 or a third 16 µm laser

$$^{235}UF^*_6 + \text{photons} \longrightarrow_{10.16\mu m}\longrightarrow {}^{235}UF_5 + F \tag{12}$$

The $^{235}UF_5$ molecules merge wherein particulates are formed that are easily separated from the remaining gas. The fluorine radical can then be removed using a suitable scavenger (Strydom, 1999; Kemp et al, 1992).

AVLIS: This uses selective photoionization to separate isotopes of elements in an atomic beam. Atomic uranium vapor-based methods of laser isotope separation are based on absorption of light of different wavelengths, by ^{235}U atoms and ^{238}U atoms (Krass et al., 1983; Benedict et al., 1981). Although the absorption wavelengths of the two isotopes differ by a very small amount, about one part in a million, the dye lasers used in these laser isotope separation methods can be tuned so precisely that only ^{235}U atoms absorb the laser light. When laser light is absorbed by a ^{235}U atom, its electrons are excited to a higher energy state. Upon absorption of laser light tuned to additional wavelengths, the ^{235}U atom is excited to successively higher energy states to the point where it ejects an electron and transforms into a positively charged ion. This is referred to as photoionization. An electric and/or magnetic field can be used to deflect the positively charged ^{235}U ions to a product collector. Most ^{238}U atoms pass through the product collector and deposit on the tails collector; however, some deposit on the product collector, largely due to hydrodynamic effects. These processes include a separator system and a laser system. The separator system contains a vaporizer, a product collector, and a tails collector. In the vaporizer, uranium metal is melted and vaporized to form a high-speed stream of atomic uranium vapor, which is illuminated by the precisely tuned laser light (Krass et al., 1983).

2.2.2.5 Electromagnetic processes

Basic principles: Electromagnetic processes use magnetic fields to accelerate uranium ions. When a charged particle enters such a field, it can feel a force that has two distinct properties:

1. It only happens if the particle moves perpendicular to the field lines.
2. The force itself is perpendicular to both the field lines and the particle's velocity (Krass et al., 1983).

Because of these two magnetic force characteristics, all charged particles (electrons or ions) in a uniform magnetic field follow circular or helical paths, with the plane of circular motion perpendicular to the magnetic field lines. The frequency of circular motion, known as the 'cyclotron frequency,' is determined solely by the particle's charge and mass, as well as the strength of the magnetic field (Krass et al., 1983).

Process: In an electromagnetic isotope separator (EMIS) ion source, solid uranium tetrachloride (UCl_4) is heated to produce UCl_4 vapour. Electrons emitted by a hot filament cathode bombard the UCl_4 molecules, ideally producing singly charged U+ ions. An electrical potential of approximately 100 V is applied between the cathode and an anode on the opposite side of the source assembly to energize the electrons. The U+ ions are accelerated to high speeds by applying a potential to a system of electrodes, each of which contains a long, narrow slit through which the high-speed ions pass as they begin their curved path toward the ion collector (Krass et al., 1983). The ion source assembly must be supplied with electrical energy to heat the feed material, to heat the hot filament cathode, and to accelerate the uranium ions. Uranium ions enter the ion collector (i.e., “ion receiver”) assembly through two long, narrow slits, which are likely to be curved to match the shape of the ion beam. The lighter $^{235}U+$ ions are more easily deflected by the magnetic field and follow a path with a smaller radius of curvature (by approximately 0.6%) than that traversed by the heavier $^{238}U+$ ions; these ions enter one of the two slits and are collected in a carefully shaped chamber (often called a “pocket”) behind the slit. The $^{238}U+$ ions enter the other slit and are collected in their pocket (Krass et al., 1983).

2.2.2.6 Aerodynamic separation processes

Basic principles: In aerodynamic enrichment processes, a mixture of gaseous UF_6 and light gas (hydrogen or helium) is compressed and then passed through separating elements wherein isotopic separation is accomplished by the generation of high centrifugal forces and pressure diffusion over a curved stationary wall geometry. Therefore, the serious mechanical problems of highly stressed rotating machines are avoided (Malling et al., 1976; Becker et al., 1977a; Van Hook, 2011). Because an aerodynamic plant necessitates several of these stages, the quantities can provide an important indication of end use. Because aerodynamic processes employ UF_6, all equipment, pipeline, and instrumentation surfaces that come into contact with the gas must be made of or protected by materials that remain stable in contact with UF_6.

Process: Numerous methods have been included in the category of aerodynamic isotope separation processes such as: the separation nozzle; opposed gas jets; the gas vortex; the separation probes; interacting molecular beams; jet penetration processes; and time of flight separation (Malling et al., 1976). However, two processes have been developed with great success: the separation nozzle process and the vortex tube process. The main components of a separation stage in both processes include cylindrical vessels that house the special separation elements (nozzles or vortex tubes), gas compressors, and heat exchangers to remove the heat of compression.

Jet nozzle technology: During this process, commonly known as the Becker process, a stream of about 5% UF_6 in 95% H_2 flows along a curved fixed wall. At the end of the deflection the flow is split into a lighter and a heavier fraction by means of a skimmer. The hydrogen, which is present in a large molar excess, increases the flow velocity of the UF_6 and, hence, adds to the centrifugal force determining the separation. With a H_2/UF_6 mixture containing 5mol UF_6, the centrifugal force acting upon the UF_6 molecules is nearly 20 times as high as with pure UF_6. A further positive influence on separation, exerted by the light gas, stems from the differing migration rates of the isotopes during establishment of the hypsometric density distribution (Boskma, 1979; Becker et al., 1977a; Becker et al., 1977b). This is demonstrated in Figure 2.7.

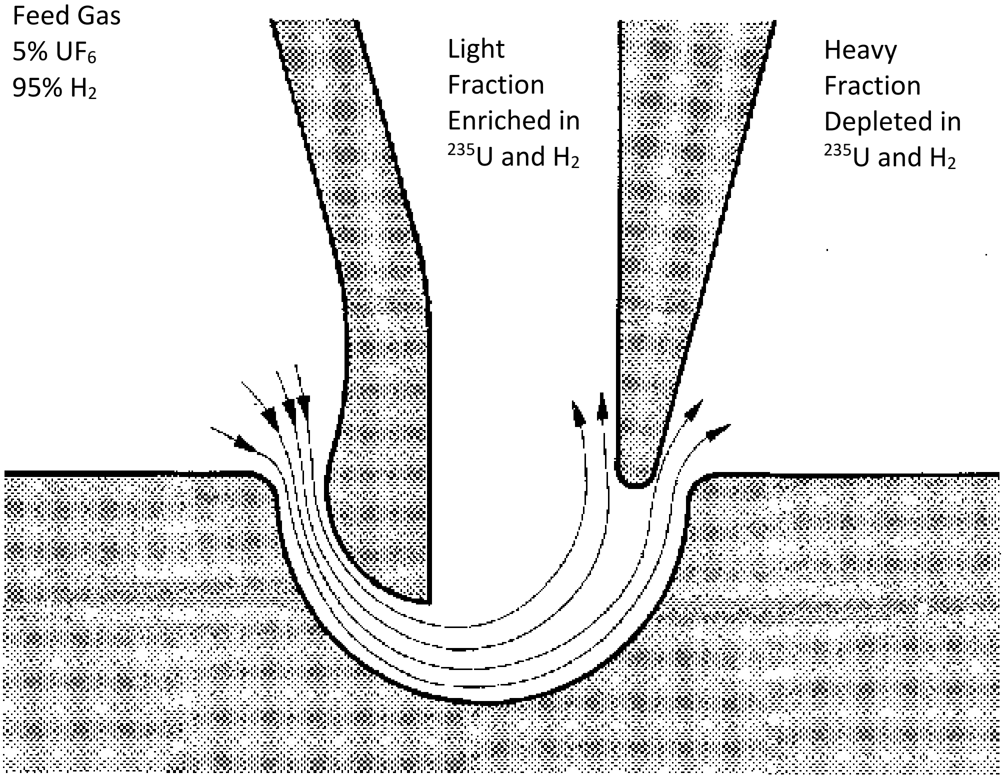


Figure 2.7 Cross section of separation nozzle system used in commercial implementation of separation nozzle process (Whitaker, 2019).

- Separation elements and operating conditions

According to the gas kinetic scaling relations, the optimum operating pressure of the nozzle system is inversely proportional to its characteristic dimensions. Thus, a separation nozzle with the smallest practical dimensions is the most attractive, economically, due to the savings in equipment sizes associated with a high operating pressure (Becker et al., 1976). To develop these elements, an extruded aluminium tube or a stack of photoetched metal foils serves as the basic unit of the commercial separation element. This tube is subdivided by partition walls into sector-shaped chambers. It carries 10 slit-shaped nozzle systems on its periphery. The separation-nozzle system proper consists of the deflection groove machined in the tube and aluminium strips, the edges of which are designed as the skimmer and the nozzle wall, respectively. The aluminium strips are fixed in the dovetail grooves of the tube and held in place by balls forced in between the strips. The deflection groove of the nozzle system normally has a radius of curvature of 1/10 mm. The feed gas for the nozzle systems is introduced at one end of the tube into the channels marked F; the heavy fraction is withdrawn at the opposite end of the tube from the channels marked H. The light fraction is pumped off from the space around the tube (Becker et al., 1976).

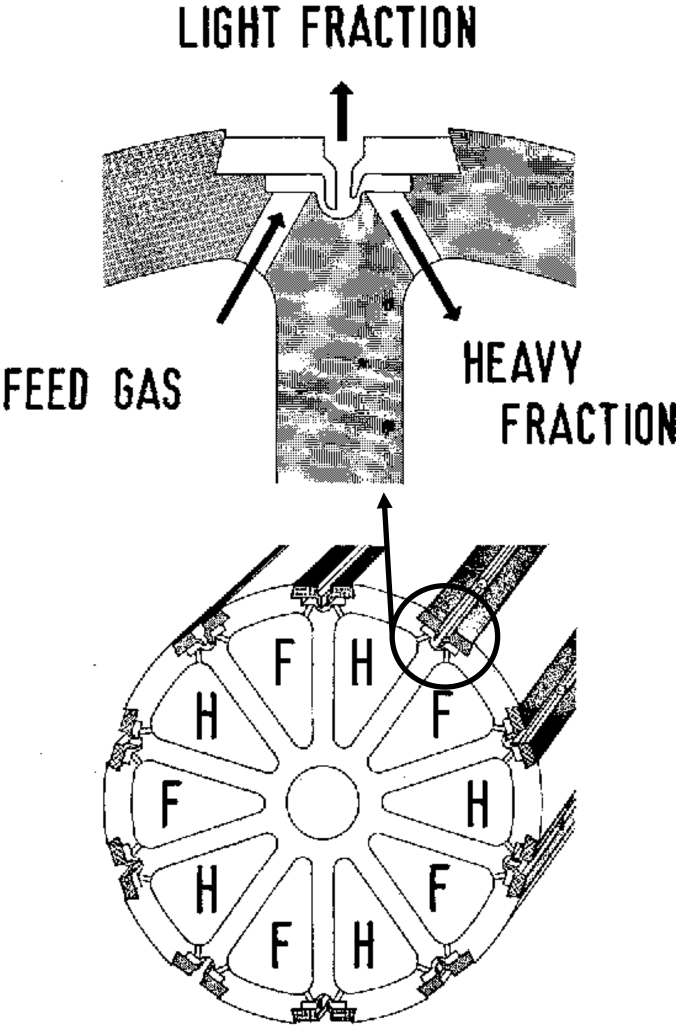


Figure 2.8 Schematic representation of a separation nozzle assembly formed from an extruded aluminium tube (Becker et al., 1976).

Intended or projected enrichment levels are achieved only when elementary uranium isotope separation effect supplied by the separating elements is multiplied in a separation cascade (Becker et al., 1976). The gas expanded in the individual separation nozzle stages is recompressed before being fed to the separation nozzle systems of the next stages. The geometric parameters and the operating conditions of the separation nozzle systems are set so that the separative work produced by the whole plant is as affordable as possible based on energy consumption during separation process (Becker, 1976). This is achieved by obtaining the minimum of the specific ideal isothermal compression energy (*ratio between the ideal isothermal compression energy to recompress the gas expanded in the separation nozzle and the separative work produced*) through:

$$E = 2\,RT \ln \pi \,/ N_0 \varepsilon_A^2 v_u (1 - v_u) \tag{13}$$

where R = gas constant, T = absolute temperature, π = expansion ratio, N_0 = UF_6 mole fraction, v_u = UF_6 cut and ε_A^2 = elementary effect of isotope separation (separation gain) squared.

Using this equation, an ideal UF_6 cut of 0.25 is achieved, with the corresponding cascade diagram in Figure 2.9. Fine adjustment of the uranium cut is possible in the individual separation stages by means of throttle valves installed in the suction lines of the heavy fractions (Becker et al., 1974; Becker, 1976).

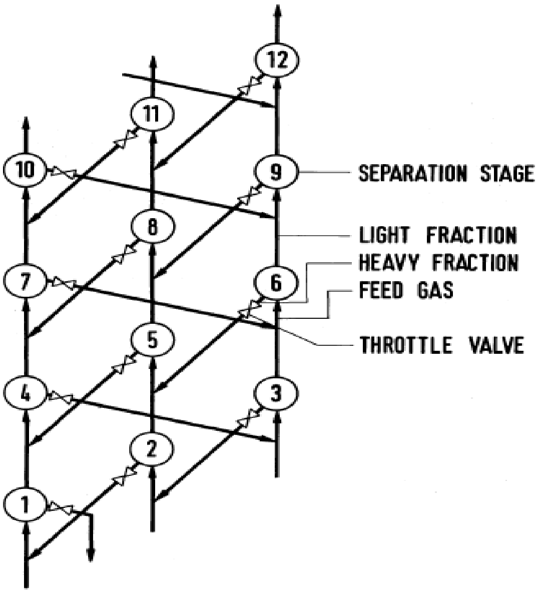


Figure 2.9 Cascade flowsheet for a UF_6-cut of 0.25 (Becker et al., 1976).

- Separation stages

The stage is constructed as an integrated unit. It consists of a tank containing the separation elements, a gas distribution system, a gas cooler, a centrifugal/two-stage radial compressor and the motor rigidly coupled to the compressor. This applies to both the large stage containing about 80 separation element tubes of 2-meter length and small stage, whose separation elements are arranged as a compact unit to allow easy installation. In a large stage, the heavy fraction is recycled by the upper closed-circuit loop and mixed with the light fraction coming from the separation elements.

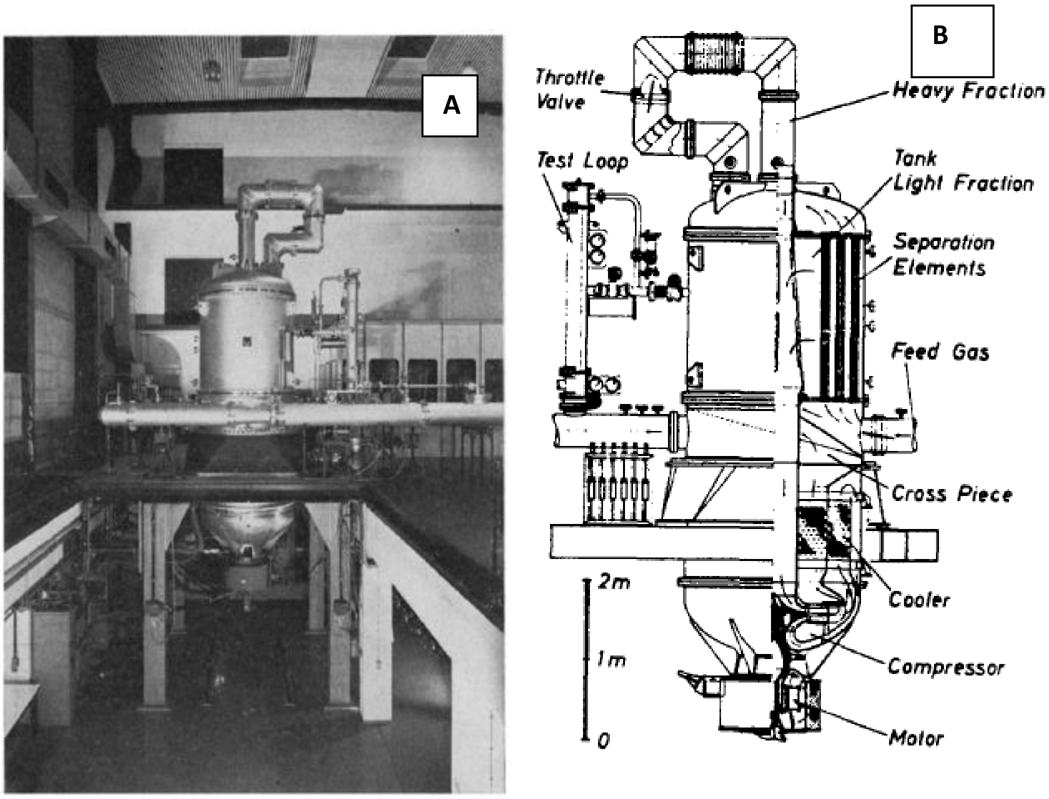


Figure 2.10 A) A prototype jet nozzle large separative stage and **B)** its schematic representation (Becker et al., 1974).

- Cascade design and UF_6-recycling

  The jet nozzle separation cascade involves two types of separation stages, the large and small stages integrated. Figure 2.11 shows the use of two types of stages with a 1:3 ratio of flows makes the performance approach that of a corresponding ideal cascade with an efficiency of approximately 90 %.

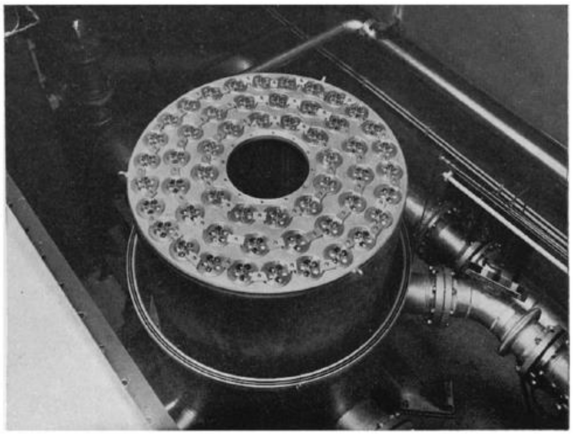


Figure 2.11 Loading of the separation nozzle elements into the small separation stage (Becker et al., 1977b).

A total of about 500 stages must be connected in series in order to produce enriched uranium containing 3% U-235 and to strip U-235 content in the waste to some 0.3% (Becker et al., 1976). A separation nozzle cascade produces a net upward transport of the light auxiliary gas, which is in the order of the stage throughput. To avoid enrichment of the light gas, the upward transport has to be extracted from the top and fed back to the bottom of the section, after passing through the UF_6-recycling facilities. Similarly, around 80 to 90% UF_6 in the upward flow is stripped off and added to the feed flows of the top stages through a separation nozzle within the recycle facilities (Becker et al., 1977b), as in Figure 2.12.

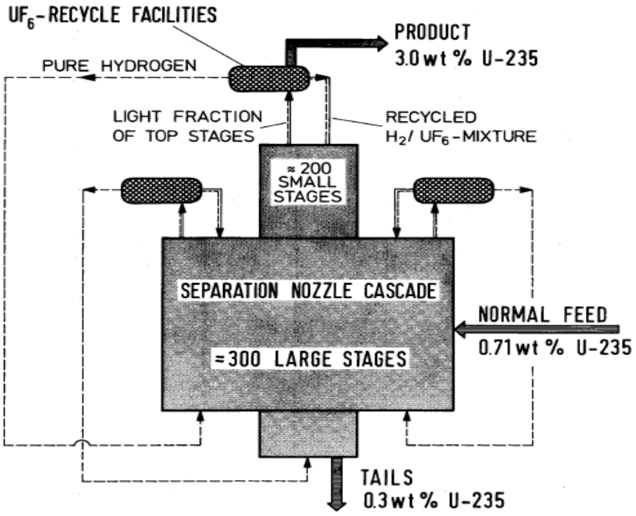


Figure 2.12 Schematic representation of a separation nozzle cascade with UF_6 recycle facilities (Becker et al., 1977b).

Advanced vortex tube technology: During this process, commonly known as the UCOR process, similarly a stream of UF_6 in H_2 process gas fluid flows along a stationary wall centrifuge, which is used as a separating element. However, the working fluid is 1-2 percent UF_6 and 98-99 percent H_2 gas mixture (USADOE, 1980). The separating element employed in the UCOR process for uranium enrichment has an enriched stream, which is much smaller than the depleted stream (Haarhof, 1976 and Kemp et al., 1992). This is attributed to 2-stream extraction that would ideally split the injected process gas into heavy (*F*) and light (*G*) mass streams. It is a simple nozzle configuration to harvest the separated streams; a conical nozzle with selected inside diameter is pushed into the centre of a hole in the vessel end, with the tip of the nozzle penetrating the separation tube (referred to as the *dispersion length* (δ) of the extraction nozzles). A drawback in this design is that the separation-neutral boundary flow (*C*) was drawn off with the heavy stream (*F*); hence diluting/destroying whatever separation occurred in the heavy stream (Ronander et al., 2012)

To deal with this small cut, a new cascade technique named "helikon" has been developed (Roux et al., 1975). It is based on the principle that an axial flow compressor can simultaneously compress several streams of different isotopic composition, which flow through it in parallel, without any significant mixing between them. The technique makes it possible to achieve the desired enrichment with a relatively small number of separating units, by making the best use of the high enrichment factor available (Alant et al., 1980; Roux et al., 1975). A further feature of the helikon technique is that a module yields an enrichment factor, which is not constant but can vary. In this way, a cascade can be built up from modules of a fixed size, which is a great advantage when compared to conventional cascade arrangements where several unit sizes are required (Haarhof, 1976).

- Separation elements and operating conditions

The design of the separating element, described as an advanced vortex tube or stationary wall centrifuge, is very flexible in that various combinations of molecular mass, operating pressure, pressure ratio and hence separative power per unit volume of installed separating elements could be achieved (Roux et al., 1977; Hutcheon et al., 2011).

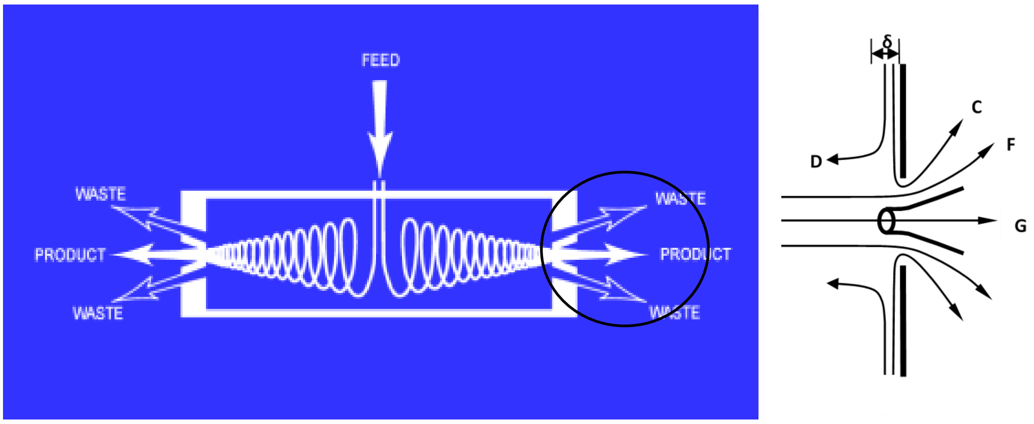


Figure 2.13 Schematic of basic separating element and possible genesis technology nozzle extraction designs (Kemp et al., 1992; Ronander et al., 2012).

The enrichment factor achieved by this type of separating device is asymmetrical, whereby the enhancement of the isotopic concentration of the enriched stream produced by the device is significantly more than the corresponding reduction in the concentration of the depleted stream leaving the element (Bredell, 1990). All process pressures throughout the system will be comfortably above atmospheric and depending on the type of ‘centrifuge" used, the maximum process pressure will be in a range of up to 600 kPa (6 bar). The UF_6 partial pressure will however be sufficiently low to eliminate the need for process heating during plant operation, and the maximum temperature at the compressor delivery will not exceed 75°C (Roux et al., 1975).

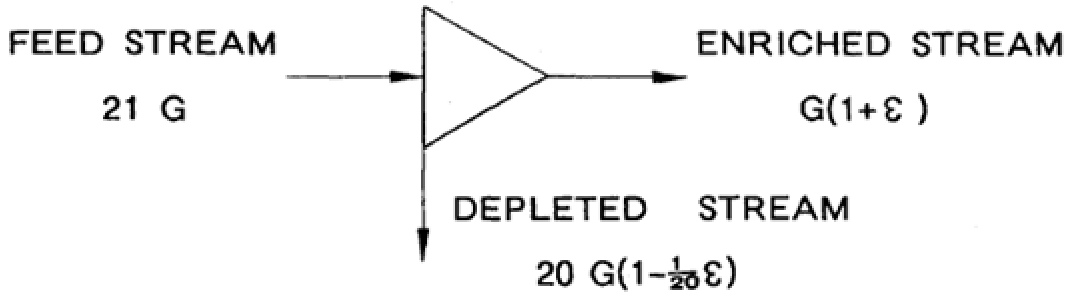


Figure 2.14 Schematic representation of an asymmetrical separating element, with G the mass flow units of Uranium and Ɛ the enrichment factor (Bredell, 1990).

The process is characterised by a high separation factor over the element, namely from 1,025 to 1,030. Furthermore, it has a high degree of asymmetry with respect to the UF_6 flow in the enriched and depleted streams, which emerge at different pressures. The feed to enriched stream pressure ratio is typically 1,5 whereas the feed to depleted stream pressure ratio is typically only 1,12. An important feature of the separation elements is that they can also be used to yield high purity hydrogen in a single-step separation of UF_6 from hydrogen, when fed with material of approximately the enriched stream composition. Separation factors greater than 10 000 to 1 in a single pass can easily be achieved (Roux et al., 1975).

- Separation stages

The UCOR separating element has a very small cut, i.e. it has a high degree of asymmetry with respect to the UF_6 flow in the enriched and depleted streams, which emerge at different pressures (Bredell, 1990). It would thus be inefficient to apply conventional cascade arrangement to such elements since they require many elaborately connected stages to attain a high separative power efficiency. In order to overcome the difficulty, the UCOR process employs separation stages with numerous interconnected separating elements and

(Figure 2.15), configured to behave in symmetrical fashion, by ensuring that the combined enriched flow produced by the separation stage is equal to the depleted flow leaving the stage (Kemp et al., 1992).

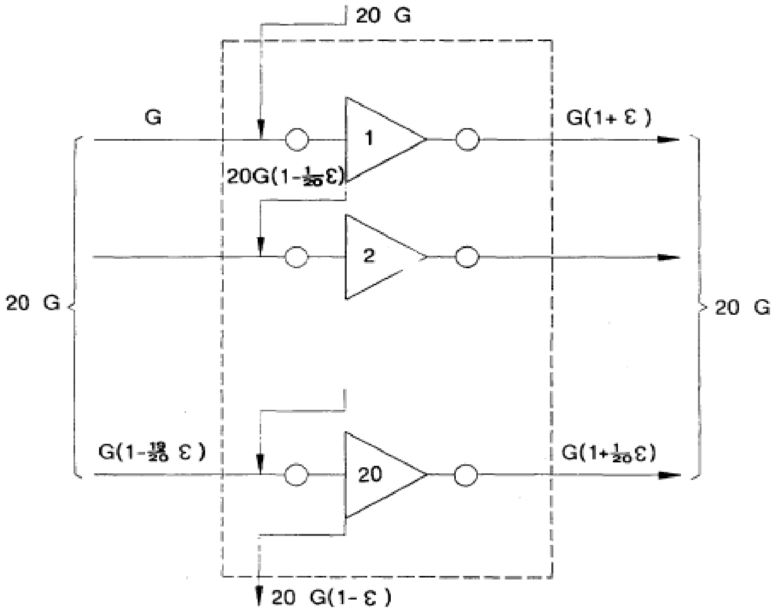


Figure 2.15 Symmetrical separation stages consisting of 20 interconnected asymmetrical separating elements (Bredell, 1990; Kemp et al., 1992).

Thus, all components belonging to a particular separation stage, i.e. separating elements, compressors and accompanying heat exchangers, are physically contained in a single cylindrical vessel, called a module, in which element gas flow inter-connection is achieved by means of partitioned channels arranged inside the module (Bredell, 1990; Kemp et al., 1992), Figure 2.16.

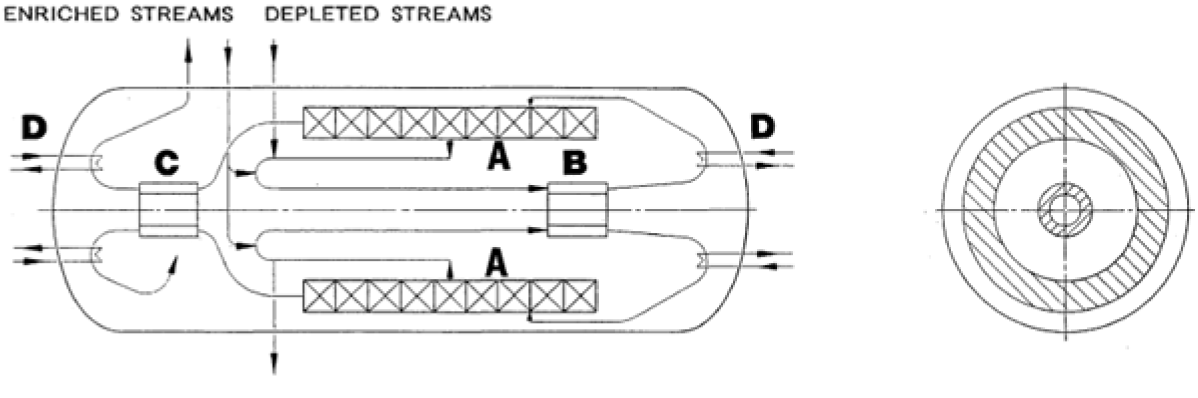


Figure 2.16 Schematic representation of a module, with A, separating elements, B, feed stream axial flow compressor, C, enriched stream axial flow compressor and D, heat exchangers (Bredell, 1990; Kemp et al., 1992).

- Cascade design

The conventional cascade technique for an element with a small cut requires many stages to achieve ideal separative work because of the asymmetry due to the UF_6 cut in the enriched and depleted streams (Grant et al., 1976). Figure 2.17 and Figure 2.18 below shows part of a cascade for an element with a UF_6 flow ratio (cut) (θ) of enriched to depleted streams equivalent to 1/3. The enriched stream from stage j goes to stage (j+3) and the depleted stream to stage (j-1). The enrichment factor between stages is 1/3 of the enrichment factor, $\epsilon_{\ell 0}$ between the enriched and inlet streams of a stage.

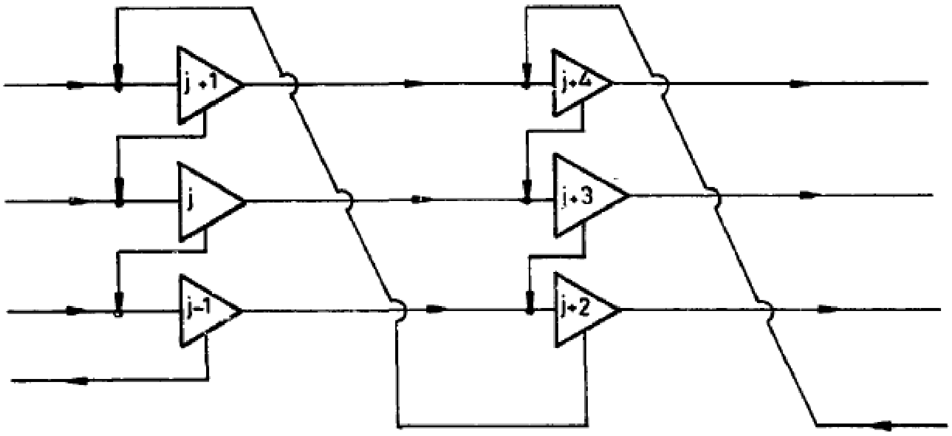


Figure 2.17 Arrangement of separating elements with θ = 1/3 in a counter current cascade (Alant et al., 1980).

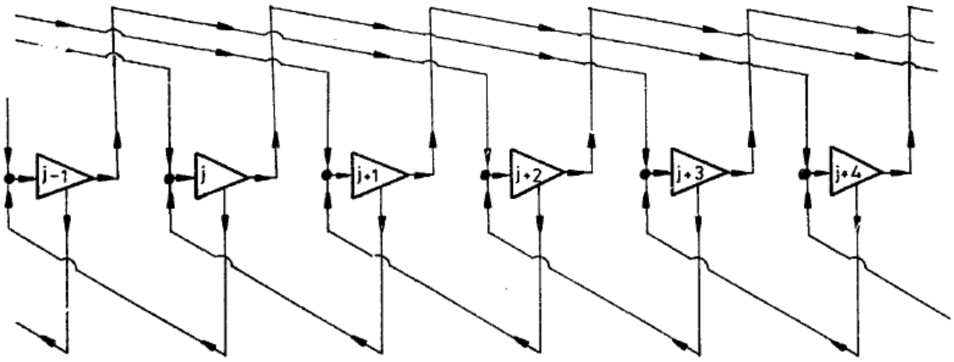


Figure 2.18 Alternative arrangement of separating elements with θ = 1/3 in a counter current cascade (Alant et al., 1980).

In the UCOR process the flow ratio θ is typically 0,045 to 0,055. For θ = 1/20, the cascade corresponding to that in Figure 2.17 and Figure 2.18 has 20 stages per group, with the enrichment factor between stages only 1/20 of the enrichment factor ($\epsilon_{\ell 0}$) between the enriched and depleted streams of a stage. The cascade can be simplified by recirculating part of the depleted stream of a stage to increase the effective cut, or by modifying the separating element. In both cases the separative efficiency is however markedly reduced (Grant et al., 1976). Separating element asymmetry is compensated for by means of Helikon Technique. The latter is based on the principle of multiple stream compression in specially designed axial flow compressors that limit inter-stream mixing to acceptable levels. Therefore, the interconnected group 20 elements producing asymmetrical cut, are linked together in stages, within the modules, thereby ensuring that the combined enriched flow produced by the separation stage is equal to the depleted flow leaving the stage (basically resulting in symmetry being achieved) (Alant et al., 1980).

Since the separation stages behave symmetrically from a separation point of view, they are arranged in a classical enrichment cascade configuration employing a counter-current inter-stage header system. Inter-stage transfer of enriched streams is achieved by means of a single partitioned pipe designed to prevent mixing between individual streams. The depleted header system, however, uses an undivided pipe (Bredell, 1990). In the Helikon technique, where many stages are in effect incorporated into a single module, the stages still share the same pair of axial flow compressors. The streams from different stages are introduced into a compressor in parallel, at different points on the inlet circumference (Grant et al., 1976).

- Helikon cascade for separating elements with a cut smaller than 1/2

The nature of the flow through an axial flow compressor is such that there is relatively little mixing of the material flowing through, i.e. should a gas be introduced at a point near the intake of the compressor, dispersion would have taken place over a very small area when the gas emerges at the compressor outlet. This creates the possibility of multichannel flow through axial flow compressors, whereby a single compressor may be used to compress several streams of different composition, with relatively little mixing taking place between the streams. A suitable method of using a single compressor for the compression of several streams of which the compositions vary systematically (Haarhof, 1976; Grant et al., 1976) is shown in Figure 2.19.

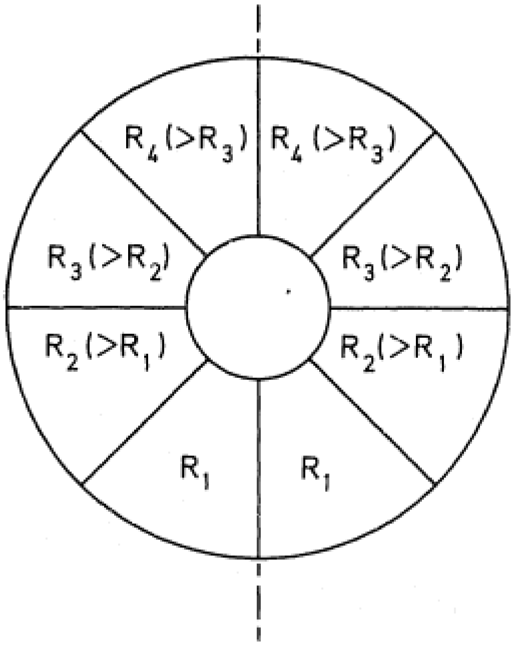


Figure 2.19 Introduction of four streams of different UF_6 mass fractions R1, R2, R3, and R4 into a compressor (Haarhof, 1976).

Each stream is divided into two, and the resulting streams are then introduced symmetrically in respect of a plane through the compressor axis, from segments formed by radially placed partitions. In this way the concentration difference between adjacent streams is minimised. The partitions stop just upstream from the compressor inlet and start again downstream from the compressor outlet. To compensate for possible rotation during compression the partitions at the outlet can be rotated with respect to the inlet and shaped to make the composition of the outgoing streams as near as possible to that of the incoming streams. Due to a cut of only 1/20, the UCOR process uses 38 (2 x 19) sectors.

During the flow path through a section of a module suitable for the Helikon technique, the feed stream is compressed and cooled before being introduced into the separating element assembly, where it is split into enriched and depleted streams.

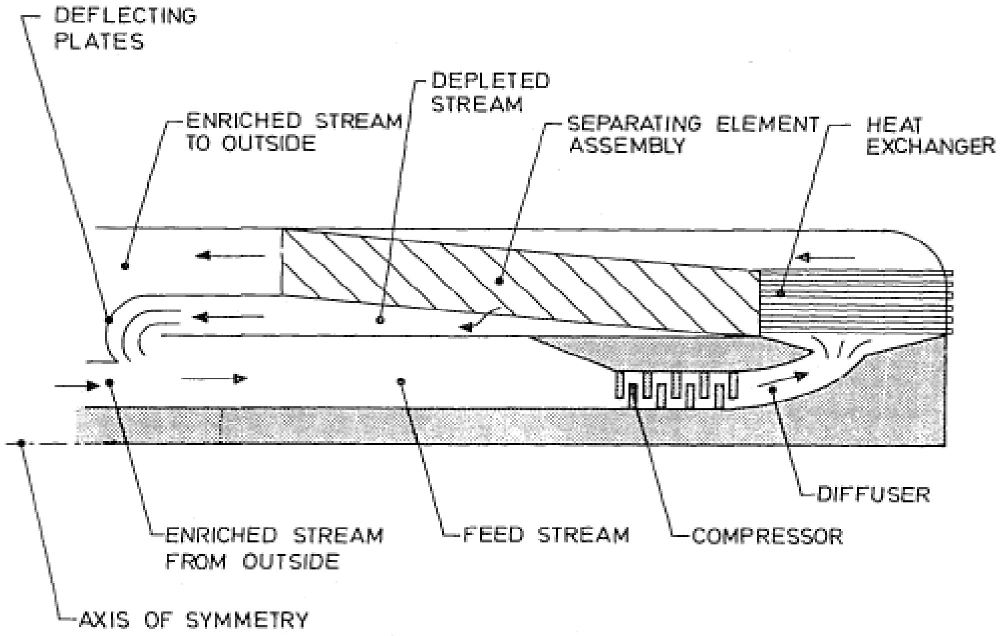


Figure 2.20 Schematic representation of flow path through part of a helikon module. (Haarhof, 1976)

Apart from for the compressor, the space in the module is divided into segments as shown in Figure 2.19. For discussions, it is better to explain Figure 2.21 than Figure 2.20 as it gives a whole cross section of the module.

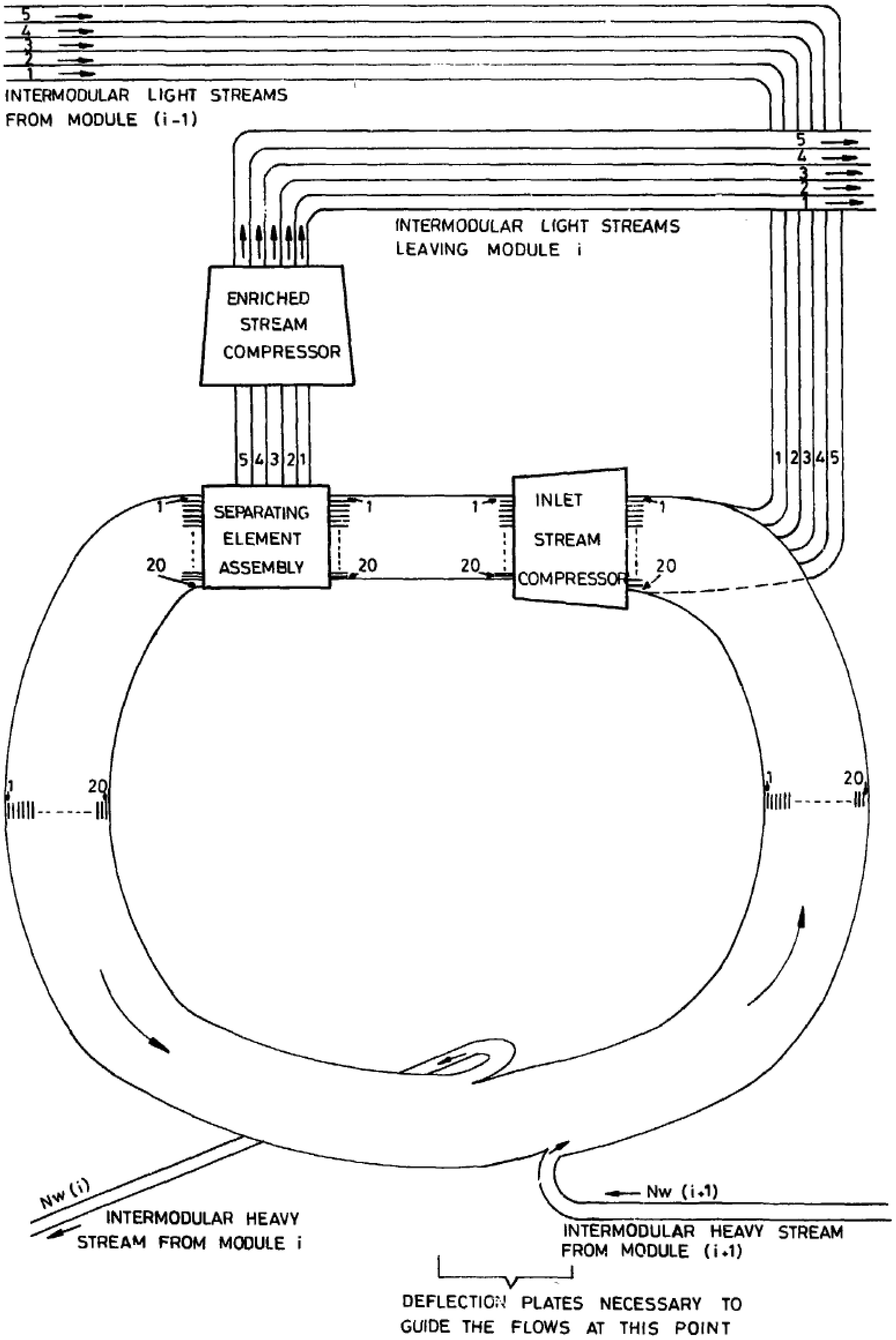


Figure 2.20 Schematic representation of flow path for a group of stages all incorporated in a single module (Alant et al., 1980).

The enriched and depleted streams leave the separating element assembly, and the enriched stream from every segment is transported by means of a pipe to the point where it is again fed into a module. The depleted stream of a segment either leaves the module container or its direction of flow is inverted by deflecting plates, which also rotate it through a certain angle around the major axis of the module, causing it to enter a different segment where it is mixed with an enriched stream from the outside. Should a carrier gas be used, and the average molar masses of the enriched and depleted streams differ, special measures must be taken to ensure effective mixing of these streams. Should the pressure of the enriched stream be lower than that of the depleted stream, it must be compressed before being re-introduced into the module, during which a scheme as set out in Figure 2.21 may also be used. The enriched stream compressor may be incorporated in the module (Haarhof, 1976).

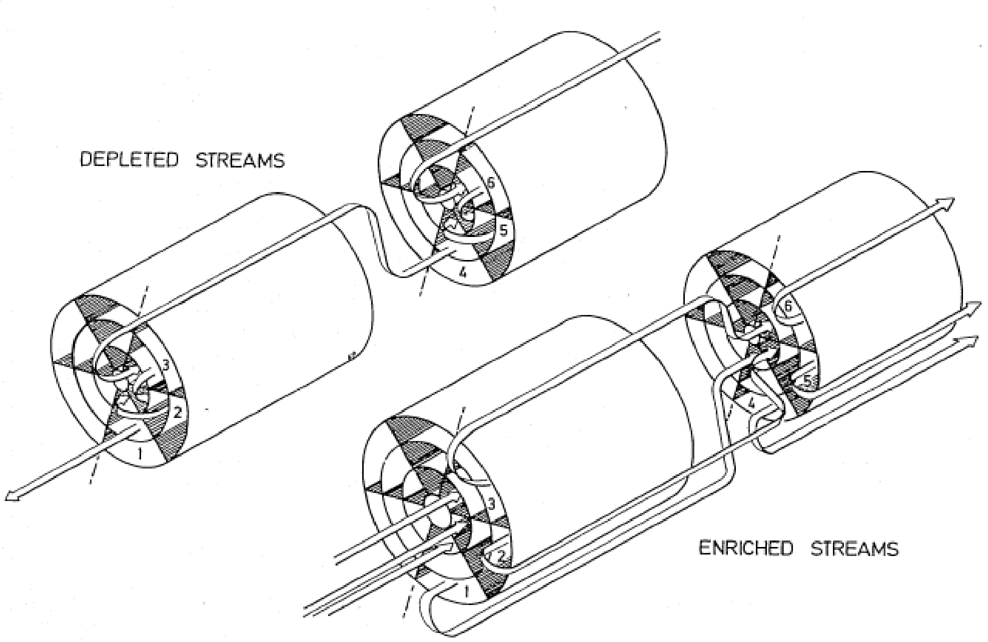


Figure 2.22 Schematic representation of a possible cascade for mass flow ratio θ = 1/3 (Haarhof, 1976).

The modules are divided into six segments, but due to symmetry only the flow through three of these needs to be considered. As depicted in Figure 2.22, the depleted stream from the following module enters the feed stream channel of segment 6, and the depleted stream from segment 6 in turn enters the feed stream channel of segment 5. In this way, the material moves in a helical path through the module until it leaves the module via the depleted stream of segment 4. The enriched stream leaving a segment is introduced into the corresponding segment of the next module. The enriched stream from segment n thus goes to segment (n + 3), and the depleted stream to segment (n - 1). If mixing between streams from adjacent segments during compression is ignored, it is clear that the segments correspond to the stages in Figure 2.16 or Figure 2.17 and that the cascade functions correctly (Grant et al., 1976).

- Implementation of the technique

For a cut of θ = 0,05 (1/20) the modules in Figure 2.21 would consist of 38 segments with 19 or 38 enriched streams between modules. It is then preferable to think in terms of a composition gradient over the module rather than a stepwise change in composition, and to regard partitions simply as a means of maintaining the gradient, rather than as the boundaries of stages. The deflection plates then do not transfer the flow from a given segment to another specific segment, but rather cause the flow to swirl through the correct angle (Alant et al., 1980; Grant et al., 1976).

For the UCOR process, 40 to 60 partitions are typically required for the depleted and feed streams which are much larger than the enriched stream. The latter may be handled with very little additional mixing losses by six to twelve segments per module (i.e., three to six segments in each half of a module), so that the intermodular piping is not prohibitively complicated (Roux et al., 1977).

- Separation work losses

During separative work, there is an amount of separative power of a module that is lost due to the mixing in the feed stream compressor. Such is calculated as follows:

$$X = \left(\frac{1-\theta}{\theta}\right)\left(\frac{\epsilon_m}{\epsilon_{lo}}\right)e^2\left(\frac{\sigma}{180}\right)e^2 \tag{14}$$

where,

ϵ_{lo} = enrichment factor between enriched and feed streams

ϵ_{m} = enrichment factor over the module

σ = standard deviation for compressor mixing (in degrees),

Thus, if θ = 1/20, $\epsilon_{\ell\mathrm{o}}$ = ϵ_{m}, σ = 8 deg, the fraction lost is 3.8%. Therefore, whilst the loss fraction is proportional to the square of the ϵ_{m}, the separative work losses as a result of mixing are inversely proportional to the square of the number of modules. Thus, the modules near the product and waste withdrawal points, which are composed of more stages than the feed point, are deemed less efficient than the feed point modules. In the Helikon process, with an enrichment factor of about 0.03 between the enriched and depleted streams, about 100 modules are needed for a cascade with a 3% product and 0.25% waste mass fraction. The separative work loss due to mixing is then conservatively estimated at about 5%. For a corresponding conventional cascade with similar enrichment factor of 0.03, about 1700 stages would be required for a cut of 1/20 (Grant et al., 1976).

2.2.3 Summary of enrichment process characteristics

Table 2.3 summarises enrichment processes that have either proven to be capable of large-scale enrichments or are thought to be likely to do so in the future due to significant research and development support. Currently, the Aerodynamic Process available for Uranium enrichment is the Jet nozzle technology commissioned through the Brazilian Resende enrichment plant (Krass et al., 1983).

Amongst the characteristics shown in Table 2.4 is the hold-up time advantage given by the Aerodynamic Process. This could be attributed to the Helikon technique where cascade arrangement is in a form of a module rather than a stage. The 'transit time' or 'hold-up time' must be supplied in order to calculate the material 'inventory' (or 'hold up') in stable operation. This is the period taken by a particular material sample to pass through a single stage, and it is governed by the precise design of the separating elements (Krass et al., 1983). The knowledge of the transit time is important for safeguarding purposes since the total material inventory can be calculated as the product of the total flow rate (*the mass of U produced per second per stage/element*) and the hold-up time.

Table 2.5 Summary of enrichment process characteristics (Krass et al., 1983).

Process		**Working Material**	**Single stage separation factor** $(\mathbf{q = 1 + g})$	**Stage cut** $(\mathbf{\theta = P/F})$	**Stage hold-up time (s)**	**Stage reflux mechanism**[e]	**Status of technique**
Gaseous diffusion		UF_6	1.0040-1.0045	$\mathbf{1/2}$	5-10	None	Mature
Gas centrifuge		UF_6	1.3-1.6	$\sim \mathbf{1/2}$	10-15	Internal countercurrent flow	Mature
Aerodynamic	Nozzle	$0.04UF_6 + 0.96H_2$	1.015[a]	$\mathbf{1/4}$	~2	Recycle intermediate fraction	Demonstration
	Advance Vortex	$0.01\text{-}0.02UF_6 + 0.98\text{-}0.99H_2$	1.025-1.030	$\mathbf{1/20}$	0.05-0.2	None	Demonstration and Production
Chemical	Solvent extraction	Aqueous and organic solutions of U compounds	1.0025-1.0030[a]	$\mathbf{1/2}$	20-30	Chemical conversions U(IV) $\rightleftharpoons$ U(VI)	Pilot plant

Process		**Working Material**	**Single stage separation factor** $(\mathbf{q} = \mathbf{1} + \mathbf{g})$	**Stage cut** $(\boldsymbol{\theta} = \mathbf{P}/\mathbf{F})$	**Stage hold-up time (s)**	**Stage reflux mechanism**[e]	**Status of technique**
	Ion exchange	Aqueous U solutions and ion-exchange resin	1.0013	$^{\mathbf{1}}/_{\mathbf{2}}$	~1	Chemical conversions $U(IV) \rightleftharpoons U(VI)$	Pilot plant
Laser	Molecular	UF_6-N_2	$(5\text{-}15)^{b,c}$	NA	NA	None	Research and Development
	Atomic	U vapour	$5\text{-}15^{c}$	NA	NA	Recover and recycle U metal	Research and Development
Electro-magnetic	Calutron	UCl_4^{d}	$20\text{-}40^{c}$	NA	NA	Recover and recycle UCl_4	Probably unsuitable for large quantities
	Ion cyclotron resonance	U plasma	$3.5\text{-}10^{c}$	NA	NA	Recover and recycle U metal	Research and Development

[a] To achieve correct estimate production values, the value of g provided is multiplied by twice the values of the stage cut.

[b] Estimated based on rough analogy with AVLIS

[c] The value entered for the last four techniques is the enrichment factor $\propto$ rather than the separation factor g

[d] UCl_4 is the usual charge material used in the ion source. U ions are produced by passing a strong electric discharge through the UCl_4 vapour in a heated oven

[e] The refers to the fraction of the stage flow at the top of a stage or cascade that is returned down or sent back down the stage or cascade to be processed.

2.3 The Nuclear Non-Proliferation Regime

The nuclear non-proliferation regime is an international legal initiative made up of numerous treaties and conventions dealing with nuclear energy and its consequences. The evolution of the non-proliferation regime is a result of the evolution of nuclear legislation, which has evolved to satisfy the needs for the non-proliferation of nuclear weapons as well as the safety and security of the peaceful use of nuclear energy. This has been attempted through enactment of a raft of international treaties, conventions, and export control regimes. For the purpose of this study, only the Treaty on the Non-Proliferation of Nuclear Weapons, Safeguards Agreement, Nuclear Suppliers Group and Zangger Committee will be discussed.

2.3.1 Treaty on the Non-Proliferation of Nuclear Weapons

Due to the nuclear bombings in 1945, governments started with proposals to control the “destructive uses” of nuclear energy. By 1970, the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), was entered in force and became an international framework for preventing the spread of nuclear weapons. Its broad objectives are: -

- To prevent nuclear weapon proliferation to states other than the five recognized as nuclear weapon states, all other States Parties (known as non-nuclear weapon states) must enter into safeguards agreements with the International Atomic Energy Agency (IAEA) to verify the peaceful nature of their nuclear programmes;
- To facilitate peaceful nuclear co-operation between Treaty members; and
- To provide the foundation for nuclear disarmament (Markram, 2004).

Under Article III (2), the NPT provides for the transfer of source or special fissionable material, equipment or material especially designed or prepared for the processing, use or production of special fissionable material to non-nuclear weapon states only if the consignment is placed under IAEA safeguards (IAEA, 2019). The pledge not to acquire nuclear weapons is verified through the application of “nuclear safeguards” measures.

South Africa became a State Party to the NPT on 10 July 1991.

2.3.2 International Atomic Energy Agency

The International Atomic Energy Agency (IAEA) was established to promote the peaceful use of atomic energy while safeguarding against its use for military purposes. The IAEA reports directly to the United Nations (UN) General Assembly and Security Council; however, it was formed independently by way of its own international treaty, the IAEA Statute. The relationship between the IAEA and UN is described in INFCIRC/11, 30 October 1959 (Cacuci, 2010). The statute prescribes that;

- the IAEA would promote research on, the development of, and practical applications for the peaceful use of nuclear energy;
- materials, services, equipment and facilities for such research would be made available, especially to developing countries;
- the exchange of scientific and technical information would be fostered;
- a system of safeguards would be designed and implemented to ensure that any nuclear assistance and materials supplied would not be used for military purposes and, if requested, to apply such safeguards in any bilateral or multilateral arrangement; and
- standards would be drawn up for the safe use of nuclear energy (von Wielligh, 2015).

South Africa is a member of the IAEA and was part of the Group of Twelve that drafted its statute in 1956.

2.3.3 Safeguards

Safeguards are measures taken to reduce proliferation risk. The terms or expressions (1) safeguards and (2) material control and accountability (MC&A) are often used interchangeably. Frequently, their definition depends on whether the audience is domestic or international. Material protection, control, and accounting (MPC&A) can be considered with the addition of physical security. The governing agencies that regulate safeguards are both domestic and international. The IAEA uses the inspection and verification system to determine whether declared nuclear material is being utilized only for peaceful purposes and is not being diverted to clandestine nuclear weapons programs, as well as to detect undeclared nuclear material and activities (von Wielligh, 2015).

The application of safeguards is the responsibility of any state that possesses nuclear materials, and the control of their use should be a priority for the security interests of the state. A state therefore is obligated to establish an infrastructure for domestic safeguards for its own domestic purposes, to ensure the protection and accountability of its nuclear assets. However, this infrastructure is also required of all states with safeguards agreement in place with the IAEA. The requirements of a safeguards agreement are that "*The state shall establish and maintain a system of accounting for and control of all nuclear material subject to safeguards under the Agreement*" (IAEA-2, 1972). The mandate for accounting and control of all nuclear materials subject to safeguards is commonly referred to as a State System for Accounting and Control (SSAC) of nuclear materials.

The system of accounting for and control of nuclear material may have dual objectives:

> (a) A national objective, to account for and control nuclear material in the state and to contribute to the detection of possible losses, or unauthorized use or removal of nuclear material.
>
> (b) An international objective, to provide the essential basis for the application of IAEA safeguards pursuant to the provisions of an Agreement between the state and the IAEA (Cacuci, 2010).

Although the Minister of Mineral Resources and Energy is responsible for Safeguards in South Africa, the South African SSAC is Nuclear Safeguards Management

Department at NECSA as delegated by the Minister in terms of Section 55 of the Nuclear Energy Act, No. 46 of 1999.

2.3.3.1. Types of Safeguards Agreements

The Safeguards Agreement between the state and the IAEA depends on a prescribed model agreement in terms of which certain obligations are imposed on the state in respect of the declared activities and material. There are several kinds of agreements, i.e., that are required by virtue of a state being a state party to the NPT; those that are only facility specific in countries that have not signed NPT; and voluntary safeguards agreements signed by non-nuclear weapon states (NNWS) as determined by the NPT.

2.3.3.1.1 Comprehensive Safeguards Agreements

Upon the entry into force of the NPT Treaty in 1970, the IAEA developed a document on the contents of safeguards agreements to be concluded between non-nuclear weapon states party to the NPT and the IAEA. The document titled “The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-proliferation of Nuclear Weapon”, circulated as INFCIRC/153 became the model for comprehensive safeguards agreement.

Provisions in this type of safeguards agreement are that all source or special fissionable material in all peaceful nuclear activities within a State, or under its jurisdiction or carried out under its control anywhere are placed under safeguards, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other nuclear explosive devices (IAEA-4, 1972).

South Africa signed the Comprehensive Safeguards Agreement with the IAEA on 16 September 1991.

2.3.3.1.2 Facility Specific Safeguards

Provisions in this type of safeguards agreement are relevant to a particular project, arrangement, or activity in the field of nuclear energy (IAEA-4, 1972).

This means the State does not put all its nuclear activities, facilities, material and equipment under IAEA safeguards but only the prescribed list. These types of agreements, circulated as INFCIRC/66, were mostly prevalent prior to the advent of CSA. Most NNWS that signed it previously, had converted it into CSA upon the entry into force of NPT.

Prior to signing the CSA, South Africa signed the INFCIRC/66-type safeguards agreement covering the activities and facilities at the then Atomic Energy Corporation, and now Nuclear Energy Corporation of South Africa (NECSA), and Koeberg nuclear power reactor units 1 and 2.

2.3.3.1.3 Small Quantities Protocol

The purpose of the Small Quantities Protocol (SQP) is to minimise activities of safeguards on States with minimal or no nuclear activities. Under SQP, which is supplementary to the CSA, implementation of most of the procedures in Part II of the CSA are held in abeyance for as long as the State continued to satisfy the specified criterion for eligibility. Such is that the quantities of the nuclear material in the State remained below the quantities specified in the SQP and that the State had no nuclear material in a facility. However, the obligation for that State to maintain an SSAC and report on the imports and exports of any nuclear material or material containing uranium and thorium were not held in abeyance. Provisions in this type of safeguards are relevant to a particular project, arrangement, or activity in the field of nuclear energy (ISCN, 2016; Stoiber et al., 2010).

2.3.3.1.4 Additional Protocol

In over the years of inspections, five states have been declared in violation of their safeguards agreements. Following revelations of clandestine activities in 1991, the IAEA developed a strengthened safeguards program named Model Protocol Additional to the agreement between the State(s) and the International Atomic Energy Agency for the application of Safeguards, (formerly called “93+2”), to improve its ability to detect unreported nuclear activities in non-nuclear weapons states. The program, *inter alia*, covered

- provision of intelligence information to the IAEA by member states about suspect nuclear activities;
- access for inspectors to any location on a timely basis;
- new safeguards technology; and
- measures to promote complete transparency and reporting of all nuclear commerce.

Under the Additional Protocol (AP), States are required to provide the IAEA with an expanded declaration that contains information covering all aspects of their nuclear and nuclear fuel cycle activities, broader access rights and ability to use advanced technologies. Whilst the CSA provide the IAEA with access to only specific strategic points in a declared facility, the AP requires that States must provide access to all sites that are or could be involved in nuclear fuel cycle activities, as well as any area within or outside a nuclear site where radioactive material is located or may be present (ISCN, 2016). According to Article 2(b) of the AP, this includes the description of: -

- the scale of activities crucial to nuclear fuel cycle programs but are not necessarily involving the use of nuclear;
- nuclear fuel cycle related research and development activities not involving nuclear material which are specifically related to enrichment, reprocessing of nuclear fuel or the processing of intermediate or high-level waste containing plutonium, high enriched uranium or U-233 that are carried out anywhere in the State, but which are not funded, specifically authorized, or controlled by, or carried out on behalf of the State; and
- activities and the identity of the person or entity carrying out such activities, at locations identified by the IAEA outside a site which the IAEA considers might be functionally related to the activities of the site.

South Africa signed the Protocol Additional to the Comprehensive Safeguards Agreement with the IAEA on 13 September 2002.

2.3.4 Nuclear Suppliers Group

The Nuclear Suppliers Group (NSG) is a group of nuclear supplier countries of nuclear material, equipment and technology and nuclear-related dual-use equipment, materials, software, and related technology, which seeks to contribute to the non-proliferation of nuclear weapons through the implementation of two sets of Guidelines for nuclear exports and nuclear-related exports. NSG Participating Governments are listed in the Annex. NSG participants pursue the aims of the NSG through adherence to the NSG Guidelines, which are adopted by consensus, and through an exchange of information, notably on developments of nuclear proliferation concern.

The aim of the NSG Guidelines is to ensure that nuclear trade for peaceful purposes does not contribute to the proliferation of nuclear weapons or other nuclear explosive devices, and that international trade and cooperation in the nuclear field is not hindered unjustly in the process. The NSG Guidelines facilitate legitimate trade by providing the means whereby peaceful nuclear cooperation can take place in a manner consistent with international nuclear non-proliferation norms. The NSG encourages all States to adhere to the Guidelines.

The first set of NSG Guidelines governs the export of items that are especially designed or prepared for nuclear use. These include: (i) nuclear material; (ii) nuclear reactors and equipment therefor; (iii) non-nuclear material for reactors; (iv) plants and equipment for the reprocessing, enrichment, and conversion of nuclear material and for fuel fabrication and heavy water production; and (v) technology (including software) associated with each of the above items. The NSG Part 1 Guidelines for Nuclear Transfers were originally published as an International Atomic Energy Agency (IAEA) Information Circular INFCIRC/254 in 1978.

The second set of NSG Guidelines governs the export of nuclear-related dual-use items and technologies, that is, items that can make a major contribution to an unsafeguarded nuclear fuel cycle or nuclear explosive activity, but that have non-nuclear uses as well, for example in industry. The NSG Part 2 Guidelines on Transfers of Nuclear-Related Dual-Use Equipment, Materials, Software and Related Technology were published as Part 2 of the IAEA's Information Circular INFCIRC/254 in 1992 (IAEA-1, 2019).

South Africa became a Participating Government of the NSG on 05 April 1995. NSG regulations and guidelines are implemented in South Africa by the Minister of Mineral Resources and Energy (nuclear direct use items) in terms of the Nuclear Energy Act, No. 46 of 1999 and supporting government notice, and by the South African Council for the Non-Proliferation of Weapons of Mass Destruction (nuclear dual use items) in terms of the Non-Proliferation of Weapons of Mass Destruction Act, Act No. 87 of 1993 and supporting government notices.

2.3.5 Zangger Committee

In 1971, a group of seven NPT nuclear supplier nations formed the Nuclear Exporters Committee, currently known as the Zangger Committee, to assist in restricting nuclear trade as called for in Article III.2 of the NPT. In 1974, the Zangger Committee compiled a list of nuclear export items that could be potentially useful for military applications of nuclear technology. The nuclear suppliers agreed that the transfer of items on the list would "trigger" a requirement for IAEA safeguards to ensure that the items were not used to make nuclear explosives. The Zangger/Trigger list included reactors, reactor components, and certain nuclear materials such as heavy water (Nikitin, 2010).

The origin of the Zangger Committee can be traced to the lack of precision in the language of Article III.2 of the NPT. According to this provision, parties to the NPT undertake not to provide (a) source or special fissionable material, or (b) equipment or material especially designed or prepared for the processing, use or production of special fissionable material', to any non-nuclear weapon state unless the source or special fissionable material is subject to IAEA

> safeguards. In practice, problems arose with the interpretation and definition of what constituted ‘equipment or material especially designed or prepared for the processing, use or production of special fissionable material’ (such material or equipment is commonly referred to as EDP, which stands for ‘especially designed or prepared’). A further problem related to the conditions and procedures that would govern exports of EDP.

South Africa joined the Zangger Committee on 21 October 1995. Zangger Committee obligations and guidelines are implemented in South Africa by the Minister of Mineral Resources and Energy (nuclear direct use items) in terms of the Nuclear Energy Act, No. 46 of 1999.

2.3.6 The difference in Nuclear Export Control Regimes

> The NSG and the Zangger Committee differ slightly in the scope of their Trigger lists of EDP items and in the export conditions for items on those lists. Concerning the scope of those lists, the Zangger list is restricted to items falling under Article III.2 of the NPT. The NSG arrangement covering exports of dual-use items is a major difference between the NSG and the Zangger Committee. As dual-use items cannot be defined as EDP equipment, they fall outside the Zangger Committee's mandate.

In South Africa, trigger list items are listed under Government Notice No. 207 of February 2009, whereas dual use nuclear items, and items related to the separation of “other elements”, are listed under Government Notice No. 319 of 08 April 2021 and of Government Notice No. 493 of 29 March 2019, respectively.

2.4 Chapter summary

Chapter 2 gave literature background on separation and enrichment techniques and development of nuclear non-proliferation regime and regulations internationally and domestically. Chapter 3 delves into development and characteristics of the Aerodynamic Separation Process and the process to conduct the survey.

CHAPTER 3: METHODS OF INVESTIGATION

According to Saunders, Lewis and Thornhill (2019), research methodology is the specific procedures used to gather and analyse data about a topic. It allows the reader to critically evaluate a study's overall validity and reliability. This study made use of a quantitative research method approach. This research consisted of two phases; namely a review and description of ASP technical documents related to the description genesis aerodynamic technologies discussed under Section 2.2.2.6 and an empirical study to determine the perceptions of relevant stakeholders regarding their understanding of UCOR and ASP technology, and regulation thereof.

3.1 Review of ASP technical documents

Although in-depth public domain patents and literature on genesis stationary-wall centrifuge technology and Becker process, respectively, are available, the UCOR process was shrouded in industrial secrecy, especially on the production data of the products (Benedict et al., 1981). A similar trend is applied when it comes to the current aerodynamic separation process plants/companies wherein information of their design, development, operation, and production data is rarely publicised partly due to Intellectual Property (IP), but mainly due to now stringent non-proliferation, safeguards and nuclear security regulations. In South Africa, such conditions are imposed by the Minister of Mineral Resources and Energy in terms of the Nuclear Energy Act, No. 46 of 1999 and supporting government notice, and by the South African Council for the Non-Proliferation of Weapons of Mass Destruction in terms of the Non-Proliferation of Weapons of Mass Destruction Act, Act No. 87 of 1993 and supporting government notices.

The first phase of the research methodology is the literature review which aimed to give an understanding to the technology. Although the researcher is involved, in certain practical aspect of the technology (through permission granted by company), there cannot be disclosure of all data as they pertain to the IP of the company and the non-proliferation legislation-imposed secrecy on the same IP. It is therefore only practical to use publications available to describe the technology, lest there is unintentional contravention of the law and compromising of company’s IP.

As a sole company with successful Si-28 test bench process and commercially active O-18 aerodynamic separation process plant, Klydon (Pty) Ltd was visited for access to confidential documentation and information on the design, development, operation and production data to compare with literature content obtained for both UCOR and Becker processes discussed in Section 2.2.2.6.

3.1.1 ASP enrichment technology

A South African company Klydon (Pty) Ltd has developed a proprietary technology for separating constituents of a gas mixture or different isotopes of a specific gaseous compound based on the mass difference of the gas components or the isotopes. This is achieved in a high-speed centrifugal rotation of the said gas mixture or isotope mixture where the separation obtained is the net effect of the centrifugal forces and the Stokes forces acting on the mass particle. The most notable embodiment is the fast-rotating gas centrifuge, which has found substantial application for the enrichment of uranium isotopes for the use in nuclear reactors.

A lesser-known embodiment of the principles of centrifugal separation is the stationary wall centrifuge that has no moving mechanical parts. Aerodynamic Separation Process relates to a device for the separation of gas components and isotopic species, which utilizes novel extensions to the genesis concepts of the stationary wall centrifuge that is currently in the public domain. This is a development based on continuous research from genesis technology famed “stationary-wall centrifuge” (Strydom et al., 2016). Whereas the Ranqe-Hilsch method is beneficial for refrigeration application, it is not useful for the separation of chemical species (Yi et al., 1995). However, the method provided the basis for aerodynamic processes used in separation of gas mixtures and isotopes based on mass difference.

Numerous characteristics of the genesis technology such as the small geometrical dimensions of the separation device, tangential injection of the incident gas, low separation performance per device, asymmetrical cut of the device and pressure range where the separation device is operated were studied to optimise the Klydon's Aerodynamic Separation Process (ASP) technology and devices.

3.1.2 Evolution of Klydon's Aerodynamic Separation Process

The ASP technology developed from genesis technology established in the mid-1970's (Strydom et al., 2016; Ronander et al., 2012). This was supplemented by theory, research, experimental and gradual improvement of the technology over a period of more than 18 years (Strydom et al., 2016). It should be noted that the development of the Klydon technology, though the technology has not been proven to separate Uranium isotopes, was derived from Uranium separation genesis technologies. Those technologies include Wikdahl vortex separation (Whitaker, 2019), UCOR stationary wall centrifuge (Vlinder, 2019), Rosengard vortex extraction and Zippe centrifuge. Figure 3.2 shows schematic representatives of the technologies in a top-down sequence corresponding to the names above.

Three operating parameters that most critically describes the separation performance of any device are: -

- the isotope enrichment factor per single step of the device,
- the associated "cut" per step of enrichment, which is the ratio of the mass flow of the desired isotope in the product stream relative to the same quantity in the feed stream; and
- the mass flow of the isotopes through the device.

As the enhanced isotope enrichment factor for ASP compared to other separation processes for the oxygen-18 and Si-28 are proven, processes and models for the oxygen-18 and silicon-28 separation were used as basis for other light isotopes such as Zr-91, -92 and -96, Mo-100 and Cl-37. The chronological and stepwise progression in the understanding and development of ASP technology is shown below. The chronology is illustrative and does not provide all the other consideration beyond 2011 such as potential hydrocarbon gas separation, the development of the Mo-100 plant in 2016, and potential Cl-37 separation plant. Whereas the application on uranium separation has not yet been demonstrated as a nuclear license is required to proceed, the results on the tungsten hexafluoride system are a good proxy for uranium enrichment augmented by the predictive mode of the theoretical model that was verified over the mass range up to tungsten (Ronander et al., 2012). Continuous research and development have led to the commercialising of O-18 separation, due to the efficiency of the model and separation tube, with an enrichment factor of 1.18 at a cut of 25%, while the 2016 studies showed a cut of 50% had been reached (Strydom et al., 2016).

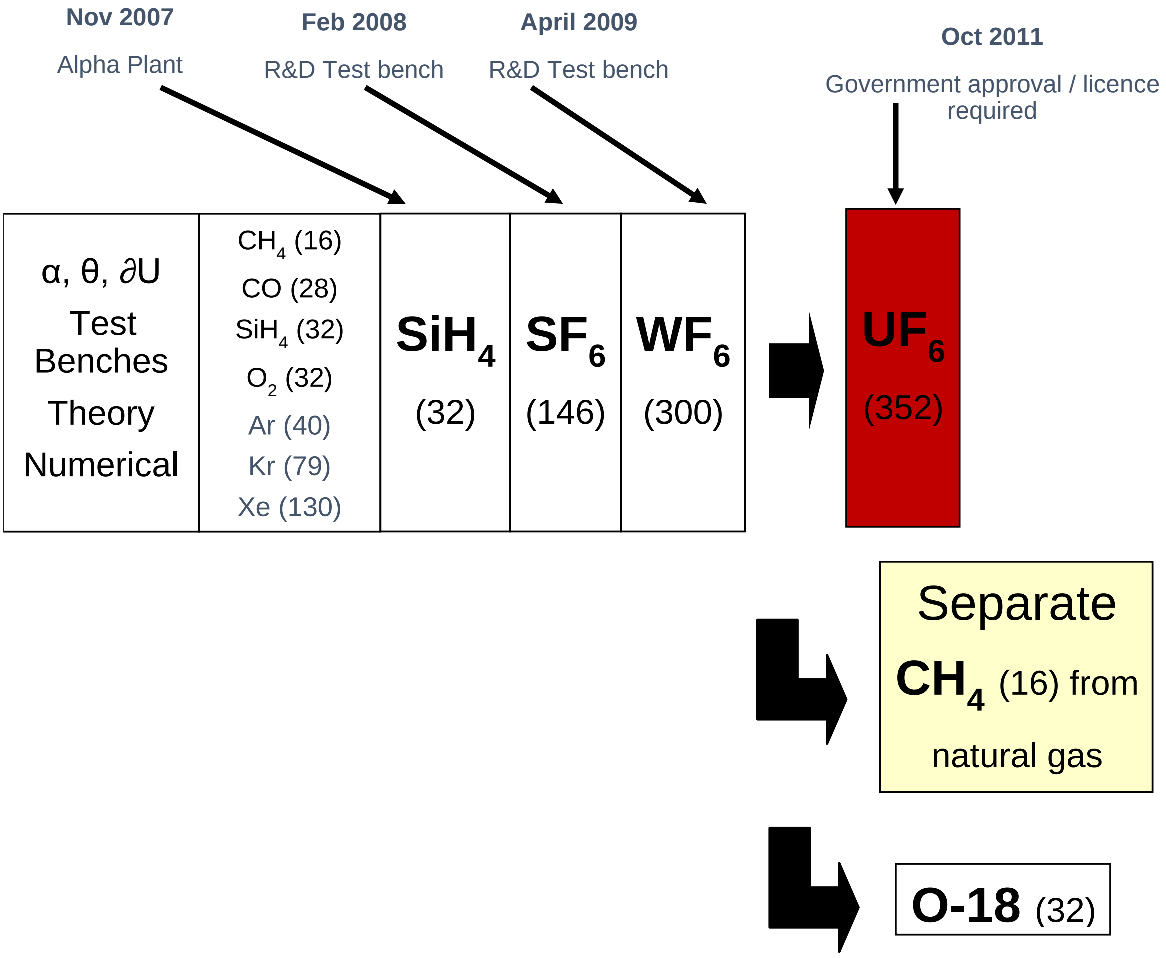


Figure 3.1 Chronological progression during the development of the Klydon's ASP technology (Ronander et al., 2012).

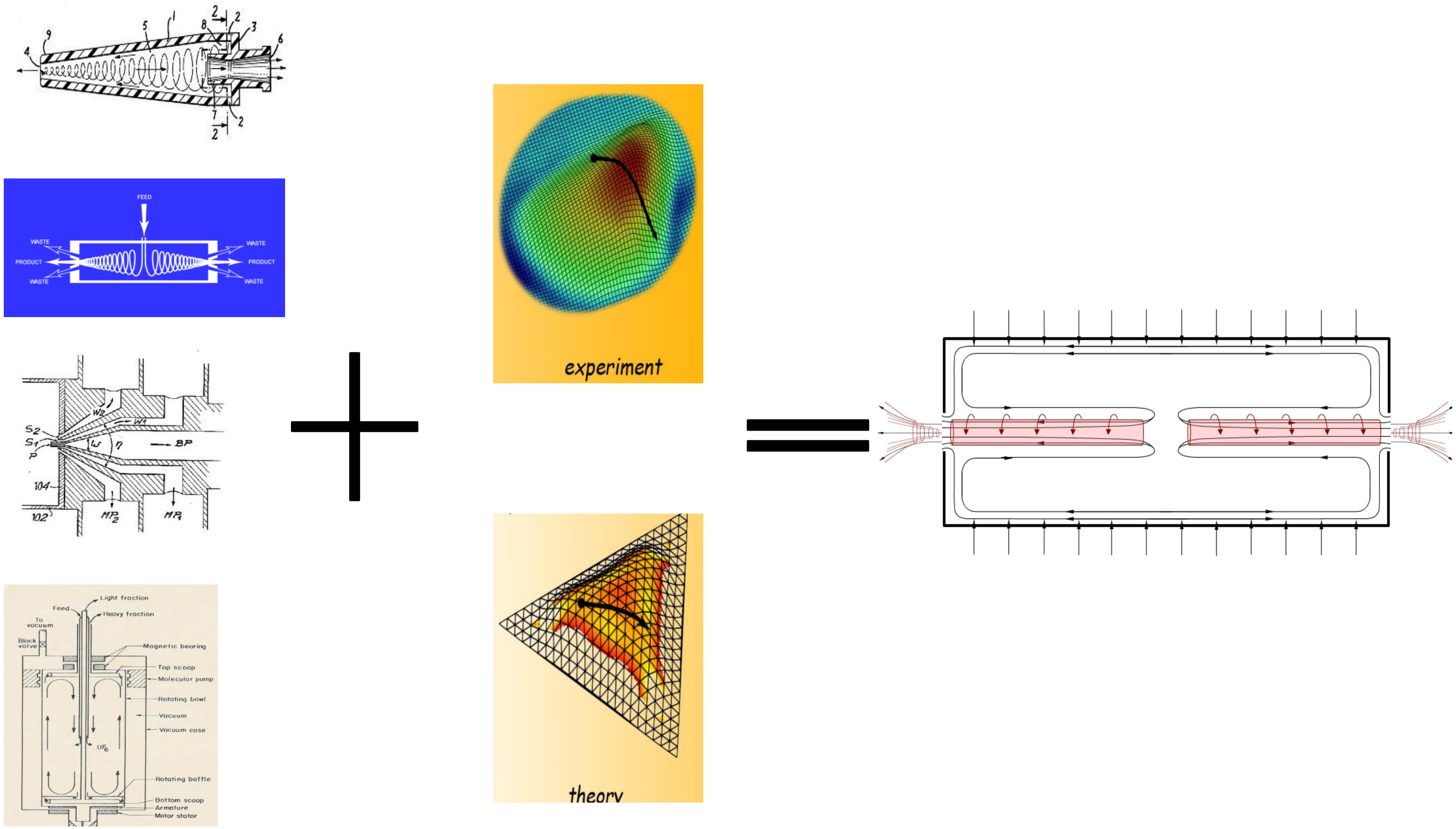


Figure 3.2 Summary of genesis technologies considered during the development of the Klydon's ASP technology (Klydon, undated).

3.1.3 A short description of the Klydon’s ASP separation process

The basic physical mechanism used by ASP isotope separators is identical to that used in gas centrifuges. In fact, several other aerodynamic processes such as those of UCOR and Becker make use of the same principle: a body of gas is injected tangentially under pressure into a stationary-wall separator tube and spun causing separation between particles based on mass differences. Heavier particles tend to settle at larger radii around the geometrical centre line than their lighter counterparts. Careful extraction allows isolation of either the heavier or the lighter particles, or both simultaneously. In the case of isotope separation, a gaseous isotopic mixture is also injected tangentially under pressure, spun, but, while it exists, the difference in mass between the different isotopes is so small that the body of gas must be spinning at very high speeds before any separation becomes noticeable. This characteristic is shared by all processes falling in the centrifugal isotope separation class: they result in bodies of gas rotating at excessively large speeds.

3.1.4 Gas flows inside the Klydon’s ASP separator tube

The process gas enters the vessel container after tangential injection through carefully placed and sized openings at the surface of the containment. The spacing between the inlet holes is dependent on and specific to the injected gas. Gas is injected at high velocities tangentially to the inner wall of the tube under pressure (1-5 bar) as shown in Figure 3.3 (b). The sides of the cylinder are closed off with two outlet openings for extracting gas. A pressure difference (1.2 – 2.5 bar) between feed and exit openings is created by varying the sizes of the inlet and outlet openings (Klydon, undated).

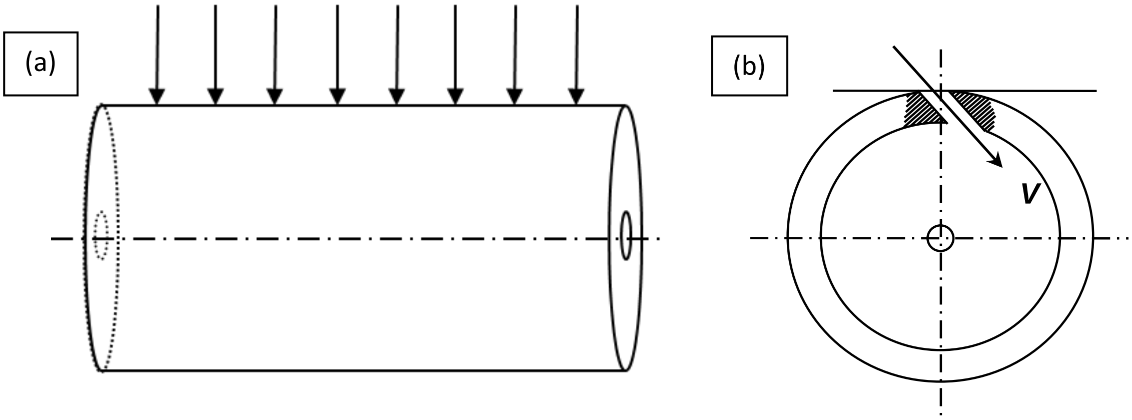


Figure 3.3 (a) A stationary-wall centrifuge tube, (b) Side-view: tangential injection (Klydon, undated).

The gas spirals around the tube with an ever increasing velocity towards the centre axis. In this spinning vortex flow the gas species are subjected to an intense centrifugal force that separates the light masses from the heavy masses due to difference in kinetic energy; hence, the higher the injection velocity the greater the separation between light and heavy.

In then follows a pattern where a boundary layer is formed near the inner wall of the tube due to the pressure differential between the inlet and outlet, making it difficult for the injected gas to penetrate this layer, instead the injected gas (A) rushes all along the inner wall of the tube (B) and a large percentage exit at the outer diameter of the extraction nozzles (C) without participating in the vortex/centrifugal flow at all (see Figure 3.4). This stream of gas (referred to as the "*recirculation stream*") experiences no separation forces; hence has the same compositional distribution as that of the injected stream. A lesser portion of the inlet gas is "spat" out towards the middle of the tube (D); becoming part of the spinning vortex that is created around the central axis. Being a symmetrical tube, a similar spat stream is flowing from the other side end of the tube. In the middle of the tube where these spat streams meet another boundary layer is formed (E) causing the spat streams to turnaround towards the extraction nozzles at the ends of the tube. All this time the process gas is subjected to an intense centrifugal force resulting in the separation of heavy (F) and light (G) mass species;

with the light mass near the axis of the tube. This is in stark contrast with conventional centrifuges where the separation takes place near the wall of the turning centrifuge.

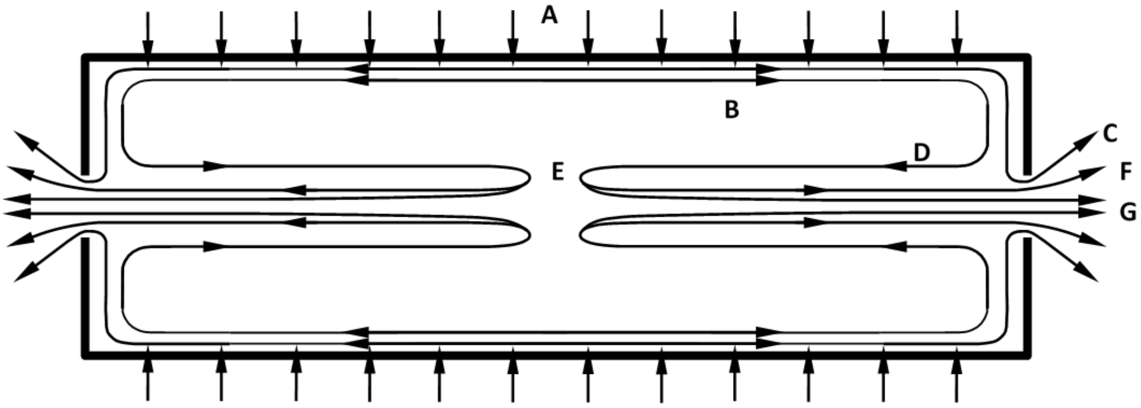


Figure 3.4 Gas flow inside a stationary-wall centrifuge tube (Klydon, undated).

The process can be summarised as concluding with two mini-centrifuges around the geometrical axis of the separator.

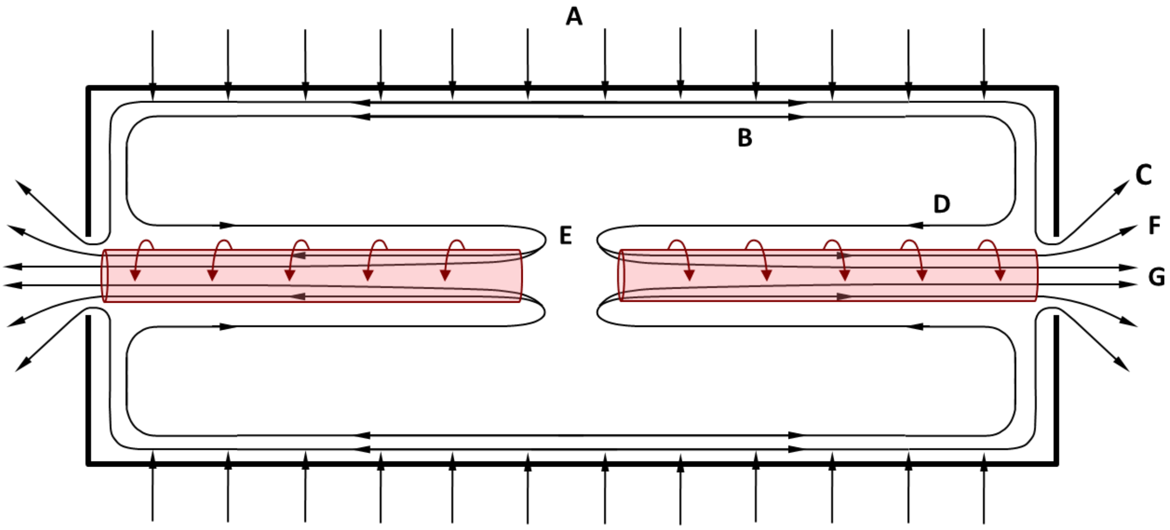


Figure 3.5 Gas flow inside a stationary-wall centrifuge tube showing the built-up radial dimension mini centrifuges (Strydom et al., 2016).

Each of the mini-centrifuges is fed material that becomes separated in the radial dimension as a result of the spin speed reaching several hundred meters per second. An axial mass flow component in each centrifuge feeds isotope material to the respective ends of the vessel where the harvesting of the portions is accomplished (Strydom et al., 2016).

ASP extraction nozzle designs have also evolved from the genesis technology designs (Figure 2.13) but provides for “symbolic multi-nozzle” rather than physical single nozzle that intruded the opening at the vessel end and symmetrically placed around the geometrical axis. This “symbolic multi-nozzle” is an appropriate mathematical model describing the separation performance of the ASP device based on well-known centrifugal equations (Ronander et al., 2012).

Due to the genesis technology extraction design configuration; the degree of enrichment that may be obtained has a clear maximum or ceiling value and any increase in the rotation speed has no further beneficial effect. This configuration also directly couples the enrichment factor and the cut; any increase in one parameter leads to a corresponding decrease in the other, which is an undesirable feature for a separation device. This ceiling value can be explained in terms of the Benedict formulism, that illustrates how the common mathematical description of centrifugal flow impacted by the geometrical limitation of the nozzle opening, when scanned in diameter, produces the combined effect of a ceiling value (Ronander et al., 2012).

The ASP extraction technology does not suffer from this limitation as it does not employ physical nozzles to harvest the product and waste portions. The advantageous mathematical equations governing the ASP extraction technology allows for harvesting of the heavy stream (F) mass species too, which could be inclusive of the light stream mass species of interest and use them as feed for the next stage.

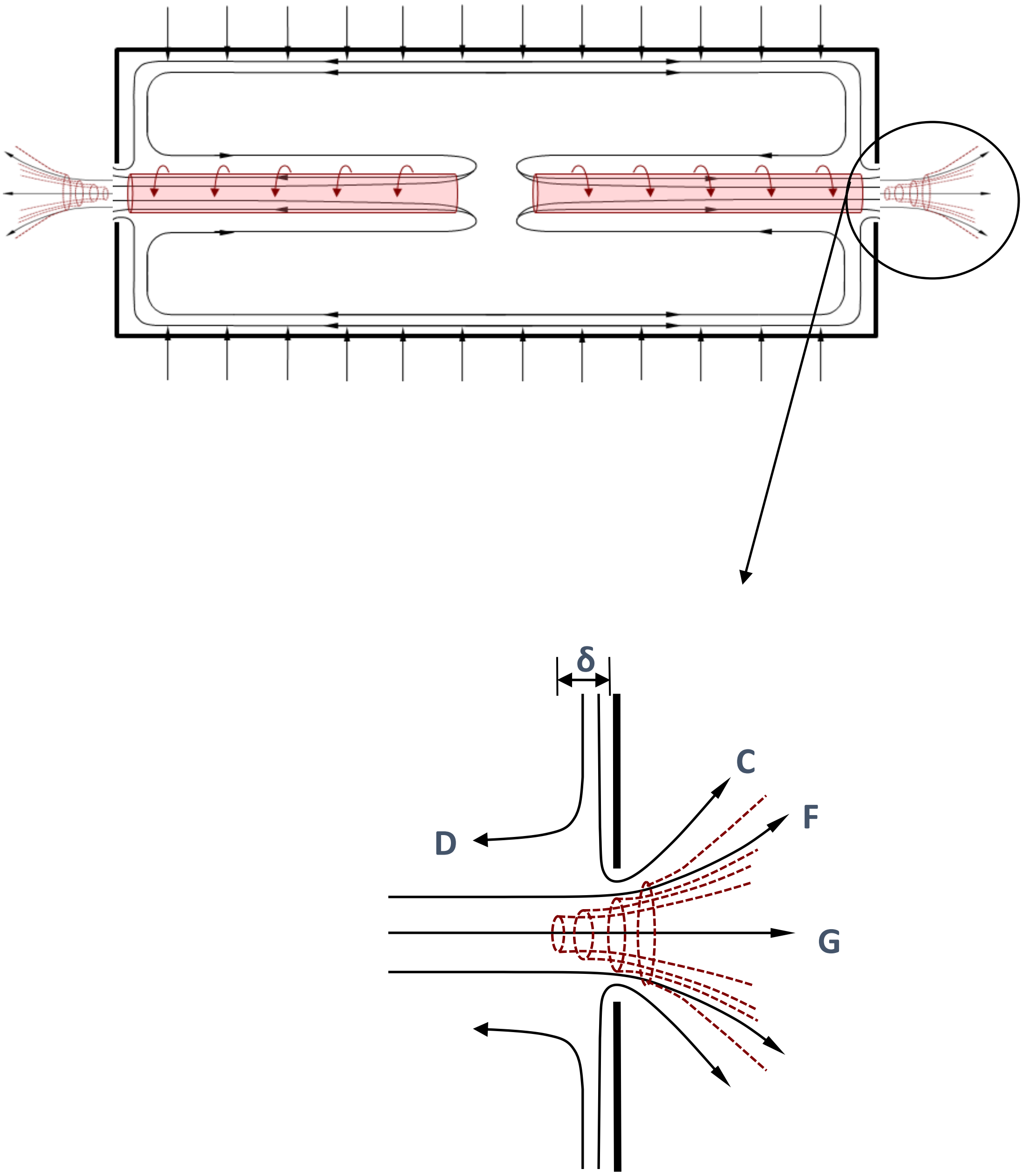


Figure 3.6 Gas flow inside a stationary-wall centrifuge tube with symbolic extraction multi nozzles (Ronander et al., 2012).

3.2.1.2 Comparison of gas flow in ASP technology versus gas centrifuge

Although the ASP separator and the gas centrifuge are related as far as basic principle is concerned, there is a fundamental difference in the methodologies used to spin the gas:

- Gas centrifuges approach the problem by filling a cylinder with gas and then spinning the cylinder as fast as possible. Radially oriented scoops fastened to the cylinder wall may be used to encourage the gas to move with the wall as it turns.

- In contrast, an ASP separator does not move at all: gas flows are manipulated causing a long gaseous cylinder to form within the separator. The gaseous cylinder is then spun at high speed. The separation process within this gaseous cylinder is analogous to that within the solid cylinder of the gas centrifuge. In essence therefore, the ASP process results in a wall-less gas centrifuge.

3.1.4 Klydon's ASP Enrichment Stage

Figure 3.7 shows a simple schematic of an ASP separation stage. Each stage has two outputs:

- X_i is the product stream, enriched in the isotope of interest.
- Y_i is the tails stream, stripped of the isotope of interest.
- The stage is configured to have a symmetrical cut with $F_i = X_i + Y_i$

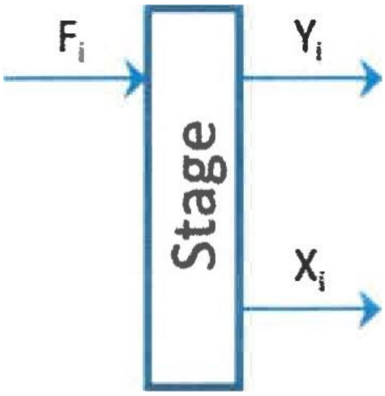


Figure 3.7 Klydon's ASP Enrichment Stage (Klydon, 2020).

3.1.5 Klydon's ASP Plant cascade configuration

Figure 3.8 is a schematic representation of an ASP cascade in operation for separation of isotope rather than gas, although the mechanism is the same (separation of gas does not involve carrier gas). The cascade consists of several enrichment stages, connected in a 1-up-1-down cascade configuration. The stages can be grouped into segments. Mathematical analysis of cascade theory in an isotope enrichment plant also reveals that the cut is one of the most important parameters for cost minimization. Accordingly, this parameter was studied intensely over several years. It is crucial to operate the separation device at a symmetrical cut, i.e. 50% mass flow in the separation configuration's product and waste streams of (Strydom et al., 2016).

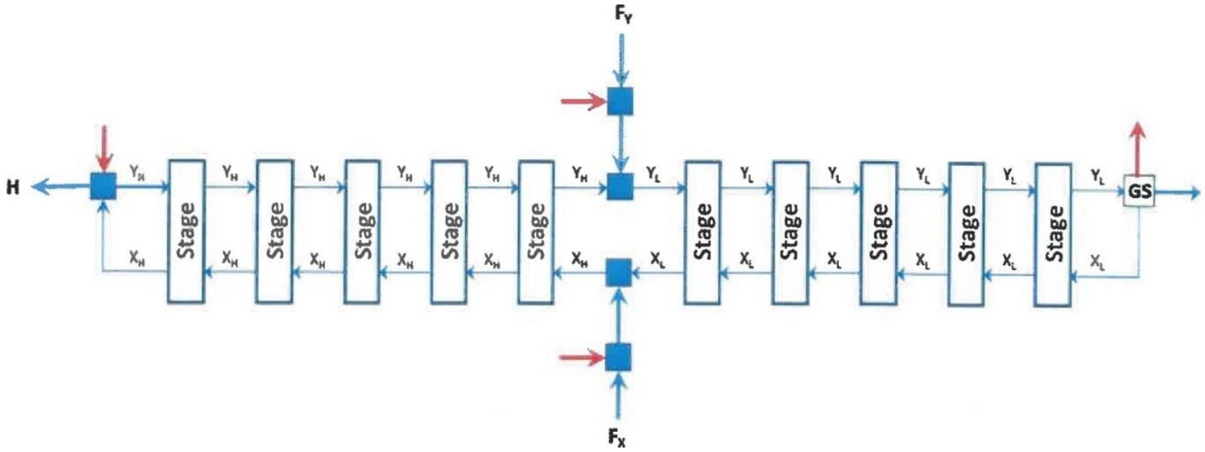


Figure 3.8 Schematic of an Klydon's ASP cascade in operation (Klydon, 2020).

The bold blue arrows represent flows of feed material into and out of the cascade:

- H is the product stream, enriched in the isotope of interest.
- L is the tails stream, stripped of the isotope of interest.
- $F = Fx + Fy$ is the feed stream at natural isotopic composition:
    - Fx is the feed into the product stream of an adjoining stage.
    - Fy is the feed into the tails stream of an adjoining stage.

Each stage in the cascade is operated in one of two configurations:

- A net backward flow of isotope of interest: $Xi > Yi$. These stages are referred to as "product", situated in the so-called "product cascade section", and their flows are marked with an "H" subscript.
- A net forward flow of isotope of interest: $Xi < Yi$. These stages are referred to as "tails", situated in the so-called "tails cascade section", and their flows are marked with an "L" subscript.

The red arrows represent the addition or extraction of carrier gas from the process. The arrows have been added for clarity and orientation, but the mass flows of the carrier gas won't be described in the rest of the discussion as they (discussions) pertain to the isotope of interest mass flows only (as represented by the blue arrows). The carrier gas mass flows can be superimposed on any isotope of interest mass balance using the molar mass characteristics of the ASP stages.

The block marked "GS" represents the gas separator: a piece of equipment used to separate the carrier gas from the feedstock to the degree necessary to provide a suitable reflux stream to the tails cascade section. The blue squares are simply suitable areas where streams can be split or mixed.

An ASP stage is characterised by functions of Y, the flow of feed material in its tails stream. The characteristics of interest are:

- α (Y): the separation factor between the tails and product streams.
- $M_Y(Y)$: the molar mass of the tails stream.
- $M_X(Y)$: the molar mass of the product stream.
- P(Y): the stage's power usage.
- $X(\theta,Y)$: the flow of feed material in the product stream, where $\theta = Y/(X+Y)$ is the cut defined in terms of feed material flows.

The cut of an ASP stage can be dynamically adjusted to any value larger than θ_{min}, allowing its operating point to be changed online during production. All stages in the product cascade section are operated at the same point $< X_H, Y_H >$, where $X_H > Y_H$, ensuring that a net backward flow of feed material, $H = X_H - Y_H$ is achieved. This corresponds to a cut of less than 50% and ensures a positive flow of enriched product.

All stages in the tails' cascade section are operated at the same point $< X_L, Y_L >$, where $X_L < Y_L$, ensuring that a net backward flow of feed material, $L = X_L - Y_L$ is achieved. This corresponds to a cut of more than 50% and ensures a positive flow of stripped tails.

Depending on the production requirements of the cascade the product and tails section operation points can be moved relative to each other during production, obtaining different combinations of H and L (and therefore different feeds $F = H + L$). The smaller H (or L) is chosen, the closer the product (or tails) section cut moves to 50%. If all stages are operated at a cut of 50%, the cascade is operated at full reflux, no product, tails or feed streams are present, and the maximum feed material concentration gradient will exist.

3.1.6 Separation factors

A separation stage is generally a portrayal of a feed stream entering the separation unit and the resultant product and tails streams generated according to the separation factors.

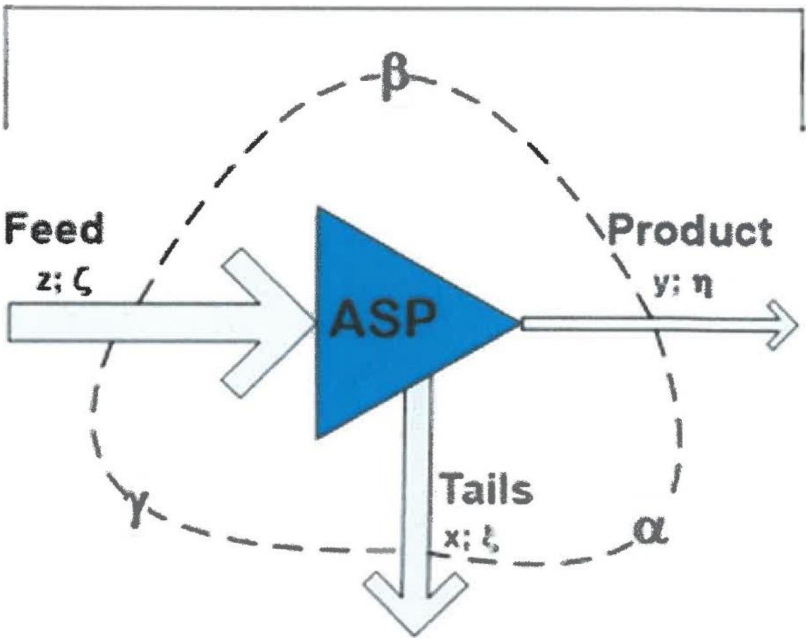


Figure 3.9 Separation stage (Klydon, 2020).

According to the separation stage, the overall material balance is given by:

Feed = Product + Tails (F = P + W)

This is because during the enrichment process the total quantity of the atom of interest remains constant even though the concentrations of the product and tails streams are different from the feed stream concentration. Thus, the total quantity of atom of interest and the total quantity of each isotope contained in the feed, product, and tails streams must balance. These balance equations apply to the separation element, stage, or cascade regardless of the enrichment method used (Whitaker, 2019). The materials balance is given by the following factors derived from Figure 3.9:

$$F_z = P_y + W_x \tag{15}$$

Therefore:

$$\frac{P}{F} = \frac{z-x}{y-x'} \tag{16}$$

and

$$\frac{W}{F} = \frac{y-z}{y-x'} \tag{17}$$

The product to feed flow rate ratio is defined as the cut, θ, where

$$\theta \equiv \frac{P}{F'} \tag{18}$$

Separation factors are used to quantify the degree of separation, achieved by a single stage. The stage separation factor is usually defined as the weight, mole, or atomic ratio of the product stream divided by that of the tails stream:

$$\alpha \equiv \frac{\eta}{\xi} = \frac{y(1-x)}{x(1-y)'} \tag{19}$$

A more useful separation factor is, however, the product separation factor and is defined as:

$$\beta \equiv \frac{\eta}{\zeta} = \frac{y(1-z)}{z(1-y)'} \tag{20}$$

The tails separation factor is defined as:

$$\gamma \equiv \frac{\zeta}{\xi} = \frac{z(1-x)}{x(1-z)'} \tag{21}$$

A relationship between α, β, and the cut, θ, can be shown as:

$$\beta - 1 = \frac{(\alpha-1)(1-\theta)}{1+\theta[(\alpha-1)(1-y)]'} \tag{22}$$

In order to achieve the targeted degree of isotope separation a cascade is designed whereby the tails stream of partially depleted material from one stage becomes the feed material to the next.

3.2 Empirical investigation

Tracy, 2013 states that quantitative research transforms data, inclusive of conversations, actions, media stories, facial twitches, or any other social or physical activity into numbers. Quantitative methodologies use measurement and numbers to develop mathematical models and estimates.

As an example, a quantitative researcher may aggregate survey answers to measure how often respondents engage in a certain activity, or how much they prefer a certain product. The method used for the collection of data was self-administered questionnaires. The questionnaires were managed through a survey type and allowed perspective on the understanding of and suggestions from the sample group. These detailed survey type questionnaires obtained information from the sample group.

3.2.1 Population and sampling

3.2.1.1 Population

A population refers to a study object and is made up of individuals/elements, groups, organisations, product or events about which you might later make claims (Welman et al., 2006 Leavy, 2017). A population is linked to a research problem and also encompasses data collection regarding all unit of analysis about which a researcher wants to make a particular conclusion.

The study therefore focused on individuals who have knowledge of nuclear in a broad sense, and expert within their nuclear field, be it regulatory, academic or commercial/industry.

A quantitative research approach was employed to gauge the participants' understanding of aerodynamic separation technologies and the non-proliferation regulation thereof. Participants were classified under different portfolios as Government Policy Maker, Manager in Regulatory Institution, Technical Expert in Industry, Business Executive in Industry, Inspector in Regulatory Institution, Technical Expert in Regulatory Institution and Academics/Researchers.

Respondents were informed that the study's intention was for the academic purpose of satisfying PhD requirements, and only respondents who were willing to participate formed part of the sample selection as well as the study.

3.2.1.2 Sampling

3.2.1.2.1 Sampling technique

In conducting a survey research, questionnaires are applied as the primary data collection tool in. A questionnaire is also referred to as the survey instrument (Leavy, 2017). Questionnaire construction and delivery to respondents are very involved processes. In this case, the researcher compiled the questionnaire which was approved by the University, before a formal request was sent to the Executives of different institutions for their experts to participate.

It should be noted that although Klydon, Department of Mineral Resources and Energy (DMRE), Nuclear Energy Corporation of South Africa (NECSA), National Nuclear Regulator (NNR) and the South African Council for the Non-Proliferation of Weapons of Mass Destruction (the Council) were approached for participation, only the NNR, Klydon and the Council experts responded.

3.2.1.2.2 Sampling size

The sample in this study is made up of a total number of 24 South African experts (government, industry, academic and regulatory) selected across the domestic academic and nuclear institutions landscape (22) while the other 2 respondents were a nuclear diplomat and a researcher from the IAEA Safeguards Division.

3.2.3 Data collection

Data collection is a process of accumulating observation or quantities when performing research for business, governmental and academic purposes. Data collection permits the researcher to gain first-hand knowledge of, and original insights into, a research problem (Bhandari, 2020).

In this study, the method applied for collecting data is quantitative and therefore the researcher made use of the self-administered questionnaire **(Appendix A)** whereby participants responded by completing the form in their own time within the provided time frames. The information collected from the respondents was held in the strictest of confidence, with the reported attributed to a portfolio rather than an individual due to the implications on those individuals, especially the non-proliferation regulators and industry expert affected by the non-proliferation regulations.

3.2.4 Response rate

The target population of this study was affected as explained in the limitation of the study. Due to the identified limitation of the study, a target sample of 50 respondents was set. To achieve this target, questionnaires were distributed to different organisations and individuals covered by the targeted portfolios.

Table 3.1 Response rate.

Statement	Number of respondents	Percentage
Questionnaires distributed	50	100.00%
Questionnaires not returned	26	52.00%
Questionnaires returned	24	48.00%

3.2.5 Data analysis

According to Neuman, 2003, data analysis refers to a technique used to examine the information, which can be content or symbolic, whereby the researcher identifies first the body of material to analyse. Data is insignificant if not analysed and translated into meaningful physical explanation. Therefore, data which was collected through self-administered questionnaires was populated into a Microsoft Excel 2016 spreadsheet for statistical analysis, through calculating mean, standard deviation and Cronbach alpha.

Descriptive research is a type of research that provides a description of a phenomenon or a group under study. It aims to generate “thick descriptions” of social life (those that provide details, meanings, and context), typically from the perspective of the people living it (Leavy, 2017). It uses descriptive statistics: frequencies, measures of central tendency (e.g., mean), and measures of dispersion (e.g standard deviation) about variables in a data set and highlight the potential involvement between variables. This study followed a descriptive data analysis technique whereby numerical data was used to draw conclusions from respondents and make recommendations to help the government in policy developments. The researcher applied the following statistical techniques to analyse data:

Mean;

$$\bar{X}\ (Mean) = \frac{\Sigma\chi}{N}$$

Where

Σx = (Sum of the terms)
N = (Number of terms)

and Standard Deviation;

$$\sigma(Standard\ Deviation) = \sqrt{\Sigma\left(\frac{(x_i - \mu)^2}{N}\right)}$$

Where

N = (the size of the population)
x_i = (each value from the population)
μ = (the population mean)

3.2.6 Data reliability

Reliability is described as the consistency of the result, regardless of who the administers are over time (Newstrom, 2011). Meaning that if the measurement must be repeated with the same results, then the research instrument is considered to be reliable. Reliability measures if a questionnaire and its underlying constructs are consistently reflecting what it is measuring, this means that:

- a person completing the questionnaire on two different points in time should get the same score for each of the constructs each time they complete the questionnaire, all other things being equal; and
- two people who are the same in terms of the constructs being measured by the questionnaire should both get the same scores for these constructs.

To test the reliability of the survey, a Cronbach's alpha test was used to measure the consistency. Cronbach's alpha is a coefficient that describes how well a group of items focuses on a single idea or construct (Cronbach, 1951). The researcher therefore applied the following for testing reliability of the survey:

Cronbach alpha;

$$\alpha(Cronbach\ Alpha) = \left(\frac{k}{k-1}\right)\left(\frac{S_{y^2} - \sum S_{i^2}}{S_{y^2}}\right)$$

Where

k = 23 (No of questions)

S_{y^2} = (Variance for total score of each question)

$\sum S_{i^2}$ = (Sum of Variance for individual score of each question).

3.3 Chapter summary

Chapter 3 detailed development and characteristics of the Aerodynamic Separation Process (Klydon) as compared to the genesis aerodynamic enrichment processes, and the process to conduct the survey. Chapter 4 present results from the comparison between Aerodynamic Separation Process and genesis aerodynamic enrichment processes. Further, it motivates for exemption of natural gas ASP from regulation and results of the survey conducted.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Klydon ASP Enrichment Plant

Section 4.1.1 describes the general aspects of Klydon's ASP plant design and technologies across all separated isotopes and potentially natural gas, whether at testbench level or commercially. Section 4.1.2 describes a specific ASP process to be followed by Klydon during the production of 10kg of 98% enriched $^{100}MoF_6$.

4.1.1 General ASP Plant configuration

4.1.1.1 The ASP Plant main components

The ASP Plant consist of the following functional units:

- Separation stage

  It is a process unit that performs a single function namely to separate isotopes. It consists of a Separation Element Assembly (SEA) that contains numbers of ASP separators in series and parallel (Figure 4.1); that as a unit has an input stream, re-circulation streams, an enriched light mass stream, and an enriched heavy mass stream. The flows and pressures in each of these streams are arranged so that the feed material mass cut in the light and heavy streams are close to symmetrical.

Figure 4.1 Primary and Secondary vessels containing ASP separating element assemblies (Strydom et al., 2016).

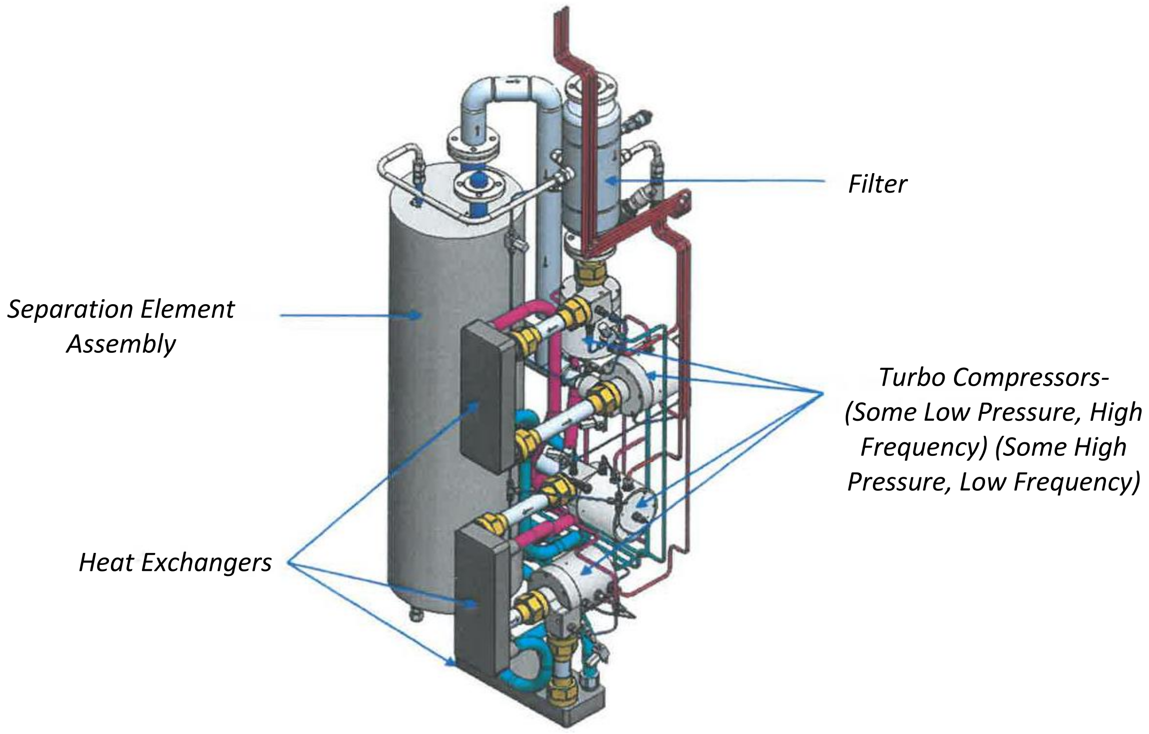


Figure 4.2 3D representation of an enrichment stage (Klydon, 2020).

The Klydon ASP separation elements per enrichment stage (or depletion) are housed together in a common vessel and each stage has 2 vessels; a primary separation vessel, and a secondary vessel. After each primary separation the pressure is sufficient to drive another separation step, which enhances the separation performance per stage by ~30%.

- Cascade segment

A process unit containing multiple separation stages in series, dependent on the intended enrichment level. Process gas is repeatedly compressed and expanded in ASP separators to obtain an isotope gradient between the inlet and outlet streams of the unit. Separation stages are grouped together in units of 12 to form a cascade segment. A segment is connected to adjacent segments via 4-way valves and backbone to form a cascade of 6-10 segments.

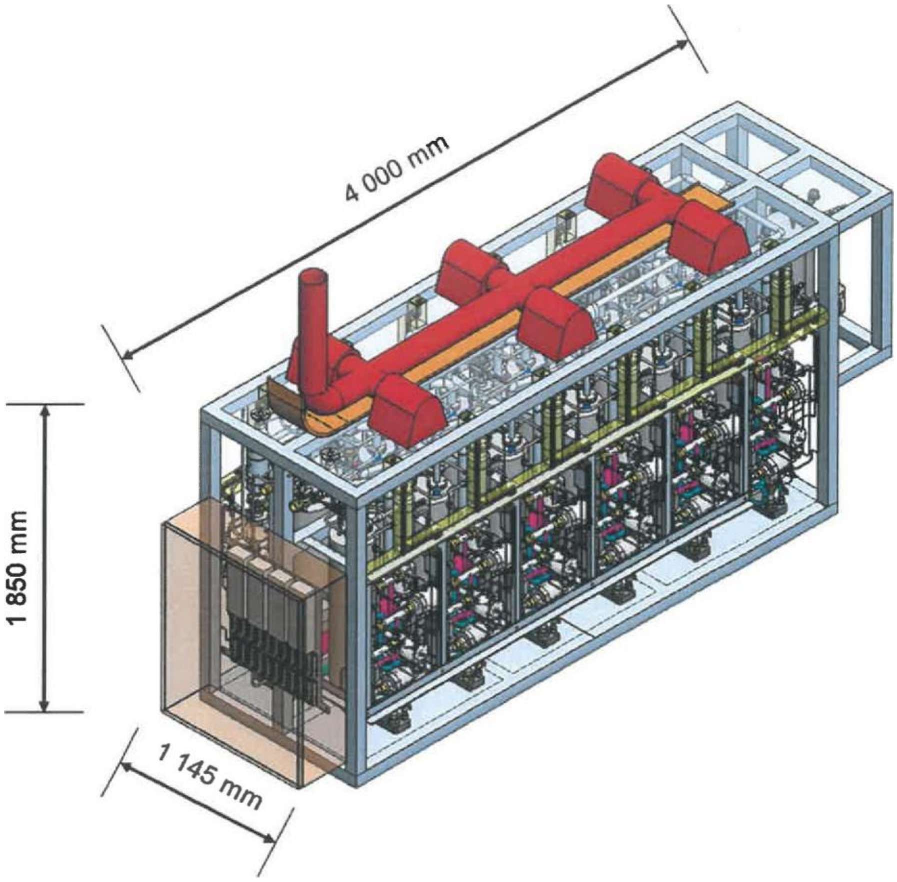


Figure 4.3 3D representation of a cascade segment (Klydon, 2020).

- Backbone

  Provides services from service areas to the various process units and connects the process units to each other. It also allows process units to be isolated from the main cascade for removal during maintenance.

- Heavy isotope recovery

  This process unit has two functions: Process gas product recovery and providing cascade reflux. A portion of the gas stream from the adjacent cascade segment is withdrawn (Process gas and carrier gas separated). The remainder of the Process gas is mixed with carrier gas to the prescribed mole mass and returned to the cascade.

- Gas separation process module

Process gas from the adjacent segment is separated into a pure carrier gas and pure process gas streams. The separation is done with a combination of pressure swing adsorption (PSA) and membrane separation technology.

- Light Isotope recovery

  Process gas from the gas separator is partially recovered as waste. The remainder of the Process gas is mixed with carrier gas and returned to the cascade.

- Feed system

  Process gas is mixed with carrier gas and a controlled quantity is fed to the cascade.

- Blowdown system

  Blowdown streams from all plant safety devices are collected in a tank. The gas in the tank can be vented trough the scrubber or treated with a mobile vacuum station and returned to the plant, if feasible.

- Carrier gas supply

  Carrier gas from the gas separator is treated to remove impurities, compressed and stored for re-use. Carrier gas losses is made up from fresh feed cylinders.

4.1.1.2 The balance of the ASP Plant.

The balance of the plant consists of:

- Mobile vacuum trolley
- Cryogenic supply (chilled water)
- Compressed air
- Process ventilation gas scrubber
- Nitrogen distribution
- HVAC system

- Cooling water distribution
- Electrical, control & instrumentation; and
- Fire protection systems.

Figure 4.4 (a) Part of the oxygen-18 enrichment production plant built by Klydon, (b) Klydon Silicon enrichment facility - 1,000 SWU Enrichment capacity/200 kg ^{28}Si.

4.1.2 Mo-100 Enrichment Plant description

A comparative study to assess different aspects of the Molybdenum 100 enrichment plant, as a representative of an ASP technology plant, against the commonly known features of a UF_6 enrichment plant was done and analysed. There were a lot of distinct features that showed the difference between the two technologies whilst some components were applicable to both technologies.

Whereas Molydenum is the heaviest isotope currently being enriched by Klydon through the ASP technology, among the responses to the questionnaire provided by Klydon expert, the technology can separate Uranium. This is based on the testbench results obtained during the previous Tungsten isotope enrichment. Despite the response, the current study focused on the commercial use of the ASP technology hence focus on Mo-100 as the heaviest isotope.

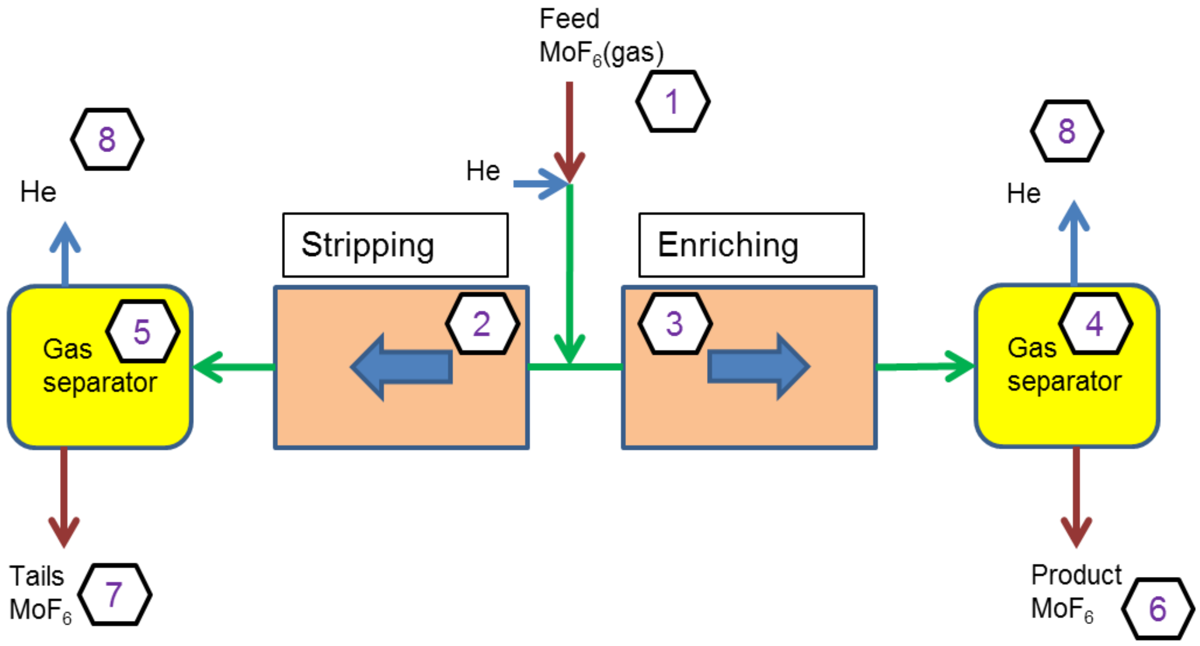


Figure 4.5 Schematic presentation of ^{100}Mo enrichment plant by Klydon.

As shown in Figure 4.5, the process gas [molybdenum hexafluoride (MoF_6)] and carrier gas [helium (He)] are mixed through a mixing station (1) to a target combined gas molecular mass in the order of 6-10 g/mol. Thereafter, the process gas is introduced into the isotope separation plant between the enrichment and stripping sections (1 and 2).

The concentration of $^{100}MoF_6$ is gradually increased as it passes through the various stages of the enriching section (3). Similarly, there is a decreasing in the concentration of $^{100}MoF_6$ as it passes through the various stages of the stripping section (2). It should be noted that there is a complex interaction between the enriching and stripping sections, but for the purpose of this document it is not necessary to go into the interconnecting details of these sections and separating elements. The process gas is forced through the separating elements with various compressors to effect the actual separation of the isotopes in the separating elements. These sections (2 and 3) mainly consist of a complex combination of compressors, separating elements and interconnecting pipes. The operating temperature throughout these sections is above 16^{o}C. As this is normally below room temperature no special heating is required on the piping throughout these sections.

The process gas is introduced into the gas separator section into one of two identical desublimer/sublimers, one which is acting as a desublimer (4) and the other simultaneously as sublimer. In the desublimer solid MoF_6 is collected while the He is unaffected and sent to the scrubber. The unit that is acting as sublimer is heated to provide a reflux stream to the isotope separation section. A part of this stream is compressed and stored as product (6). The He gas is further processed with a scrubber containing MgF_2 or NaF (design still to be finalised) (6) to clean the He to the required purity to be used again as the carrier gas (1). This process is duplicated at the tails end of the stripping section (5, 8 and 7).

The plant is designed to work in a batch process where the product would be re-introduced as the feed, and this is repeated several times to finally produce 10kg of 97% enriched $^{100}MoF_6$. Based upon on the information given above, Table 4.1 has been compiled in order to assist in distinguishing between the proliferation risk associated with ASP plants for MoF_6 and theoretical UF_6.

Table 4.1 Comparison of MoF_6 and potential UF_6 enrichment plants.

Comparison of MoF_6 and potential UF_6 enrichment plants (This study findings)			
Label	**Similarities**	**Differences**	**Comments**
1 Gas supply		MoF_6 gas feed is directly fed from a gas bottle. In case of UF_6, the solid is introduced into a plant and heated inside an autoclave to sublimate into the process gas before it is mixed with helium.	The MoF_6 plant would require modification to be converted to a UF_6 plant. For example, there is no autoclave required for the MoF_6 gas feed.
1 Gas supply	Construction materials are compatible with both MoF_6 and UF_6	None	The corrosiveness of the process gas ($-F_6$) is a common denominator.
2 and 3 Stripping and Enrichment	Separating elements could be used in a UF_6 plant	Separation efficiency of the plant, if used on UF_6, would only be about 40% compared to a plant that has been optimised for MoF_6. (The 40% efficiency determination is based on the mass proportion between UF_6(352) and MoF_6(210) as well as the separation element optimised for MoF_6 being misused on UF_6.)	The separation efficiency would not be the same due to the difference in molecular mass between Mo and U. Basically the UF_6 product harvested (weight) would be around 40% of what would have been obtained if the plant was used for enriching MoF_6. However, the enrichment level would still be the same for both compounds. It should be noted that the plant is optimised to enrich MoF_6 to 97%. This is based on theoretical calculation as there is no factual verification done on a testbench. Additionally, the theoretical data for UF_6 ASP plant efficiency is also based on the Benedict theoretical data and analysis (Benedict et al, 1981).

Comparison of MoF_6 and potential UF_6 enrichment plants (This study findings)

Label	Similarities	Differences	Comments
2 and 3 Stripping and Enrichment	The plant layout would follow the same general configuration.	Heating requirements in the case of MoF_6 would be limited to initial selective heating for drying purposes prior to the introduction of the process gas.	Heating requirements in the case of UF_6 Plant is throughout the process piping as the UF_6 needs to be kept as a gas throughout.
		UF_6 Plant would require optimised separating elements to increase its operating efficiency.	The separation efficiency of the plant would still not be the same due to the difference in molecular mass between MoF_6 and UF_6. This would affect the specifics e.g separating assemblies, the PLC, if the plant was to be used for U separation
		Mass flow design would be an order of magnitude smaller than encountered in UF_6 commercial plants.	Capacity of compressors and vacuum pumps would be much smaller than those in commercial enrichment plants. As such, the PLC/SCADA would need to be modified to accommodate Uranium flow.
2 and 3 Enrichment and stripping	Construction materials are compatible with both MoF_6 and UF_6	None	
4 and 5 Gas separation and He gas scrubber	A simultaneous and interchangeable desublimer/sublimer setup would probably be used in both cases. The design principles would be the same.	The desublimer/sublimers would not function optimally if it is applied in the UF_6 role. The capacity would not be matched to the plant output.	Desublimer/sublimers would need replacement if the plant is to be modified for UF_6.
4 and 5	If NaF is used for scrubbing material, it would be applicable to	If MgF_2 is used for the scrubbing process of the He gas, it would only be	It should be noted that MgF_2 is an important substance in the

Comparison of MoF_6 and potential UF_6 enrichment plants (This study findings)			
Label	**Similarities**	**Differences**	**Comments**
Gas separation and He gas scrubber	both MoF_6 and UF_6 plants.	applicable to the MoF_6 plant.	FLUOREX process to reprocess nuclear fuel.
4 and 5 Gas separation and He gas scrubber	Construction materials are compatible with MoF_6 and UF_6	None	
6 and 7 Product and tails		Solid UF_6 is stored in standardised UF_6 container. MoF_6 gas is extracted from the sublimer and transferred into a gas cylinder with the aid of a compressor.	The MoF_6 plant would require extensive modification to accommodate this.
8 Helium recycling	Pure (order 50 – 100 ppm) He gas is required to be used as a carrier gas in both MoF_6 and UF_6 plants.	None	
Instrumentation	Sensors and PLC are applicable in both cases	All ranges and instrumentation system designs are different and require a complete redesign. Additional PLCs are required for the new and modified feed product and tails sections and integrated into the existing system.	Instrumentation system requires essentially a redesign from scratch.
2, 3, 4, 5, 6 and 7 Cold traps and sampling points	NaF type cold traps are applicable in both MoF_6 and UF_6 plants.		Standard for UF_6 enrichment plants.

4.2 ASP Technology versus UCOR and Becker process

While the separation process proposed by Becker and the one implemented by UCOR are completely distinct from one another, they share characteristics with each other as well as with the ASP separator, the most important one being that no moving parts are involved. In this sense, they are closer to each other than to the gas centrifuge. In the case of the UCOR process this is no coincidence: the UCOR process counts among the genesis technologies of the ASP separator. However, ASP represents a significant improvement on its genesis technology (Ronander et al., 2012).

The easiest way to demonstrate this is to compare the separation characteristic resulting from theory for the UCOR process (Benedict et al., 1981) to the corresponding ASP theory result. The two theories clearly indicate a prominent difference between the UCOR and ASP separation processes: the latter has more degrees of freedom, i.e., more parameters to be chosen.

Figure 4.6 shows separation factors for the ASP and UCOR processes (the higher the factor, the better the separation performance of the element). The former is predicted by the ASP theory, the latter by Benedict's theory (*both using assumed* UF_6 *separation values*). The curves are normalized:

- The spin speed is normalized with the speed resulting in maximum separation for the ASP separator.
- The separation measurement is normalized using the maximum separation that can be achieved for the UCOR process.

The parameters for the ASP process were configured in such a way that it matched the UCOR process as much as possible. Representative values were chosen for those parameters that have no analogue in the UCOR process. Note that it is possible to achieve significantly higher separation with the ASP process compared to the UCOR process at the same conditions: the Figure 4.6 shows a 70% increase for the case considered. While the UCOR process reaches a ceiling for high spinning speeds, there is no corresponding theoretical limitation on the ASP separation. The maximum shown in the Figure 4.6 is for a specific case and can go much higher.

The UCOR process was typically operated at normalized spin speeds of 100% or a bit higher, where it was practically at its ceiling for separation. It is important to realise that the 70% higher ASP separation is achieved at 100% normalized spin speed, i.e., at a speed equal to, or lower than, that of the typical UCOR process speed range. The reason this is significant is because energy usage of both the ASP and UCOR separators is determined to a large extent by the spin speeds necessary to achieve acceptable separation. This means that higher separation is achievable by an ASP separator with an energy usage similar to that of the UCOR process. This is a strong indicator that the specific energy usage (energy used for separating work done) of the ASP separator is significantly lower than that of the UCOR process: ASP uses the same energy to do more work than the UCOR process.

The operating speed for ASP separators is not determined by the point of maximum separation, but by the point of minimum specific energy usage. As it happens, however, these two points are close to each other.

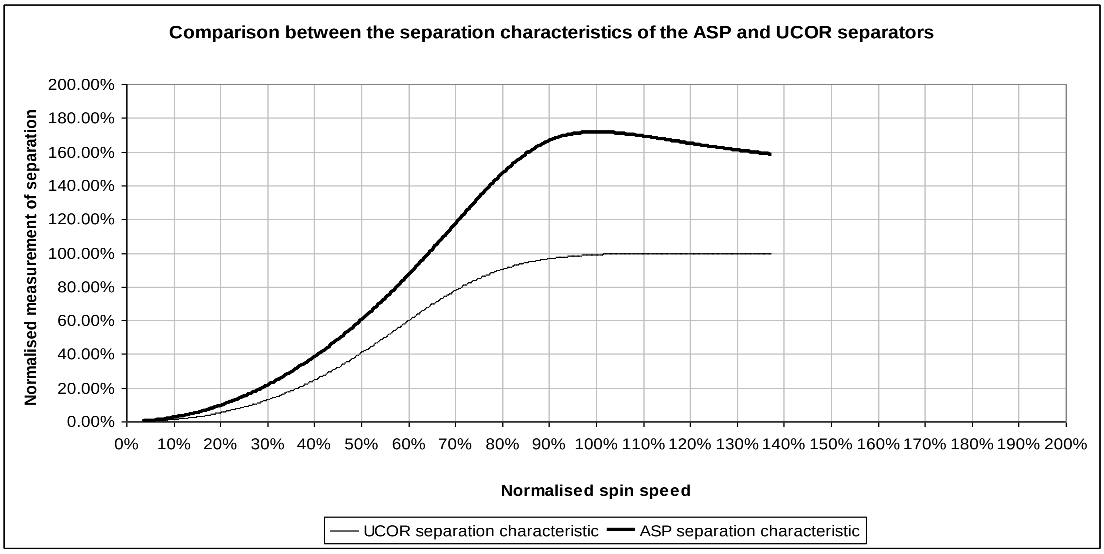


Figure 4.6 ASP versus UCOR separation characteristics (Klydon, undated).

Figure 4.7 shows an ASP separation characteristic similar to the one in Figure 4.6. A specific energy usage curve (kWh/SWU) is also shown. The minimum specific energy usage is achieved at a spin speed only slightly higher than the one at which maximum separation is achieved, i.e., at the speeds almost identical to those used in the UCOR process. This confirms that the ASP separator exhibits a significantly lower specific energy usage that the UCOR device.

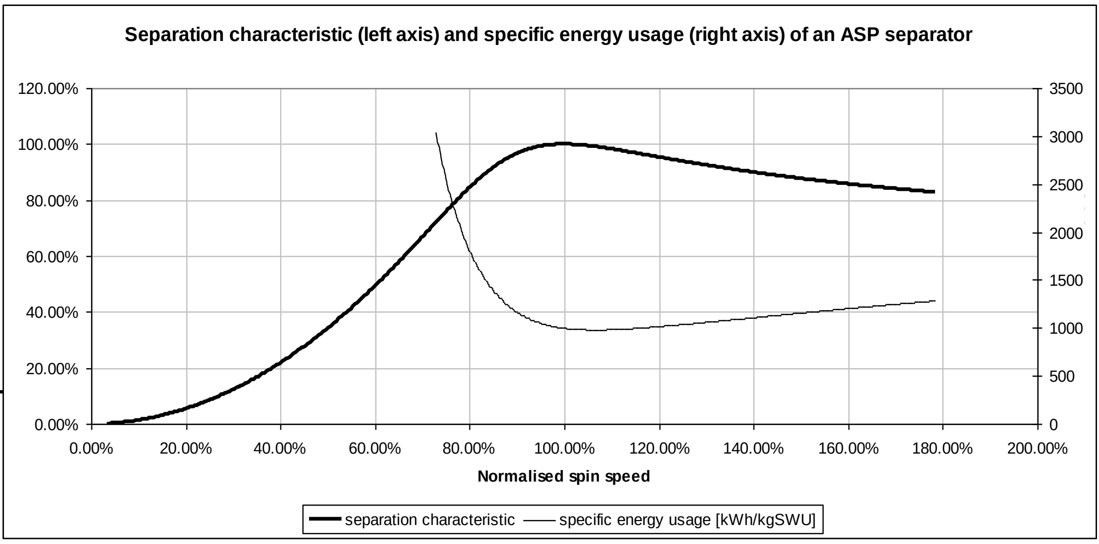


Figure 4.7 The specific energy consumption of the ASP Separator (Klydon, undated).

Whereas the details covered in sections 4.2 show similar characteristics between UCOR and Klydon ASP technology, with better efficiency perceived for the Klydon ASP technology, the controls according to the NSG and IAEA's Model Additional Protocol does not distinguish between aerodynamic separation technology for Uranium enrichment (UCOR) and aerodynamic separation technology for non-fissile material (ASP technology).

Furthermore, the ASP technology, with its optimised cut of 50% compared to the 4-6% of genesis technology (Strydom et al., 2016), is subjected to similar controls irrespective of whether the plant is meant for gas or isotope separation. This is despite the fact that the separative work achieved for gas separation is in a different order than that achieved for isotope separation.

Figure 4.7 shows the gradual improvement of the ASP technology "cut" during separation of an isotope or gas of interest throughout the period of research. The current separation of Si-22, O-18, and now Mo-100 are commercially viable due to the improved "cut" and less energy consumption.

Section 3.1.3 indicates that the ASP does not suffer from nozzle geometry limitations as per the genesis technologies, e.g UCOR. Figure 4.8 gives a clear advantage of ASP separation characteristics versus UCOR separation characteristics, which also emphasise data reflected in Figure 4.7

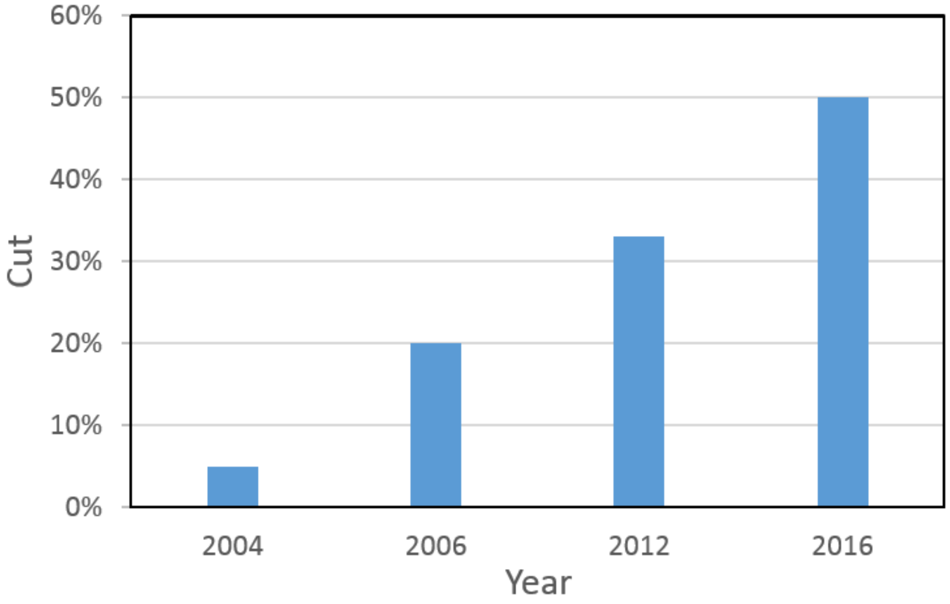


Figure 4.9 The gradual improvement of the “cut” parameter of ASP technology (Ronander et al., 2012).

4.3 Gas Separation vs Isotope Separation

Due to its characteristics of separating volatile compounds, the ASP has been studied, but not practically proven, for applicability in separating gas, whether Binary component gasses or complex mixture gasses. However, the makeup of the plant, though using the similar technological basis, is different from the isotope separating ASP plant. This includes parameters, tangibles, and intangibles such as materials, product extraction, etc.

Table 4.2 gives a comparison of parameters appearing on an isotope separating ASP plant and a gas separating ASP plant. It is noticeable that there is a marked difference, especially of materials, between the two plants. However, the regulation of ASP in a gas plant is the same. Similarly, the separation elements in an isotope separating ASP plant and in a gas separating ASP plant show a remarkable difference, especially the gas/isotope inlet jets (Figure 4.10). The production extraction is tangible mechanical nozzle in a gas plant while in an isotope plant it would be virtual nozzles because of the difference mass ranges between the two products of interest.

Table 4.3 Comparison between Isotope and Gas separation ASP plants

Parameters	**Isotope Separation**	**Gas Separation**
Carrier Gas	Hydrogen / Helium	None
Mass Range	up to 352 for Uranium (UF_6)	16 – 44 (CH_4 – CO_2)
Inlet Jets	Multiple rows, End-compression Small diameter (μm scale) Tangentially	Single row, Equally spaced Medium diameter (mm scale) Straight
Flow Pattern	High spin velocities Slender wall-less centrifuge Complex Flow Guide/Restrictors	Medium spin velocities Short, Fat wall-less centrifuge No Flow Guides/Restrictors
Product Extraction	Multiple streams; Virtual nozzles – Dimensions (μm)	Two streams; Mechanical nozzle – Dimensions (mm)
Materials	UF_6 Corrosion Resistant	Brass, PVC, etc.

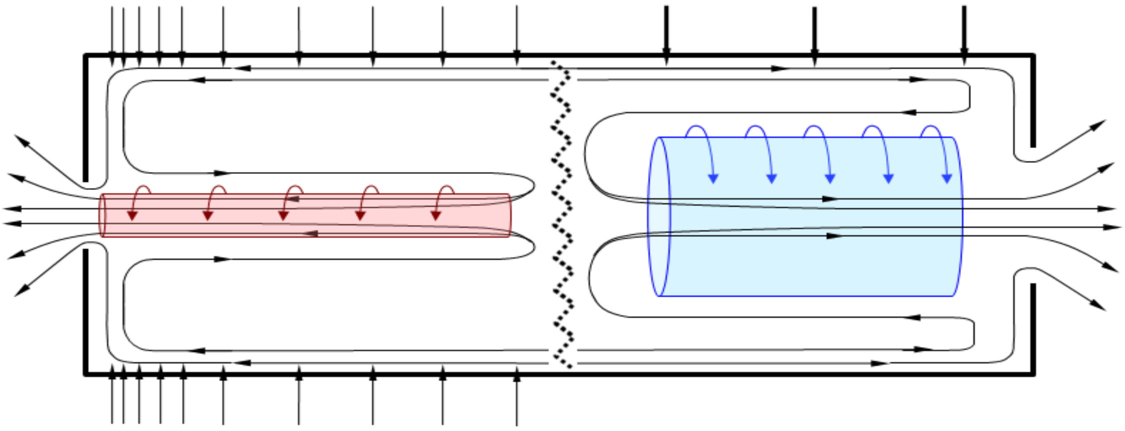


Figure 4.11 Illustration showing the difference in design between separation elements of Isotope (left) and Gas (right) separation

The illustration in Figure 4.12 clears shows the flow patterns of the extracted products with a clear indication of the difference in size of the extracting nozzle. The mass difference for methane and carbon dioxide is 175%, whilst uranium isotopes is merely 0.85%; this difference requires vastly different extraction or harvesting configuration and dimensions.

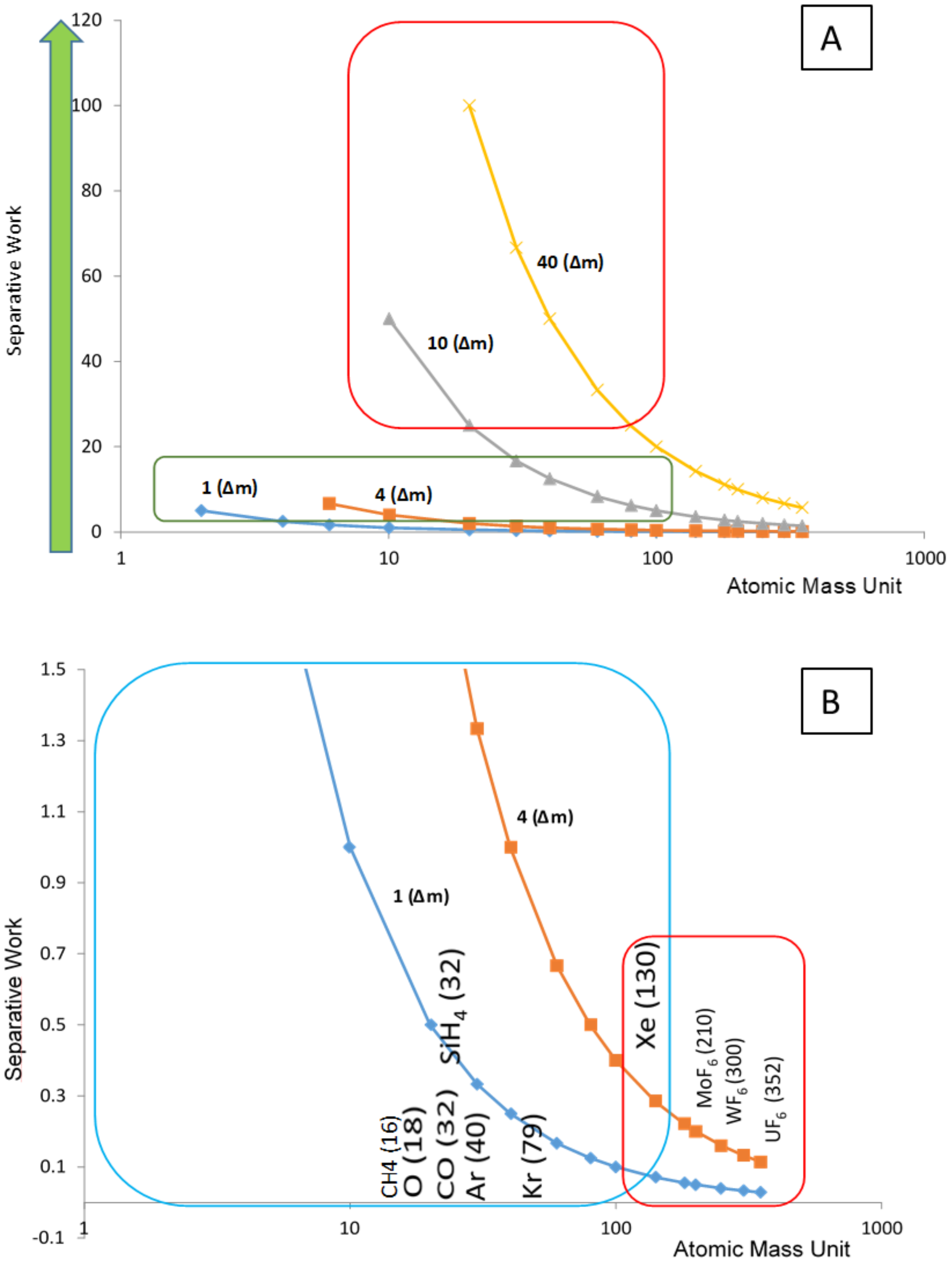


Figure 4.13 A) Gas separation (Separative work achieved vs Atomic mass unit), B) Isotope separation (Separative work achieved vs Atomic mass unit)

The gas and isotope separation graph (Figure 4.13. A) shows typical curves for various different mass ranges (Δm) for both gasses and isotopes. Greater efficiencies can be obtained at lower atomic mass units for both gasses and gaseous compounds containing a variation of isotopes. The ASP is not proven to be applicable to higher atomic mass unit isotope separation applications. The separation efficiency is dependent on various factors and the graphs shown only serves the purpose of getting a feel of one factor (amu). To overcome this drawback a carrier gas (H or He) is used to lower the effective combined atomic mass units of the gas mixture. The subsequent graph (Figure 4.13.B) shows the operational area of ASP with a carrier gas.

4.4 Regulation of Aerodynamic Processes by the NSG

4.4.1 Nuclear Suppliers Group's determination on the regulation of the ASP technology

The Nuclear Suppliers Group (NSG) has, under Section 5.5 Annex B of the INFCIRC/254/Rev.13/Part 1 of 18 October 2019, provided for the regulation of aerodynamic processes applicable in the separation of uranium. These type of technologies fall squarely within the trigger list and are subjected rightfully to Safeguards and other applicable stringent regulatory principles.

Similarly, according to the Guidelines for the Export of Nuclear Material, Equipment and Technology, INFCIRC/254/Rev.13/Part 1 of 18 October 2019, the NSG provides for the regulation of plant, paraphernalia and expertise for the enrichment of “other elements” (every element except hydrogen, uranium and plutonium) under General Notes.

This is because, according to the NSG, nuclear technology suppliers recognize the strong link between plants, equipment, and technology for uranium enrichment and that for isotope separation of "other elements" for research, medicinal, and other non-nuclear industrial uses for specific isotope separation procedures. In this regard, suppliers should carefully review their legal measures for isotope separation activities involving "other elements," including export licensing regulations and information/technology classification and security practices, to ensure the implementation of appropriate protection measures as warranted.

Furthermore, these suppliers acknowledge that, in certain situations, acceptable safeguards for isotope separation activities involving "other elements" will be substantially the same as those for uranium enrichment, as reflected in introductory note in section 5 of the Trigger List. As such, suppliers noted that it is vital that they communicate with other suppliers in order to develop common policies and processes in the transfer and preservation of plants, equipment, and technology involving isotope separation of "other elements," in line with the prescripts of paragraph 17(a) of the Guidelines of INFCIRC/254/Rev.13/Part 1 of 18 October 2019. Suppliers should also take sufficient prudence in circumstances involving the deployment of equipment and technology, resulting from uranium enrichment procedures, for other non-nuclear purposes such as in the chemical sector (IAEA-1, 2019).

Furthermore, the introductory note of section 5 Annex B states:

Quote:

Plants, equipment and technology for the separation of uranium isotopes have, in many instances, a close relationship to plants, equipment and technology for isotope separation of "other elements". In particular cases, the controls under Section 5 also apply to plants and equipment that are intended for isotope separation of "other elements". These controls of plants and equipment for isotope separation of "other elements" are complementary to controls on plants and equipment especially designed or prepared for the processing, use or production of special fissionable material covered by the Trigger List. These complementary Section 5 controls for uses involving "other elements" do not apply to the electromagnetic isotope separation process, which is addressed under Part 2 of the Guidelines.

Processes for which the controls in Section 5 equally apply whether the intended use is uranium isotope separation or isotope separation of "other elements" are: gas centrifuge, gaseous diffusion, the plasma separation process, and aerodynamic processes. ………….. end of quote (IAEA-1, 2019).

The introductory note quoted above was placed in the Guidelines to cater for the control of "other elements" separation plants and technology. From the extracts, it can clearly be seen that the NSG, in recognising the sensitivity of plant, equipment and technology for the enrichment of "other elements" has recommended that transfers of such items should be handled in a similar way as trigger list enrichment technologies.

Again, the general note emphasises the close relationship between the plant, equipment and technology for the separation of "other elements" and the plant, equipment and technology for the separation of uranium. Although enrichment of other elements using ASP would be different from uranium enrichment, data obtained could be, theoretically, used to modify the ASP plant to suit uranium enrichment. It should be emphasised that this is based on the theoretical calculations, as factual testing of application of ASP technology, and actually ASP in general, on uranium has not been done.

4.5 Regulation of Aerodynamic Processes by the IAEA

Aerodynamic process items listed under NSG Section 5.5 Annex B of the INFCIRC/254/Rev.13/Part 1 of 18 October 2019, are covered under safeguards agreement with the IAEA as they are regarded as trigger list items due to their applicability in the separation of Uranium. The development of nuclear fuel-cycle capabilities, on the other hand, necessitates research and development that does not always include the use of radioactive material (IAEA-5, 2016).

A description of the research, its aim, the organizations or individuals doing it, and its location are among the details that must be given for nuclear fuel cycle-related research and development activities. There may be times when research and development is carried out in multiple places, potentially even in different states or by different organizations. Each organization and the sites where the activities take place, including locations in neighbouring states, shall have their own entry in the declaration.

The above are listed under INFCIRC/540 of September 1997 as follows:

Quote: (IAEA-3, 1997)

Article 2.a.(i): [The State] shall provide the Agency with a declaration containing: A general description of and information specifying the location of *nuclear fuel cycle-related research and development activities* not involving *nuclear material* carried out anywhere that are funded, specifically authorized or controlled by, or carried out on behalf of, [The State].

Article 2.a.(iv): [The State] shall provide the Agency with a declaration containing: A description of the scale of operations for each location engaged in the activities specified in Annex I to this Protocol.

Article 2.a.(ix)(a): [The State] shall provide the Agency with a declaration containing: The following information regarding specified equipment and non-nuclear material listed in Annex II:

> (a) For each export out of [The State] of such equipment and material: the identity, quantity, location of intended use in the receiving State and date or, as appropriate, expected date, of export;

Article 2.b.(i): [The State] shall make every reasonable effort to provide the Agency with the following information:

> A general description of and information specifying the location of *nuclear fuel cycle-related research and development activities* not involving *nuclear material* which are specifically related to enrichment, reprocessing of nuclear fuel or the processing of intermediate or high-level waste containing plutonium, *high enriched uranium* or uranium-233 that are carried out anywhere in [The State] but which are not funded, specifically authorized or controlled by, or carried out on behalf of, [The State]. For the purpose of this paragraph, "processing" of intermediate or high-level waste does not include repackaging of the waste or its conditioning not involving the separation of elements, for storage or disposal.

Article 3.d. [The State] shall provide to the Agency on a quarterly basis the information identified in Article 2.a.(ix)(a). This information shall be provided within sixty days of the end of each quarter. End Quote

4.6 Regulation of Aerodynamic Processes in South Africa

The Nuclear Energy Act, No. 46 of 1999 Section 2 provides that the Minister of Mineral Resources and Energy may, by notice in the *Gazette*, declare

- any substance with a degree of purity as specified in the notice, to be restricted material;
- any substance containing uranium or thorium with concentration and mass limits higher than those specified in the notice, to be source material;
- Pu-239; U-233; U enriched in its 235 or 233 isotope; transuranium elements; or any composition of any of the aforementioned materials, or any composition of

those materials and any other substance or substances with concentration and mass levels higher than those specified in the notice, to be special nuclear material;

- equipment and material specially designed or prepared for the processing, use or production of nuclear material, to be nuclear-related equipment and material.

Thus, the Minister through the Notice No 207 in Government Gazette of 27 February 2009, issued under the Nuclear Energy Act, No. 46 of 1999: declared aerodynamic process plants, systems, equipment and components regulated as follows:

Quote: (DMRE-2, 2009)

4 Plants for the separation of isotopes of uranium and equipment, other than analytical instruments, intended or especially designed or prepared therefor…

(v) Systems, equipment and components for use in aerodynamic enrichment

plants, including

1) *Separation nozzles*
2) *Vortex tubes*
3) *Compressors and gas blowers*
4) *Rotary shaft seals*
5) *Heat exchangers for gas cooling*
6) *Separation element housings*
7) *Feed systems/product and tails withdrawal systems*
8) *Header piping systems*
9) *Vacuum systems and pumps*
10) *Special shut-off and control valves*
11) *UF_6 mass spectrometers/Ion sources*
12) *UF_6 and carrier gas separation systems*

End of quote

Further, the Minister is empowered through the Nuclear Energy Act, No. 46 of 1999 Section 33. (1) to act as the national authority of South Africa for the purposes of the implementation and application of the Safeguards Agreement and additional protocols in order to timeously detect and identify nuclear material intended to be used for peaceful nuclear activities and deter the diversion of such nuclear material to the manufacture of nuclear weapons or other nuclear explosive devices or for use in connection with any other purpose that is unknown.

Whereas technology (*according to the NSG, "technology" refers to definite data needed for the "development", "production", or "use" of the products appearing in the control in the List*.) related to systems, equipment and components listed under Section 4 (v) of the Notice 2017 above is controlled through the Notice, the technology related to aerodynamic processes for the separation of "other elements" is not.

In South Africa, these controls are introduced under the Non-Proliferation of Weapons of Mass Destruction Act, No 87 of 1993, and Government Notice No. 493 of 29 March 2019.

According to paragraph 4(1)(a) of Government Notice No. 493 of 29 March 2019, quoted below, the Notice controls the aerodynamic process plants for separation of isotopes other than hydrogen (H), uranium (U) and plutonium (Pu).

Quote: (**the dtic**-1, 2019)

4. (1) Nuclear-related dual-use equipment, materials and software, and related technology, which can be used in their entirety or in part for the separation of uranium isotopes, are as follows:

(a) Equipment, assemblies and components of any plant or component parts of such plants, including the separating elements, which match all of the following conditions:

(i) Designed for the separation of other elements;

(ii) Can be used directly or can be modified to separate uranium isotopes; and

(iii) Are made of materials resistant to uranium hexafluoride (UF_6);

(b) software that is designed specifically for the use of equipment indicated in paragraph (a); and

(c) technology directly applicable to the development, production or use of equipment, materials or software as indicated in paragraph (a) or (b).

(2) Plants, equipment and technology specially designed or prepared for the separation of uranium isotopes, as contemplated in paragraph 4(1), have, in many instances, a direct relationship to plants, equipment and technology designed or prepared for the isotope separation of other elements. Control over plants, equipment and technology for the isotope separation of other elements is, in terms of the Act, additional to control over plants, equipment and technology specially designed or prepared for the processing, use or production of special nuclear material in terms of the Nuclear Energy Act, 1999 (Act No. 46 of 1999).

End of quote

4.7 Regulation of Mo-100 ASP plant and Gas ASP plant

4.7.1 Regulation of Mo-100 ASP plant

The $^{100}MoF_6$ enrichment plant is designed for the separation of ^{100}Mo isotopes and not for hydrogen, uranium or plutonium. As seen in the plant description and comparison to the possible application of the plant to the separation of uranium isotopes, the plant would require extensive modification to enable the separation of uranium isotopes. However, it would be theoretically possible to separate fissile material, based on Tungsten separation ASP testbench studies conducted by Klydon. Additionally, the materials, resistant to UF_6 are also resistant to MoF_6.

With reference to Article 2.a.(ix)(a) of the Additional Protocol that the notification to the IAEA on the export of non-nuclear enrichment facilities does not cover the export of aerodynamic process plant such as the Mo-100 ASP plant because the items covered by Article 2.a.(ix), strictly refers to ***Plants for the separation of isotopes of uranium and equipment, other than analytical instruments, especially designed or prepared therefor*** as listed under Annex II of the Additional Protocol.

This researcher therefore, feels that it would have been ideal to include the Section 5.5 Annex B of the INFCIRC/254/Rev.13/Part 1 of 18 October 2019 under Annex II of the Additional Protocol to ensure similar conditions of reporting exports of aerodynamic process plants separating other elements is applicable. This is because where “especially designed or prepared (EDP)” language is used in the Additional

Protocol, it was intended to as a guide to ensure that only nuclear-use (single-use) items are referred to (Mayhew, 2022).

Given significant advances in technology, the EDP concept is important to bear in mind in the interpretation of Annex II entries and in contemplating other technologies that it does not currently include. However, it is ideal observing that Annex II was specifically and intentionally formulated so as not to limit the list solely to single-use items, should the IAEA Board decide to expand the list. The purpose of the Annexes is not to control the transfer of non-nuclear material and sensitive technology, but rather to provide the IAEA with a fuller picture of a State’s nuclear-related activities. This helps the IAEA to plan for, implement and evaluate safeguards (Mayhew, 2022).

Furthermore, Article 18.a. of the Additional Protocol defines nuclear fuel cycle-related research and development activities as activities that deals with nuclear material conversion, nuclear material enrichment, nuclear fuel fabrication, reactors, facilities that are critical, nuclear fuel reprocessing and processing. The processing, however, excludes the repackaging or conditioning that does not entail the separation of elements for storage or disposal, of U-233, or high-enriched uranium (HEU) or intermediate or high-level waste containing plutonium.

However, efforts relating to the theoretical or fundamental scientific research, as well as research and development on industrial radioisotope uses, medicinal, hydrological, and agricultural applications, health and environmental consequences, and enhanced maintenance, are not included as nuclear fuel cycle-related research and development activities (IAEA-3, 1997).

If the interpretation of the Article 18.a. is taken verbatim, the envisaged Mo-100 plant that Klydon is considering might be regarded as not covered as the product, Mo-100 isotope, would be used in pharmaceuticals/medical applications. However, Section 7(e) of the Guidelines for Nuclear Transfers of the INFCIRC/254/Rev.14/Part 1 of 18 October 2019 insists on controls over those facilities through the special arrangements for export of such enrichment facilities, equipment and technology (IAEA-1, 2019).

Therefore, suppliers of these technologies are required to make extra effort ensure that IAEA Safeguards are effectively implemented at supplied enrichment facilities, in accordance with paragraphs 14 and 15 of the guidelines of the Nuclear Transfers of the INFCIRC/254/Rev.14/Part 1 of 18 October 2019. When transferring an enrichment facility, the supplier and the recipient states should collaborate to ensure that the transferred facility's design and construction are done in a way that allows for the IAEA Safeguards to be applied (IAEA-1, 2019).

The supplier and the recipient states should also engage with the IAEA regarding such design and construction elements as soon as practicable during the facility design process, but before the construction of the enrichment facility begins. Both states should also collaborate to help the recipient state implement appropriate nuclear material and facility protection procedures that are compatible with the 13 and 15 of the guidelines of the Nuclear Transfers of the INFCIRC/254/Rev.14/Part 1 of 18 October 2019 (IAEA-1, 2019).

Therefore, although there is a potential loophole created by Article 2.a.(ix)(a) of the Additional Protocol, the IAEA would still need to be informed on potential exports of separation technologies of other elements so as to ensure relevant safeguards mechanisms are implemented by the recipient.

In South African legislative context, the transfer of aerodynamic process plant, equipment and technology for

- Uranium separation, would be processed through the Nuclear Energy Act, No. 46 of 1999 and its supporting Government Notice No. 207 of 27 February 2009; and
- Separation of other elements would be processed through the Non-Proliferation of Weapons of Mass Destruction Act, No 87 of 1993, and Government Notice No. 493 of 29 March 2019.

Guidelines on Special controls on sensitive exports and Special arrangements for export of enrichment facilities, equipment and technology, as required by INFCIRC/254/Rev.13/Part 1 of 18 October 2019 are listed in Appendix B. These equally apply whether for the transfer of enrichment technologies of Uranium or other elements.

4.7.2 Regulation of gas ASP plant

While the NSG provides for the regulation of aerodynamic process for other elements, and the IAEA seeks declarations general description of and information specifying the location of nuclear fuel cycle-related research and development activities not involving nuclear material whether or not funded by the state, both institutions do not expand the controls to cover Gas separation aerodynamic process plants.

Whereas section 5.5 Annex B of the INFCIRC/254/Rev.13/Part 1 of 18 October 2019 clearly indicates that procedures, for which regulations or guidelines in Section 5 are similarly relevant, whether the planned application is uranium isotope separation or isotope separation of “other elements” include aerodynamic processes, the Additional Protocol under Article 2, also does not cover gas separation aerodynamic process plants.

Furthermore, Table 4.1 shows the comparison between Isotope and gas separation ASP plants. The tangibles clearly show the difference in the two plants, which is complementary to Article 2.a.(ix), which strictly refers to *Plants for the separation of isotopes of uranium and equipment, other than analytical instruments, especially designed or prepared therefor*. However, due to the basis for the development of the plant being the regulated ASP technology, controls for the gas ASP plant are implemented.

In South African legislative context, the application of safeguards and any additional protocols for aerodynamic process plant, equipment and technology would be done through the Nuclear Energy Act, No. 46 of 1999 for Uranium separation, and separation of other elements.

4.8 Results from the survey

The questionnaire was compiled in a way that allows each participant to provide their response (Yes or No) for each statement/question, through a range from 0 to 3 to show level of conviction and confidence on response. **0 for no conviction and confidence, 1 for a low level of conviction and confidence, 2 for general conviction and confidence and 3 for a high level of conviction and confidence.**

Due to the broad range of questions (scientific to legislation) and of respondents (pure academics, nuclear technical experts to regulatory and policy experts), different responses were anticipated.

4.8.1 Response rate

Figure 4.14 shows the data reflecting the number of participants per portfolio. Although the respondents chose the portfolio based on their current responsibilities and expertise, there is a clear difference in opinion, according to the responses given. It should be noted that the portfolio with the highest number of respondents is composed of individuals from different regulatory institutions. Additionally, even those experts from the same regulatory institution have different level of ASP knowledge as the individuals might have different professional background, e.g., Council experts, who responded include biologists and chemists, and not only nuclear physicists.

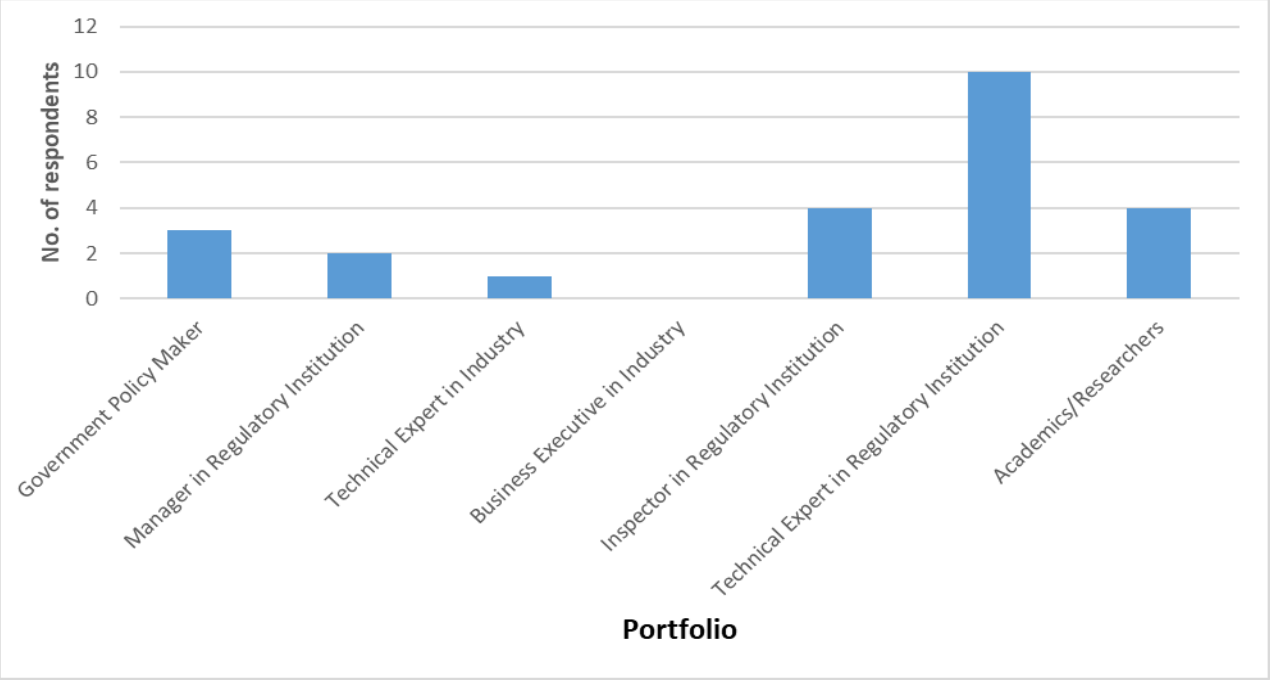


Figure 4.15 Illustration of number of respondents per portfolio.

4.8.2 Data resulting from the questionnaire

The calculations below only covered 5 portfolios because there was no response from business executive and a single response from the technical expert from industry that could be used to measure the mean, standard deviation and Cronbach alpha between individual responded of the same portfolio. This is because the calculations were done per portfolio.

Whereas data from Cronbach Alpha is normally used to see correlation of questions by virtue of answers from a similar group, which might lead to second piloting of questionnaire, this was not done here because the difference in views were anticipated. This is because the questions were not meant to correlate and the technical expertise of respondents was not homogenous.

Table 4.4 Mean, standard deviation and Cronbach alpha values derived from the responses

Response	**Yes**			**No**		
Portfolio	Mean	Standard deviation	Cronbach alpha	Mean	Standard deviation	Cronbach alpha
Government policy maker	1,188406	1,138676	-8,6049	0,565217	0,919017	-0,8961
Academics/ researchers	1,152174	1,065232	1,04205	0,434783	0,906996	1,000072
Manager in regulatory institution	0,782609	0,876481	1,037091	0,478261	0,643027	0,842172
Inspector in regulatory institution	0,728261	0,86568	1,037978	0,717391	0,828735	1,021874
Technical expert in regulatory institution	1,217391	1,098188	1,040593	0,534783	0,769326	1,040593

Table 4.5 above shows the mean, standard deviation and Cronbach alpha values derived from the responses to the questionnaire. The questionnaires were grouped per portfolio as indicated by the respondent, and each response of the 23 questions was taken into consideration. Despite the Cronbach alpha coefficient exceeding the band (0 to 1), no review of questions and secondary piloting was done as the resultant values were expected. The mean and standard deviation values were closer on the

Yes responses than on the No responses. This is because most respondents opted for **0 with no conviction and confidence** when they were responding negatively (No) to a statement/question. There was better **conviction and confidence** on positive (Yes) responses to a statement/question with higher than **0** values indicated.

Table 4.6 Questions, responses and level of conviction of individuals grouped under their specific portfolio.

		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16		17		18		19		20		21		22		23	
		Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Gov Policy Maker	1	1		1			2	1		2			1	2		2		2		2		2			2	2		2			2		1		1	2			1	3			2	2			2
	2	1		1		2		2			2		2	3		3		3		3			2		3	3			3		2	1			2	1			2		3		1	2			
	3	1		1		2		2		0		0		2		3		3		3			3	1		1			1		2		1	0		1			1	3			3	2		1	
Academic/Researcher	4		3		3	2		1		0		0		3		3		3		2			0		0	3			0	1		0		1		2			0	3		2		1		1	
	5	3		3		1		1			2		2				1		1																												
	6	2			3	2		2			2		3	3		3		3		3			2	3		2		3		2		3		3		2		3		3		3			3	2	
	7	1		1		2		1			1		3	2		2		2		2		2		1		2			1		2	1			2	2		3		2		2			3		1
Tech Exp in Industry	8	3		3			3	3		3		3		3		3		3		3		3			3		3	3		3		3					3		3	3			3		3		3
Man. in Reg. Institution	9		1		1				1					1		1			1		1																	1							
	10		1		1		1		1	1		1		3		3		3		3			2		2		2	2		2		3			2	3		3		3		3		2			2
Inspector in Reg Institution	11		0		0		0		0		0		0		1		1	0		0		0			0		0		0		0		0		0		0		0		1		0		1		0
	12	1		1		1		1			2		1	2		2		2		1			3	2		2		1		3			2	2			3	2				2			3	2	
	13		0		1	0			0		0		0	2		2		1		0			0	0			1	1			3	3			3	2		2		3			2	2			2
	14	1		1			0	0		0			0	3		3		3		3		0		0		0			3		3	3			3	3			2	3			3	3			3
Technical Expert in a Regulatory Institution	15		1	1		1		1			1		1	3		3		3		2		1		1			1	2		2		1		1		0		3		3		1		0			1
	16		3		3	2		2			3		3	3		3		3		3		2			3		2	2			2	3			3	2		3		3			3	3			2
	17	1		2		2		3		2		2		3		3		3		3		1			3		3		3	2		2		1			1		1	3		3			2		3
	18		3		3	2			2		2		0	3		3		3		2			1	2			1	2		1		2			1	2		2			1	2		2		2	
	19	1		1		1		1		0			0	2		2		2		2			0		0		0		0	0		0		0		1		3		3		1		2		2	
	20		3		3		1		3		2		1		3	1			2		3		1	1		1		2			1	1					1	1			2	1			1		1
	21		3		3		0		3		0		0	2				2		2				0		0		0		0		0		0		0		2		3		2		2		2	
	22	3		3		1		1		1			1	2		2		2		2			1	2			1	2			1	2		2		2		2		3		2			1	2	
	23	3		3		3		3		0		0		3		3		3		3		3			2	2			2		1	2			1	2			1	3		2		3			1
	24	3			1		1	1			1	1		2		2			1	2		2			1	2			1		1	2			1		1		1	3		2		2			1
	Sum	25	18	22	22	24	8	26	10	9	18	7	18	52	4	52	2	49	5	46	4	16	15	13	19	20	14	22	14	16	20	32	4	10	19	27	9	29	12	51	7	28	17	28	17	14	22

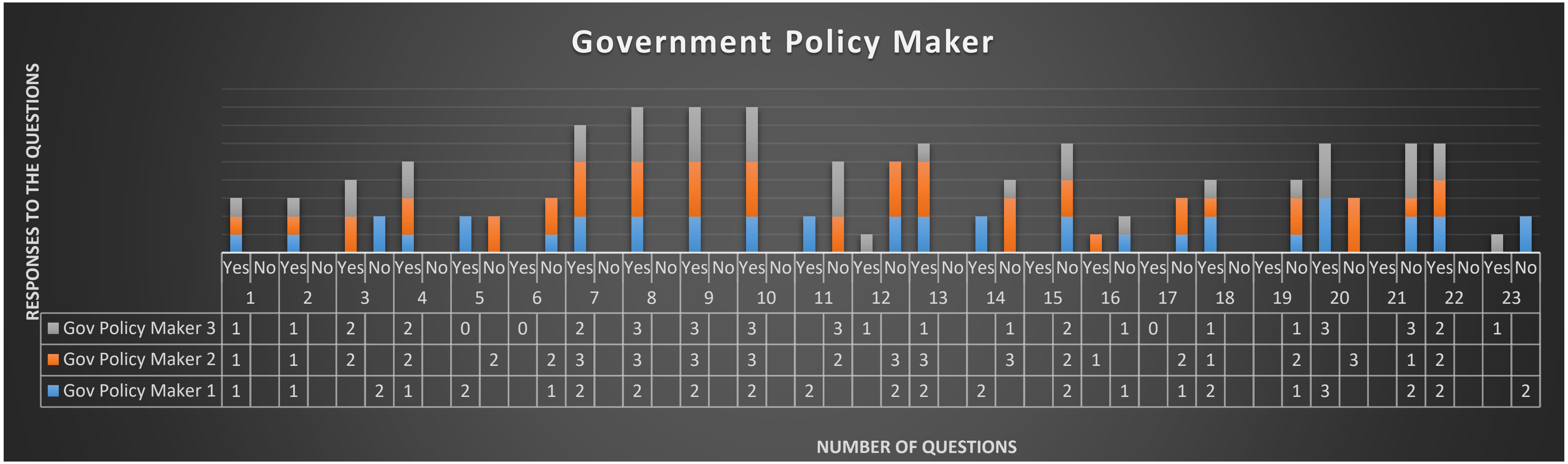


Figure 4.16 Illustration of responses under government policy maker portfolio

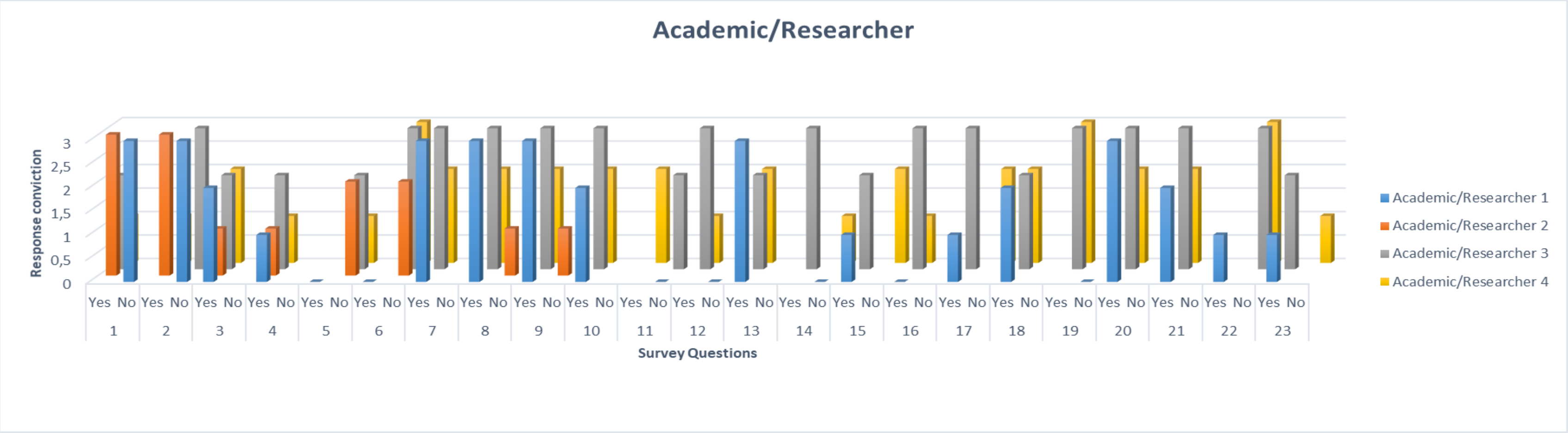


Figure 4.17 Illustration of responses under academic/researcher portfolio

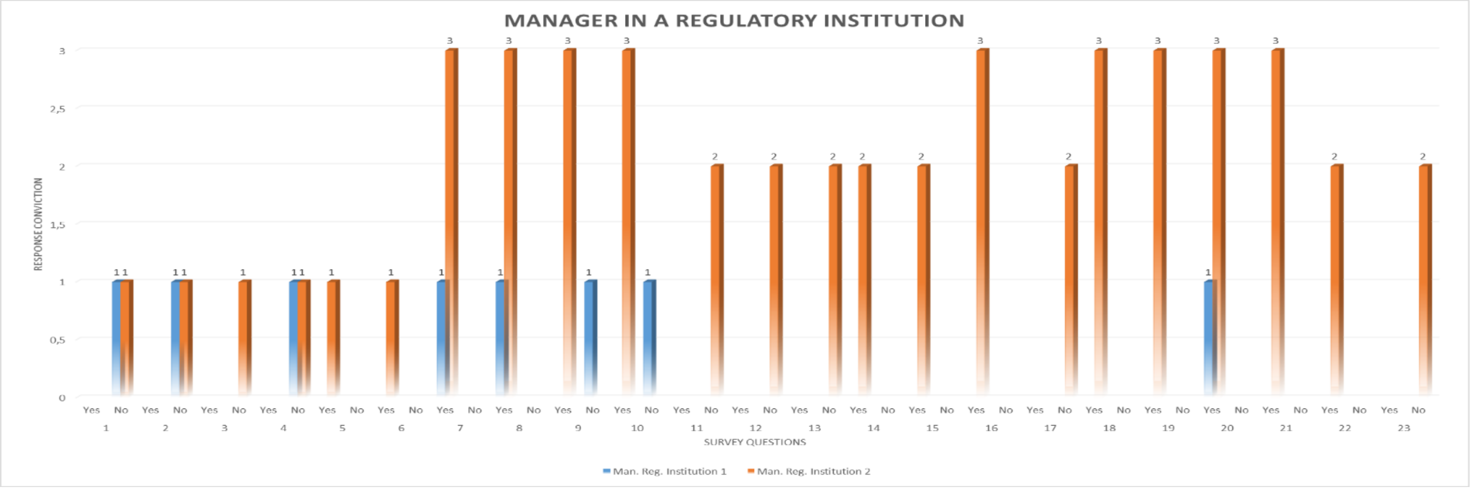


Figure 4.18 Illustration of responses under the manager in a regulatory institution portfolio

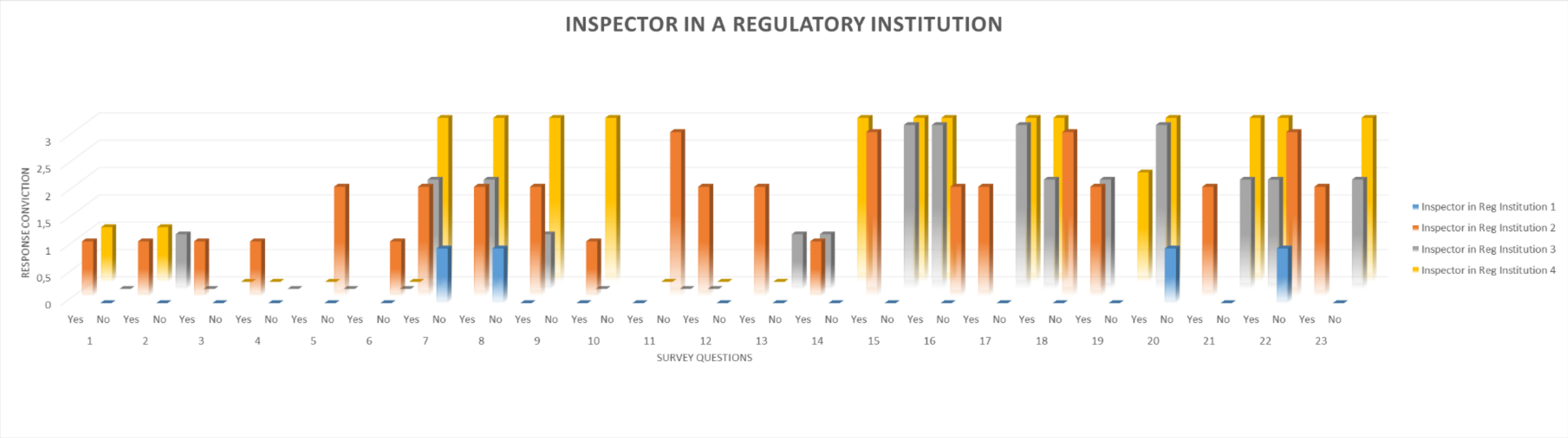
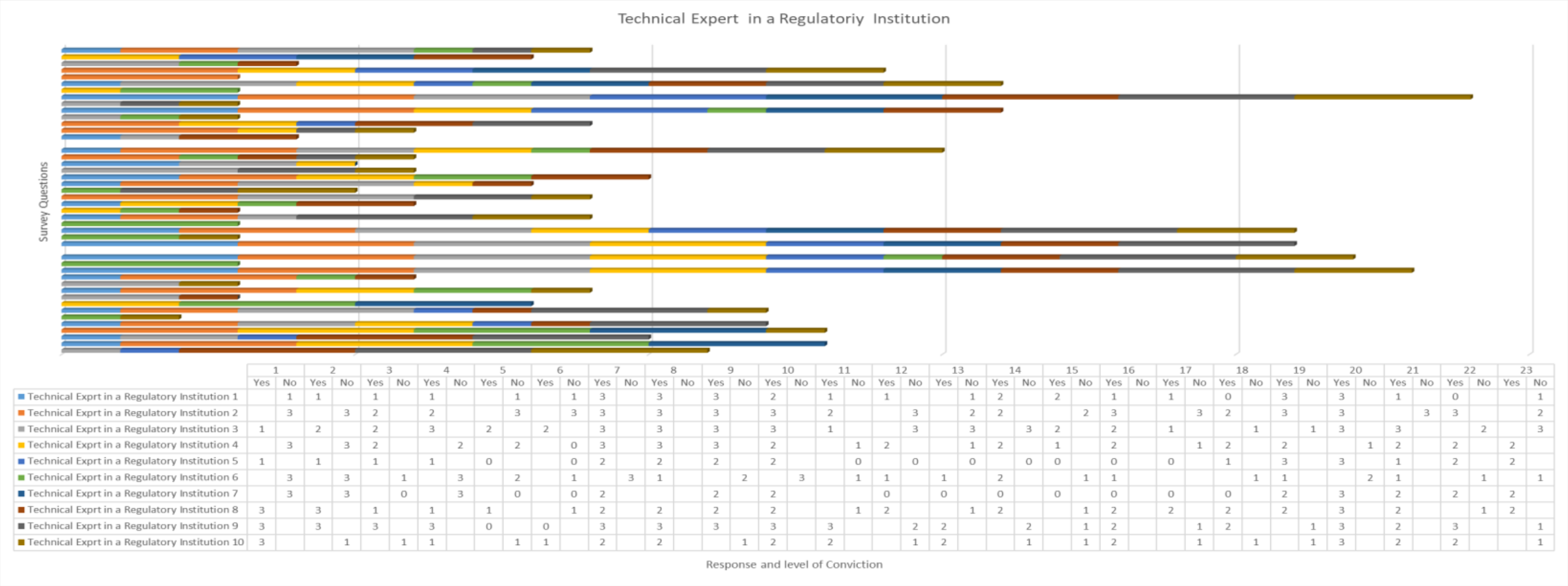


Figure 4.19 Illustration of responses under the inspector in a regulatory institution portfolio



	1		2		3		4		5		6		7		8		9		10		11		12	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
🟦 Technical Exprt in a Regulatory Institution 1		1	1		1		1			1		1	3		3		3		2		1		1	
🟧 Technical Exprt in a Regulatory Institution 2		3		3	2		2			3		3	3		3		3		3		2			3
■ Technical Exprt in a Regulatory Institution 3	1		2		2		3		2		2		3		3		3		3		1			3
🟨 Technical Exprt in a Regulatory Institution 4		3		3	2			2		2		0	3		3		3		2			1	2	
🟦 Technical Exprt in a Regulatory Institution 5	1		1		1		1		0			0	2		2		2		2			0		0
🟩 Technical Exprt in a Regulatory Institution 6		3		3		1		3		2		1		3	1			2		3		1	1	
🟦 Technical Exprt in a Regulatory Institution 7		3		3		0		3		0		0	2				2		2				0	
🟫 Technical Exprt in a Regulatory Institution 8	3		3		1		1		1			1	2		2		2		2			1	2	
■ Technical Exprt in a Regulatory Institution 9	3		3		3		3		0		0		3		3		3		3		3			2
🟫 Technical Exprt in a Regulatory Institution 10	3			1		1	1			1	1		2		2			1	2		2			1

	13		14		15		16		17		18		19		20		21		22		23	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
🟦 Technical Exprt in a Regulatory Institution 1		1	2		2		1		1		0		3		3		1		0			1
🟧 Technical Exprt in a Regulatory Institution 2		2	2			2	3			3	2		3		3			3	3			2
■ Technical Exprt in a Regulatory Institution 3		3		3	2		2		1			1		1	3		3			2		3
🟨 Technical Exprt in a Regulatory Institution 4		1	2		1		2			1	2		2			1	2		2		2	
🟦 Technical Exprt in a Regulatory Institution 5		0		0	0		0		0		1		3		3		1		2		2	
🟩 Technical Exprt in a Regulatory Institution 6	1		2			1	1					1	1			2	1			1		1
🟦 Technical Exprt in a Regulatory Institution 7	0		0		0		0		0		0		2		3		2		2		2	
🟫 Technical Exprt in a Regulatory Institution 8		1	2			1	2		2		2		2		3		2			1	2	
■ Technical Exprt in a Regulatory Institution 9	2			2		1	2			1	2			1	3		2		3			1
🟫 Technical Exprt in a Regulatory Institution 10	2			1		1	2			1		1		1	3		2		2			1

Figure 4.20 Illustration of responses under the technical expert in a regulatory institution portfolio

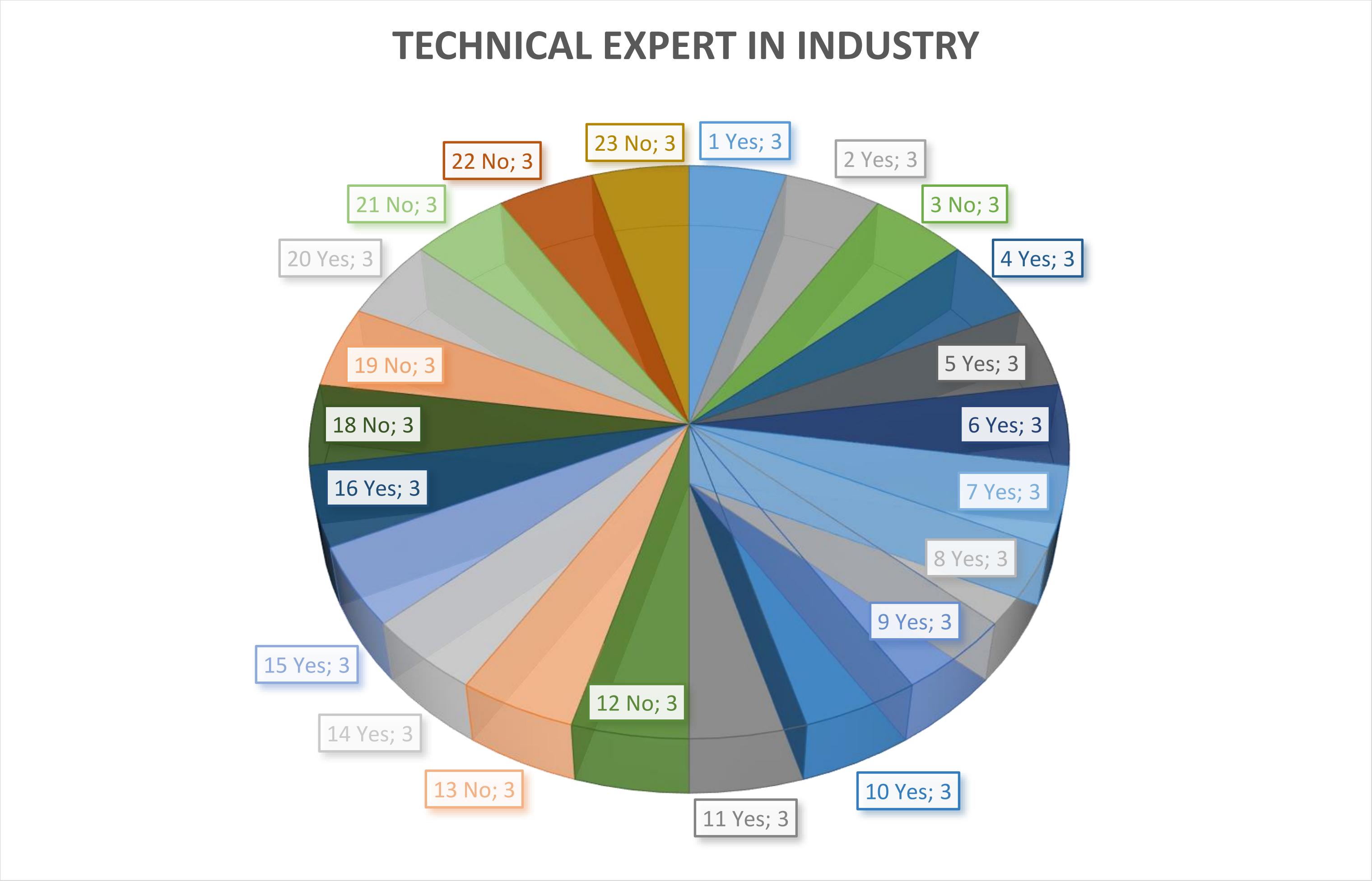


Figure 4.21 Illustration of responses under the technical expert in industry portfolio

Table 4.7 shows the responses to each of the twenty-three survey questions and the level of conviction and confidence by each of the 24 respondents. The colour schemes in the Table 4.8 were done to show survey questions of a similar construct as per Table 4.9 below.

Table 4.10 Grouped questions and their constructs

Question Number	Construct
1, 2, 4, 5 & 6	The historical link between UCOR and ASP
7, 8, 9, 10 & 11	The understanding of regulation
3, 12, 13 & 14	Nuclear Science and application of the regulations
15, 16, 17, 18 & 19	Understanding and application of international regulations and guidelines
20, 21, 22, & 23	Application of non-proliferation and safeguards regulations in South Africa

The aggregation of the responses in **Table 4.4** through the summation of the level of conviction and confidence shows a similar agreement with the statement or positive response to the question apart from questions 15, 17 and 23, whereas under question 11 there was almost an equal share. Under grouped questions, there is also a clear similar understanding of nuclear regulation (question 7, 8, 9, 10) except for question 11, which possibly received different responses due to the additional methane gas control question.

Question 20 also received an overwhelming positive response, however, the subsequent questions 21, 22 and 23 received lesser positive response. It shows the lack of understanding of the division of nuclear non-proliferation controls. However, some respondents motivated for a singular regulatory body and legislation.

Responses for grouped questions (constructs) followed a pattern of responses in Table 4.11 with *The understanding of regulation* and *application of non-proliferation and safeguards regulations in South Africa* receiving positive responses.

Government policy makers in Figure 4.22 shows variety in the responsibilities of respondents. Whereas they would be involved in developing nuclear non-proliferation policy, their responsibilities (scientific and compliance) led to different responses although synergy does appear under, *The understanding of regulation.*

Academic researcher 3 under in Figure 4.23 shows consistent and positive response due to the involvement with Safeguards matters at the International Atomic Energy Agency, whereas academic researcher 1 has historical understanding of UCOR technology only, and no knowledge of regulation nor the South African regulatory framework. *Possible contravention of the non-proliferation legislation might arise as nuclear innovation developed during academic research is regarded as controlled technology when it reaches technology readiness level 4.*

Although the managers in the regulatory institution are both based at the same National Nuclear Regulator, there is some understanding of nuclear non-proliferation in Manager 2 and total lack of knowledge in Manager 1. *This might lead to lack of coordination between the safety regulator and non-proliferation regulators to the detriment of South Africa's international obligations.*

Figure 4.24 and Figure 4.25 covers inspectors and technical experts in regulatory institutions. As the Inspectors were only from the National Nuclear Regulator, hence there were inconsistencies in responses in Figure 4.26. Figure 4.27 has a mixture of experts from the National Nuclear Regulator and considerable number of experts from the Non-Proliferation Council. Figure 4.28 has some consistency in the positive responses because questions from the survey would be part of the considerations done by the Non-Proliferation Council experts in their routine analysis of ASP technology and its regulation. *National Nuclear Regulator inspectors regularly visit industry plants and although their primary mandate is safety, basic understanding of nuclear non-proliferation would allow for referrals and closer cooperation with the Non-Proliferation Council.*

The only response received from the technical expert in Industry portfolio is from Klydon (Figure 4.29). Despite confident and conviction shown in the responses there is a deliberate omission of Question 17 because there is no provision of the regulation specifications of technologies, plants and equipment meant for separation of “other elements”/“stable isotopes” by the Nuclear Suppliers Group, and the Zangger Committee. *However, there is still acknowledgment by industry that it may not be possible to provide the specifications as the technologies, plants and equipment meant for separation of “other elements”/“stable isotopes” are dependent on the isotope of interest.*

4.9 Limitations of the study

The Non-Proliferation of Weapons of Mass Destruction Act, 1993 (Act No. 87 of 1993) **Section 21** prohibits disclosure of information by stating “*A member of the Council, a member of any committee of the Council, any officer or employee of the Department, an inspector or any other person who is or was concerned in the performance of any function in terms of this Act, shall not disclose, transmit or make known to any person, whether within or outside the Republic, any information which he obtained in the performance of such a function or cause such information to be disclosed, transmitted or made known*”. It therefore proved a difficulty to seek total disclosure of data from such officials via the questionnaire. Additionally, the Act defines

“technical assistance” *includes the giving of instructions, teaching of skills, training, imparting working knowledge, consulting services or the transfer of data; and* ***“technology”*** *means any specific information, data or technical assistance required for the design, development, manufacture, deployment, maintenance or use of any weapon of mass destruction, or the execution of any activity related thereto*;. As technology is controlled and its transfer subject to permit issued by the South African Council for the Non-Proliferation of Weapons of Mass Destruction (the Council), there were certain data that could not be disclosed in this study, despite approval to undertake the study by the Council and support provided by Klydon. This is because the data is deemed to be technology that is controlled, and furthermore the IP of Klydon, hence cannot be displayed in public.

The lack of response from the DMRE and NECSA is very critical to the study as, together with the Council, are the institutions mandated to regulate non-proliferation and safeguards in South Africa, and hence directly impacts the findings of the study. It should be noted though that the experts of the two institutions would still have had limitations in their responses because the Nuclear Energy Act, 1999 (Act No. 46 of 1999) **Section 33(4)(a)** states; "*All information furnished or disclosed by any person in compliance or supposed compliance with this section, as well as all accompanying information contained in the communication or presentation of the first-mentioned information, is highly confidential and may not be published or otherwise made known or disclosed by the Minister or any official of the State while serving as such*".

Although the response from the technical expert from Industry gave insight technically on the ASP, the lack of response from the business executive from Klydon also denied the researcher the perspective of how business deem South Africa's regulation of ASP.

4.10 Chapter summary

Chapter 4 shows results from the comparison between Aerodynamic Separation Process and genesis aerodynamic enrichment processes, and the resultant regulation implications. Further, it motivates for exemption of natural gas ASP by showing the difference between ASP for isotope separation and ASP for gas separation. It delves into the results of the survey and analysis the meaning thereof. Chapter 5 provides conclusion and recommendations.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The goal of this research project was to review the Aerodynamic Separation Process (ASP) relative to the genesis technologies, especially the UCOR Stationary Wall Centrifuge and the Becker Jet Nozzle technique and to consider the Nuclear Suppliers Group's determination on the regulation of the ASP technology relative to the South African legislation. The study further intended to determine the view of relevant stakeholders with regard to the NSG's determination on the regulation of aerodynamic technologies, their understanding of UCOR and ASP technology and the regulation of ASP through the South African non-proliferation legislation, and propose recommendations on how to enhance the regulation thereof.

Although South Africa no longer enriches uranium, ability to develop the capability is available based on technologies such as ASP. Whereas ASP has not been proven to enrich uranium, its capabilities has made the NSG to make provisions for it to be controlled as stringently as other technologies, including its preceding aerodynamic processes, that have been proven to enrich uranium. Table 4.2 shows the similarities in certain instances between ASP and fissile material enriching technologies.

The ASP and other technologies such as a laser-based separation technology called separation of isotopes by laser excitation (SILEX), which has not been proven to enrich Uranium either, are seen as commercial enrichment technologies that may be subject to safeguards but could pose unique challenges for the IAEA (Laughter, 2009).

The difficulties of regulating these technologies are already being reflected by the interpretation of the Additional Protocol. Whereas transfers (exports) of plants and technologies for enrichment and reprocessing of Uranium are subject to Safeguards Agreements, the export of plants and technologies for the enrichment of other elements are subject to Additional Protocol or the country has signed, ratified and is implementing a regional arrangement approved by the IAEA, which operates to achieve the same objective by providing confidence in the peaceful nature of civilian nuclear programs (Pretorius, 2012).

Similarly, due to Section 5.5 Annex B of the INFCIRC/254/Rev.14/Part 1 of 18 October 2019, which clearly indicates that controls for aerodynamic processes for uranium isotope separation or isotope separation of “other elements” equally apply, it may be deemed that Safeguards Agreement and Additional Protocol, or regional arrangement, as a condition of supply, is applicable.

It should be noted though that the Section 5.5 Annex B makes technologies for separation of other elements to be controlled as trigger list separation technologies, Guidelines for Nuclear Transfers of INFCIRC/254/Rev.13/Part 1 of 18 October 2019 contradicts itself because in instances such as Physical Protection of nuclear materials and facilities as set out in Information Circular (INFCIRC)/225, the reference to nuclear material excludes facilities for other elements. According to Information Circular (INFCIRC)/225 nuclear material means plutonium, uranium-235, and uranium-233.

However, according to the guidelines, irrespective of the element to be separated, if the used technology is covered by Section 5.5 Annex B, the recipient would need to ensure that the facility complies with the prescript of Information Circular (INFCIRC)/225.

Similarly, both the Safeguards Agreement and Additional Protocol focus on the regulation of the tangible items. However, due to the similarity of in technical characteristics (stationary-wall centrifuge) between the genesis aerodynamic processes, which were only built to enrich uranium, and the ASP plant built for natural gas and production of medical isotopes are controlled. This is despite the definition of Article 18.a of the Additional Protocol.

Amending the Additional Protocol will not be an easy task whilst negotiations at the NSG on the amendments of the guidelines are lengthy, but possible. It is thus ideal that the domestic legislation be amended to assist with clarifying the confusion brought by the contradiction alluded to above, for local implementation.

The Nuclear Energy Act, No. 46 of 1999 needs to be amended to control technology. Currently, technology is only controlled under Schedule IV Category B of Notice No 207 in Government Gazette of 27 February 2009, which limits it to Uranium separation technologies only. The Government Notice No. 493 of 29 March 2019 is published as a dedicated Notice for the regulation of plants, technology and equipment separating other elements. In addition, Government Notice No. 319 of 08 April 2021 is a list of nuclear dual use items, as appearing in INFCIRC/254/Part 2 Annex.

The Dual-Use List covers both nuclear fuel cycle activities and weaponization. Items listed on the list have both nuclear and non-nuclear applications and could make a significant contribution to an unsafeguarded nuclear fuel cycle or nuclear explosive activity. The Dual-Use List is a definitive list in which entries for the controls are described with a degree of technical detail and narrowly worded to cover only those items that are "significant" and "controllable" (NSG).

ASP technology is classified as "dual use technology" (Strydom et al., 2016). Although the technology potentially has both nuclear and non-nuclear applications and could make a significant contribution to an unsafeguarded nuclear fuel cycle or nuclear explosive activity, their description in the list for controls are not described with a degree of technical detail and narrowly worded to cover only those items that are "significant" and "controllable". Information pertaining to the aerodynamic plants for separation of other elements is kept confidential as per the trigger list separation technologies. Thus, the technology does not meet the definition of dual use list entry as provided by the NSG.

The survey revealed lack of understanding in nuclear non-proliferation and safeguards regulations especially among management and inspectors from the National Nuclear Regulator, and academia. This shows deficiency of coordination between the National Nuclear Regulator and the South African Council for the Non-Proliferation of Weapons of Mass Destruction, and inadequate outreach to academia and research institutions.

As the separation of non-proliferation controls between the Council and the DMRE is not understood nor can be justified, majority of responses from survey participants indicated the need for consolidation of the two regulatory institutions. Whereas the NSG regulation of aerodynamic separation of other elements can be substantiated due to the confirmation by the technical expert in Industry that heavier isotopes (e.g tungsten) can be separated, there is a need to exempt ASP for natural gas separation.

5.2 Recommendations

It is therefore recommended that

- the NSG could make a distinction between gas and Isotope aerodynamic separation, with gas aerodynamic separation technology, equipment and plants exempted from the application of Guidelines for Nuclear Transfers.

- the minister issue regulations that clarify any contradictions that seem to arise from the interpretation of the NSG guidelines and also the Additional Protocol's Articles and Annexes, in terms of Section 33 of the Nuclear Energy Act, No. 46 of 1999, which gives the minister powers to ensure safeguards and any additional protocols are implemented locally.

- Section 2 of the Nuclear Energy Act, No. 46 of 1999, be expanded to cover technology, equipment, components, and plants for separation of other elements. This would allow the controls of these technologies under a single regulatory body which is also responsible for Safeguards and Additional Protocol which affect these technologies. This would be in line with the NSG where controls of these technologies are all under Part 1 guidelines.

- following the amendment of section 2 of the Nuclear Energy Act, No. 46 of 1999, that the Government Notice No. 493 of 29 March 2019 be repealed.

- the nuclear non-proliferation regulatory bodies should intensify outreach activities to academic and research institutions and educate them about nuclear non-proliferation obligations and legislation.

- the South African Council for the Non-Proliferation of Weapons of Mass Destruction, the Directorate: Nuclear Non-Proliferation and NECSA Safeguards Management be amalgamated to form a single regulatory body. The body be independent rather the current autonomous model.

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Appendix A: SURVEY QUESTIONNAIRE

Topic: A review of Aerodynamic Separation Process and regulation by Nuclear Suppliers Group

Guidelines for completing the survey:

- Please provide your portfolio, amongst the following, i.e **Government Policy Maker, Manager in Regulatory Institution, Technical Expert in Industry, Business Executive in Industry, Inspector in Regulatory Institution, Technical Expert in Regulatory Institution** and **Academics/Researchers**.
- Each participant provides their response for each question/statement, described by a Yes or No, and maybe supported by motivation.
- Yes, to agree with the statement/question and No, to disagree with the statement/question.
- The motivation is optional, but its inclusion would assist the assessor better understand the response given. You can even include the motivation where it was not requested, if you have any.
- Each participant provides their response (Yes or No) for each statement/question, through a range from 0 to 3 to show level of conviction and confidence on response. **0 for no conviction and confidence, 1 for a low level of conviction and confidence, 2 for general conviction and confidence and 3 for a high level of conviction and confidence.**

Table A1: Survey Questionnaire.

Portfolio (check the letter for your options): ----									
Question/Statement		Yes				No			
		0	1	2	3	0	1	2	3
1)	Stationary-wall or aerodynamic process Uranium separation technology development is not prevalent with only South Africa (UCOR Advance Vortex Tube Technology) and Germany (Becker Jet Nozzle Process) having managed to industrialise the technology. Do you have a general understanding of stationary wall separation technology?								
2)	Although the two processes (UCOR Advance Vortex Tube Technology and Becker Jet Nozzle Process) are similar (aerodynamic process), the distinct feature is the cascading technique called the helikon technique, applied in the UCOR Advance Vortex Tube Technology. In the UCOR technology the flow of the UF_6-H_2 gas mixture through the separating element is such that the cut is highly asymmetrical. The cascading is implemented to avoid/or reduce the isotopic mixing of the products from the cut. Do you have a general understanding of the helikon cascading technique?								
3)	Production quantities are smaller for “other elements”/“stable isotopes” than in commercial uranium enrichment applications. Often, the scale of “other elements”/“stable isotopes” equipment may also be similar to what is needed for proliferation-scale HEU production, which, because of smaller flows and nuclear criticality concerns, requires smaller equipment. Despite the need to also consider the physical items and inherent information, such as technology, at face value, it is correct to subject the “other elements”/“stable isotopes” plant, equipment and technology to Part 1 guidelines. Do you agree with the statement?								
4)	Klydon has developed a successor to the Stationary-wall or aerodynamic process Uranium separation technology through the innovation named Aerodynamic Separation Process (ASP) technology, which has only been proven to separate non-fissile isotopes. Do you have a general understanding of the ASP technology?								
5)	UCOR process counts among the genesis technologies of the ASP technology, although ASP represents a significant improvement on its genesis technology due to the improvement in the cut parameter obtained. Can, by virtue of ancestral lineage to the UCOR process, ASP								

	technology, having only been proven to separate light elements only, be deemed to have capabilities to separate fissile material?								
6)	If the ASP Technology did not have ancestral lineage to the UCOR process, but proven to be able to separate light elements only as is, would there be theoritical assumptions that deem it to have capabilities to separate fissile material?								
	Motivate your answer.								
7)	Regulation in the nuclear space cuts across non-proliferation, safeguards, safety and security. Although the four parameters overlap, each of them still has its own distinct application. Do you specifically have an understanding particularly of non-proliferation and safeguards?								
8)	Certain nuclear exports trigger IAEA Safeguards requirements in terms of the Treaty on the Non-Proliferation of Nuclear Weapons. Do you have a general idea of what the intention of the Treaty is?								
9)	In order to reduce the possibility of proliferation of nuclear weapons, the Nuclear Suppliers Group and the Zangger Committee regimes develop nuclear export control mechanisms and guidelines to ensure that the trade in nuclear items does not result in the development of nuclear weapon and/or explosives. Do you specifically have an understanding of the regimes?								
10)	Nuclear items can be regarded trigger list (Part 1) item or dual use list (Part 2) item because of their application. Do you have an understanding of the difference between the two lists?								
11)	Under General Note and Introductory Note in Section 5 of the Trigger List, Suppliers recognise that, in particular cases, appropriate protection measures for isotope separation activities involving “other elements” will be essentially the same as those for uranium enrichment. As "other elements" means elements other than U, Pu and H, Klydon's Aerodynamic Separation Process (ASP) can be used for methane recovery from landfills. Does this mean ASP plants, equipment and technology for methane recovery are not controlled?								
	Motivate your answer								
12)	Additional Protocol Article 2.a.iv mentions that activities under Annex I (vi) needs to be declared. Since it is clear methane gas do not form part of "other elements", would the manufacture of aerodynamic separation nozzles or vortex tubes (basically separation elements of								

	Klydon's ASP) for methane gas recovery warrant a declaration under Additional Protocol Article 2.a.iv?								
13)	Since the Additional Protocol Article 2.a.ix.a is only applicable to plants separating Uranium, suppliers of aerodynamic process separation techniques separating "other elements" would need not put up declarations on each export because Annex II mentions export related to Uranium enrichment. Do you agree with statement?								
14)	Whereas Suppliers recognise that, in particular cases, appropriate protection measures for isotope separation activities involving “other elements” will be essentially the same as those for uranium enrichment. And since the plant for the separation of a particular "other element" would be subjected to similar part 1 guidelines as those for fissile material separation plant, should a replacement component of the plant, that does not meet Part 1 nor Part 2 specifications be controlled?								
15)	Whereas NSG talks of "other elements" which means elements other than U, Pu and H, and the Zangger Committee refers to "stable isotopes" without definition, as there is no commonly agreed definition for the term, but both regimes implore Suppliers to control isotope separation activities involving “other elements”/"stable isotopes" the same as those for uranium enrichment. Does the two makes it easier for industry to comply?								
16)	The term "Especially Designed or Prepared", as referring to Trigger List items, is not defined, but a designation of equipment or material especially designed or prepared for the processing, use or production of special fissionable material. The inclusion of terms such as “other elements”/“stable isotopes”, which refer to more than fissionable material, and their controls in the Trigger List affect the specifics/concept of Especially Designed or Prepared and the triggering of safeguards. Do you agree with the statement?								
17)	The Nuclear Suppliers Group, and the Zangger Committee, use General Note and Introductory Note in Section 5 of the Trigger List to clarify the separation technologies that are deemed to be complementary to those that are meant for separation of fissile material. However, it is clear for the fissile material related technologies, plants and equipment what actually is controlled, as specifics are given. With the use of explanatory note(s) only, is the regulation specifics of technologies, plants and equipment meant for separation of “other elements”/“stable isotopes” clear?								
18)	The Nuclear Suppliers Group, through Para 6(c) of Part 1 guidelines, has inadvertently made the Protocol Additional (AP) to Safeguards a								

	condition of supply for export of separation techniques of other elements. This is because declaration regarding nuclear fuel cycle related research and development activities not involving nuclear material are only listed under AP, otherwise these technologies would need a specific appropriate safeguards agreement with the IAEA. Do you agree with the statement?								
19)	If the recipient does not have a signed AP with the IAEA, should the export of the aerodynamic process separation techniques separating "other elements" be denied?								
	Motivate your answer								
20)	In order to reduce the possibility of proliferation of nuclear weapons, countries implement export control mechanisms to ensure that the trade in nuclear items does not result in the development of nuclear weapon and/or explosives. Do you know which South African government institutions are responsible for domestic implementation of nuclear export controls and safeguards?								
21)	The IAEA Safeguards and/or Additional Protocol are domestically implemented through the Nuclear Energy Act, 1999 (Act No. 46 of 1999) whereas the regulation (possession, manufacture, use, transfer, etc) of Klydon ASP plant, equipment and technology is implemented through the Non-Proliferation of Weapons of Mass Destruction Act,1993 (Act No. 87 of 1993) (Non-Proliferation Act). Is this viable?								
22)	The division of controls of separation technologies in South Africa means the misalignment of implementation of the control guidelines. The Non-Proliferation of Weapons of Mass Destruction Act,1993 (Act No. 87 of 1993) (Non-Proliferation Act) does not require the implementation of IAEA Safeguards and/or Additional Protocol, as the Nuclear Energy Act, 1999 (Act No. 46 of 1999) does. However, despite the Non-Proliferation Act regulating the ASP Technology, the need to impose Additional Protocol requirements in case of transfer, especially, arises. Does the consolidation of all separation technologies under the Nuclear Energy Act, 1999 (Act No. 46 of 1999) reasonable?								
	Motivate your answer								
23)	Does the cause of the current division understandable?								