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HEALTH PHYSICS ASPECTS OF A URANIUM LASER ISOTOPE SEPARATION FACILITY

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Abstract

Laser isotope separation is an advanced uranium enrichment technology. It selectively enriches ^{235}U without incurring the negative health physics consequences associated with increased ^{234}U enrichment. Laser technology increases the efficiency of the ^{235}U enrichment process, but also presents a proliferation risk.

Keywords

Laser isotope separation; uranium enrichment; health physics; nuclear proliferation

1.0 Introduction

Commercial uranium enrichment has been accomplished using gaseous diffusion [1-8] and gas centrifuge technologies [1-11]. These technologies utilize uranium hexafluoride (UF_6) as the working fluid in the form of a hot, pressurized gas. These UF_6 based technologies separate uranium isotopes based on their mass differences. Since the working fluid and basis for separation are similar, gaseous diffusion and gas centrifuge technologies have similar health physics issues. These issues include contamination control, control of internal and external doses, and criticality safety.

Laser techniques [1-8, 12-17] are based on the isotopic differences in atomic or molecular energy levels. These unique level energies permit significantly greater efficiency in selectively enriching ^{235}U. The introduction of lasers and the use a working fluid other than UF_6 present unique health physics challenges that are addressed in this paper.

Gaseous diffusion is energy intensive and requires large facilities with significant electric power requirements. As such, gaseous diffusion facilities are difficult to operate clandestinely which makes them proliferation resistant. Centrifuge facilities are less energy intensive, but generally require facilities with an observable footprint. Advanced centrifuge technologies [10-11] are more efficient and can be more easily operated in a clandestine manner.

Laser enrichment technologies are significantly more efficient and require a smaller footprint and limited electrical power requirements. This efficiency offers the potential for small facilities that can be clandestinely operated which presents a proliferation concern.

In order to appreciate the unique health physics aspects of laser enrichment, a brief review of the characteristics and health physics aspects of traditional uranium enrichment technologies are provided. Given this background, the health physics aspects of laser approaches are presented. This paper also reviews the proliferation potential of laser isotope separation. Both the health physics and proliferation aspects of laser isotope separation are related to the unique nature of this technology. This uniqueness includes the methods used to generate the working fluid, produce ^{235}U ions or an excited $^{235}UF_6$ molecule, and collect the enriched product to selectively enrich ^{235}U.

The discussion begins with a review of the naturally occurring uranium isotopes and their health physics significance. For specificity, enrichment facilities are assumed to utilize virgin material. The health physics aspects of using reprocessed uranium introduces a degree of complexity that is not warranted in this initial presentation.

The reader should note that this paper is based on open literature sources and the projected performance of laser enrichment technology. Actual health physics issues will not be known until an operational facility is designed, constructed, and operated.

2.0 Uranium Isotope Characteristics

Natural uranium consists of three primary isotopes, namely ^{238}U, ^{235}U, and ^{234}U whose natural abundances are 99.2739, 0.7204, and 0.0057, respectively [18]. Given their respective half-lives, noted in parenthesis, ^{238}U ($4.468\text{x}10^9$ y), ^{235}U ($7.04\text{x}10^8$ y), and ^{234}U ($2.46\text{x}10^5$ y) contribute 49%, 2%, and 49% of the specific activity of natural uranium, respectively [4,5].

Using 20th Century enrichment technologies, the radiological hazard of the uranium material increases as the ^{235}U enrichment increases [4,5]. This occurs because gaseous diffusion and gas centrifuge technologies increase both the ^{234}U and ^{235}U enrichments. The increase in ^{234}U enrichment increases the radiotoxicity of the enriched product relative to the feed material. The decay products of these uranium isotopes consist of long decay chains that decay by alpha, beta, and photon radiation.

Uranium and its decay products are predominantly an internal radiation hazard and standard internal dosimetry models can assess their associated radiological hazard [4,5]. In addition, the ^{238}U natural decay series and its decay products produce a significant external hazard (2.33 mSv/h beta radiation at 7 mg/cm^2 from a equilibrium thickness of uranium metal) [4,5]. This absorbed dose rate arises primarily from the beta decay of ^{234m}Pa.

Historically, the radiological concerns of natural uranium have been overshadowed by its chemical toxicity. As a heavy metal, uranium is chemically toxic to the kidneys. The radiological hazards become more significant as the ^{235}U enrichment increases [4,5]. For example, neutron radiation levels from UF$_6$ increase from about 2 μSv/h for low enriched material (<5% ^{235}U) to about 40 μSv/h for highly enriched material (>97% ^{235}U) [4,5]. These dose rates are applicable to enriched natural uranium. Higher dose rates arise from reprocessed uranium.

3.0 Overview of Enrichment Technologies

The enrichment step in the commercial uranium fuel cycle is intended to increase the ^{235}U content from its nominal value of 0.72% by weight in natural uranium to 3 – 5% reactor grade material. Traditional methods for enriching uranium are the gaseous diffusion and gas centrifuge technologies. More advanced methods include advanced centrifuge and laser isotope separation technologies. These technologies and their health physics characteristics are examined in subsequent discussion.

3.1 Gaseous Diffusion

Isotope separation by the diffusion process is accomplished by flowing uranium hexafluoride gas through a porous membrane. The various uranium isotopes reach an equilibrium condition after numerous collisions as gas flows into the separation device. With equilibrium established, each UF$_6$ molecular form has an equal momentum ($\vec{\mathbf{p}}$):

$$\vec{\mathbf{p}}\left({}^{234}\mathbf{UF_6}\right) = \vec{\mathbf{p}}\left({}^{235}\mathbf{UF_6}\right) = \vec{\mathbf{p}}\left({}^{238}\mathbf{UF_6}\right) \quad (1)$$

Since the momentum is given by the product of the molecular mass (m) and velocity (v), the diffusion velocity through a membrane is inversely proportional to the molecular mass.

The different molecular weights of ^{235}UF$_6$ and ^{238}UF$_6$ and their resulting difference in molecular velocities are used as the basis for separating ^{235}U from ^{238}U [1-8]. In a mixture of ^{235}UF$_6$ and ^{238}UF$_6$, the average speed of the lighter ^{235}UF$_6$ molecules is greater than that of the heavier ^{238}UF$_6$ molecules. When the mixture contacts a porous barrier, the lighter ^{235}UF$_6$ molecules strike the barrier and diffuse through it more quickly than the heavier ^{238}UF$_6$ molecules. Since the velocity difference is small, the enrichment through each gaseous diffusion chamber or stage is small. Consequently, thousands of stages are required to increase the assay from 0.72 % ^{235}U to the desired enrichment of 3 – 5 % for power reactor use [4,5].

The ^{234}U content is also enriched in gaseous diffusion since the technology is based on molecular mass differences. Since the uranium specific activity is increased following enrichment of ^{234}U, product material has a greater radiological hazard than the feed material.

A gaseous diffusion stage consists of a motor, compressor, and converter that contains the porous barrier or membrane. The uranium hexafluoride is introduced as a gas and flows through the inside of the barrier tube. A portion of the gas, about half, diffuses through the barrier and is fed to the next higher (increased ^{235}U enrichment) stage. The remaining gas that did not diffuse through the barrier is fed to the next lower enrichment stage. The diffused or product stream is slightly enriched in ^{235}U, and the gas remaining in the tube is slightly depleted in ^{235}U.

The stages above the location of feed entry are the enriching section, and the ^{235}U concentration exceeds that of the nominal feed concentration. In the stripping section, below the feed point, the concentration of ^{235}U is less than the nominal feed concentration. The enrichment increases (decreases) the further the stage is upstream (downstream) of the feed point.

Feed for each stage in the gaseous diffusion cascade is a mixture of the enriched material from the stage immediately below and the depleted material from the stage immediately above. The cascade operates continuously with new feed material. Enriched product is directed upstream, and depleted tails material is directed downstream in the cascade sequence.

The number of stages in a cascade will be a function of a number of variables including the isotopic concentration of the feed material, the desired product and tails concentrations, and the efficiency of the diffusion barrier material. For a typical application of natural uranium feed material, reactor grade fuel product of 3 to 5% ^{235}U enrichment, and a tails assay of 0.2% ^{235}U, about 2000 stages are required [4,5,7].

The number of stages could be altered if the product or tails assay were altered. For example, the number of stages would be reduced if the ^{235}U content of the tails material were increased. However, this change would reject a larger amount of ^{235}U that would be eliminated as tails material.

In a gaseous diffusion plant an acute exposure can result from a release of uranium hexafluoride from the process equipment. Chronic exposures may arise from routine maintenance or processing operations. The radiological hazard varies with the ^{235}U enrichment [4-7] and internal doses are the primary concern.

Minor leakage of UF_6 from process equipment leads to surface contamination that can eventually become an airborne hazard. Health physics hazards are minimized by timely maintenance of leaking components and decontamination of affected areas. External radiation concerns are managed by good radiological controls practices and dose reduction measures [4,5].

The uranium feed materials for the enrichment process may include small quantities of neptunium and plutonium if reprocessing is incorporated into the fuel cycle. Good radiological controls practices will usually be adequate to control the presence of these transuranic contaminants. However, these transuranics represent a significant internal radiation hazard because their specific activities and effective dose conversion factors [19] are generally more limiting than those of the uranium isotopes.

For low enrichments, chemical toxicity remains the controlling hazard. At higher enrichments, radiation effects become the primary concern [4,5]. Criticality must also be considered in the higher enrichment stages primarily at stages near the top of the cascade.

In a gaseous diffusion plant, or other facility utilizing uranium hexafluoride, the probability of a criticality is minimized by controlling the process parameters to prevent the solidification of the uranium hexafluoride. The integrity of the process stages is also maintained to prevent the inleakage of water or moist air. This is important because UF_6 is hygroscopic.

Radiation monitors located in key locations provide early detection of an accumulation of solidified uranium hexafluoride. For plant components containing or storing uranium compounds, various criticality controls are applied. These controls include geometry and batch control, limitations on the uranium concentrations and enrichment, and administrative or procedural controls.

The primary radiological hazards from a criticality event are neutron and photon radiation to personnel in the immediate vicinity of the event. Timely evacuation of personnel is an effective radiation control measure. Criticality alarms will not prevent an inadvertent criticality, but they facilitate the evacuation of personnel from the immediate area of the event.

3.2 Gas Centrifuge

Gas centrifuge technology also utilizes uranium hexafluoride as its working fluid. Consequently, the health physics considerations are similar to those in a gaseous diffusion facility.

As applied to uranium enrichment, the centrifuge is a cylindrical device that rotates about its long axis. Its enrichment capacity increases with the length of the device, the radius of the device, and with an increase in its rotational velocity, which is called speed in most literature [1-11]. Limits in material properties restrict the available values of these parameters. As noted in Table 1, the actual design of a centrifuge depends upon the enrichment desired, the technology level of the group developing the device, and the materials available for device construction.

The centrifugal force (F) imposed on a molecule within a centrifuge traveling at a velocity v is

$$\mathbf{F} = \frac{\mathbf{m\,v^2}}{\mathbf{r}} \qquad (2)$$

where m is the molecular mass, and r is the radius of its circular path relative to the machine's axis. For a given centrifuge design, heavier molecules (i.e., $^{238}UF_6$) are subjected to a larger force, and will tend to be moved to a larger radial distance than lighter molecules (i.e., $^{234}UF_6$ and $^{235}UF_6$). This difference in trajectories permits the heavier and lighter molecules to be separated. The mass difference of the different UF_6 molecules is the basis for the use of a centrifuge for the enrichment of $^{235}UF_6$.

The working fluid in a gaseous centrifuge is composed of primarily $^{235}UF_6$ and $^{238}UF_6$. Consequently, when normal uranium hexafluoride is centrifuged, material drawn off from the interior region will be somewhat enriched in the lighter ^{235}U isotope. $^{234}UF_6$ is also enriched in a gas centrifuge.

The uranium hexafluoride feed material is introduced at or near the axis of the device. Since separation is based on centrifugal force, the product withdrawal point is located at a smaller radius than the tails withdrawal location.

In order to obtain the desired ^{235}U enrichment, the gas centrifuge process is operated in a facility utilizing thousands of machines. Although the centrifuges operate in a similar cascade structure as the gaseous diffusion stages noted in Section 3.1, the degree of ^{235}U enrichment per separating unit (i.e., the centrifuge or machine) is greater for centrifuge technology. Therefore, a smaller number of machines are required to obtain the same enrichment with centrifuge technology. 20th Century centrifuge and gaseous diffusion facilities are observable structures.

Their size provides a natural obstacle to the clandestine development of enrichment technology and diversion of that material for clandestine purposes (e.g., nuclear weapons production). As the efficiency of a centrifuge improves, its facility footprint decreases and its proliferation potential increases.

The health physics hazards encountered in a centrifuge facility are similar to the hazards noted previously in the gaseous diffusion discussion. This is expected because the working fluids are the same, the separation basis is molecular mass, and the technologies require thousands of separating units to achieve a commercial production scale facility [11].

3.3 Advanced Centrifuge Technology

The gas centrifuge for uranium enrichment has assumed an increasingly important role in the nuclear fuel cycle [4]. This is attributed to their improving efficiency and economics compared to conventional gaseous diffusion technology. Their improved efficiency is accompanied by nuclear proliferation concerns and the possibility of covert construction or converting a civilian enrichment facility into one that produces highly enriched uranium [10,11].

The proliferation concerns associated with advanced centrifuge machines limit publication of an operational envelope and associated characteristics. Since available information is limited, only general machine characteristics and operating parameters are provided through reference to specific literature sources.

Numerous centrifuge designs have been developed and these incorporate a variety of rotor materials, lengths, and speeds. Table 1 lists estimated design characteristics of historical and advanced centrifuge machines. For consistency with the literature common shorthand notation (e.g., P-1, P-2, etc.) is used to refer to some of these machines [11].

The P-1 design is based on early Dutch machines designated scientific nuclear orbital rotor (SNOR) and cultivated nuclear orbital rotor (CNOR) developed by an international corporation URENCO. URENCO operates enrichment facilities in Germany, Netherlands, UK, and US.

The P-2 machine is a modified version of the German G-2 centrifuge that was a pre-URENCO design. As noted in Table 1, it has an improved capability for performing separative work than the P-1 machine. Separative work is defined in Eq. 3. The P-3 and P-4 designs represent evolving URENCO machines.

The additional machines listed in Table 1 illustrate the increasing enrichment power of centrifuges designs. TC-11, -12, and -21 are URENCO machines with carbon fiber construction. The estimated separative power of the American Centrifuge (AC100) has significantly more enrichment capability than the URENCO devices [11].

Publicly available information for other centrifuge machines listed in Table 1 is more uncertain. Glaser [11] estimated the characteristics of the advanced centrifuge designs based on known characteristics of older machines and the projected improvements.

Table 1 also provides machine specific information including characteristics of the rotor (e.g., materials of construction, physical envelope, and operating characteristics). The machine's capacity is also provided in terms of separative work units (SWU) / y.

A SWU is a measure of work or separative power (W) expended by an enrichment device to separate a mass m_F of assay (in wt %) x_F into a mass m_P of product with assay x_P and mass m_T of tails with assay x_T:

$$\mathbf{W_{SWU} = m_P\, V(x_P) + m_T\, V(x_T) - m_F\, V(x_F)} \quad (3)$$

where V(x) is the value function defined by the relationship:

$$\mathbf{V(x) = (1-2x)\ln\left(\frac{1-x}{x}\right)} \quad (4)$$

The masses are often expressed in units of kg/y. Another parameter used to describe an enrichment device is the cut (θ) which is the fraction of the feed material that leaves the device as product ($\mathbf{m_P = \theta m_F}$). Centrifuge cascades typically have cut values in the range of 0.4 – 0.5 [11].

Machines with larger separative power produce more separative work. A device with a larger separative power will more easily increase the enrichment of ^{235}U. Machines with larger separative power permit an enrichment facility to be smaller and more efficient. This increased efficiency and smaller size has the potential for an increased proliferation potential, and the clandestine use of the facility for the production of weapons grade materials.

Although the health physics hazards of gaseous diffusion and gas centrifuge technologies are similar, laser enrichment introduces additional concerns. The health physics considerations of a laser enrichment facility are addressed in the next section.

3.4 Laser Isotope Separation

Laser methods for uranium enrichment are an emerging technology, and are projected to be more economical and efficient than either the gaseous diffusion or gas centrifuge processes. As noted in Table 2, electrical energy consumption is also expected to be significantly less than used in existing enrichment technologies. With its significantly higher enrichment factors, laser technology could recover the residual ^{235}U residing in the tailings from either diffusion or centrifuge plants or be used in a traditional enrichment role.

The separative power of a uranium enrichment device is defined as a function of its design and operational parameters, and its capability to increase the ^{235}U concentration in the product material. Parameters that define the separative power include the enrichment factor α and the depletion factor β:

$$\alpha = \frac{x_P/(1-x_P)}{x_F/(1-x_F)} \quad (5)$$

and

$$\beta = \frac{x_F/(1-x_F)}{x_T/(1-x_T)} \quad (6)$$

These factors are not independent, and are related. Equivalently, the capability of the enrichment device can be defined by its separation factor (S)

$$S = \alpha\beta = \frac{x_P/(1-x_P)}{x_T/(1-x_T)} \quad (7)$$

Applicable separation factors and associated facility characteristics for various enrichment technologies are summarized in Table 2. The parameters summarized in Table 2 support the previous discussion regarding the efficiency of laser isotope separation enrichment technology and its potential for reduced reactor fuel costs.

Laser isotope separation techniques rely on the property that different isotopic species, in either an atomic or molecular form, exhibit small differences in their atomic or molecular energy level spectra. That is, equivalent transitions from one energy level to another are isotope specific and require a different energy to induce the transition. Thus, selective excitation is possible, and this property is a critical factor is the viability of laser isotope separation. With laser techniques, the enrichment of the ^{235}U isotope is not accompanied by ^{234}U enrichment. This is a significant change from the gaseous diffusion and gas centrifuge enrichment technologies.

In order to utilize the selective excitation property, an energy source is tuned to the desired excitation energy. Lasers offer an useful tool for this selective excitation.

A laser is a source of radiation that can be designed to operate at a specified frequency and intensity. Therefore, it is possible to preferentially excite one isotopic species via a precisely tuned laser, and leave other isotopic species in their ground states.

Two general laser techniques have been proposed for the enrichment of ^{235}U [1-8,12-17]. One technique involves the use of uranium vapor and it is based on the selective photoionization of atomic ^{235}U atoms. A second method of laser enrichment is based on the photodisintegration of ^{235}UF$_6$ molecules. The molecular laser isotope separation (MLIS) and atomic vapor laser isotope separation (AVLIS) technologies will be briefly addressed. The first commercial deployment of the molecular process is also discussed.

3.4.1 MLIS

In the molecular process an infrared (IR) laser is utilized to preferentially excite ^{235}UF$_6$ vibrational energy levels until the molecule dissociates:

$$^{235}\mathbf{UF_6} + \gamma_{\mathbf{IR}} \rightarrow {}^{235}\mathbf{UF_6^*} + \mathbf{n}\gamma_{\mathbf{IR}} \rightarrow {}^{235}\mathbf{UF_5} + \mathbf{F} \tag{8}$$

Multiple infrared absorptions (n) are required to fully dissociate the excited ^{235}UF$_6$ molecule. However, the ^{234}UF$_6$ and ^{238}UF$_6$ molecular are not excited and remain in their ground states.

The excitation process is based upon the inherent assumption that all UF$_6$ molecules are in their ground states before being illuminated by the laser radiation. Thus, it may be necessary to cool the molecules via flow through an expansion nozzle in order to ensure the vibrational ground states condition is met [4,5,12,14].

The UF$_6$ dissociation may be enhanced with other lasers types. For example, an ultraviolet (UV) laser could be utilized to cause further excitation of the vibrationally excited $^{235}\mathbf{UF_6^*}$ molecule. The excited state may then dissociate immediately.

$$^{235}\mathbf{UF_6^*} + \gamma_{\mathbf{UV}} \rightarrow {}^{235}\mathbf{UF_5} + \mathbf{F} \tag{9}$$

Once formed, the ^{235}UF$_5$ molecule precipitates as a solid and is collected. The unaffected ^{234}UF$_6$ and ^{238}UF$_6$ gas flows through the enrichment device and is separated from the ^{235}UF$_5$ product.

The health physics concerns associated with gaseous diffusion and gas centrifuge noted previously also apply to the molecular separation process. The use of laser components with high voltage power supplies introduce x-ray and nonionizing radiation hazards that need to be addressed. Other health physics issues associated with laser technology are addressed in subsequent discussion.

3.4.2 SILEX

The first commercialization of a molecular laser isotope separation process is a joint Australian-General Electric-Hitachi venture located in Wilmington, NC in the US. The separation of isotopes by laser excitation (SILEX) [12-17] is under the regulatory jurisdiction of the United States Nuclear Regulatory Commission (USNRC).

The SILEX technology is a proprietary commercial uranium enrichment process. The subsequent discussion is derived from regulatory documentation and open literature sources [12-17].

SILEX is a variation of the MLIS process described previously. It is believed [12,14] to be based on the selective excitation of $^{235}\mathbf{UF_6}$ using a 16 μm infrared laser radiation which pumps energy into one of the $^{235}\mathbf{U_5} + \mathbf{F}$ bonds. The IR laser creates a $^{235}\mathbf{UF_5} + \mathbf{F}$ excited molecular state with the uranium pentafluorine-fluoride bond weakened by the absorption of IR radiation. A second laser adds sufficient energy to initiate a photochemical reaction that severs this bond to create a new $^{235}\mathbf{UF_5}$ molecule and an unbound fluorine atom. The $^{235}\mathbf{UF_5}$ particulate separates from the $\mathbf{UF_6}$ gas, which forms the physical basis for enrichment.

Hecht [14] notes one possible laser configuration uses a pulsed CO_2 laser. High-pressure para-hydrogen cells convert the 10.8 μm output to produce the desired 16 μm infrared radiation. SILEX is projected to increase the $^{235}\mathbf{U}$ concentration by a factor of 2 – 20 [14]. However, licensing basis documents submitted to the USNRC only authorize enrichment of $^{235}\mathbf{U}$ to 8 wt% [15,16].

As noted in Table 2, SILEX enrichment factors are higher than gas centrifuge (1.3) or gaseous diffusion (1.004). The higher enrichment factors projected for SILEX reduce costs, which would provide a significant economic advantage over diffusion and centrifuge technologies. SILEX health physics issues are similar to those encountered in an MLIS facility and are reviewed in subsequent discussion. Possible proliferation concerns are also addressed.

3.4.3 AVLIS

Laser enrichment methods can also utilize uranium vapor as the working fluid. The use of metallic uranium impacts the conventional fuel cycle chemical conversion requirements since UF_6 is no longer used as the working fluid. The extent of these chemical conversion changes will be governed by the manner in which this technology is implemented on a production scale.

The United States Department of Energy developed the atomic vapor laser isotope separation process, but did not deploy it as its next generation of enrichment technology. In the AVLIS process, uranium metal is fed into a vacuum vessel where it is melted and then vaporized [4,5]. Vaporization can be achieved using a variety of heat sources (e.g., conventional heating elements, sputtering methods, and electron beam impingement). The uranium vapor is illuminated by laser radiation, which is tuned to selectively ionize only the ^{235}U atoms. Collection of the ^{235}U ions is accomplished by electromagnetic (EM) fields that alter the ion's trajectory. The unionized ^{234}U and ^{238}U atoms pass through the collection region and are separately collected on a tails collector.

The AVLIS enrichment process produces both internal as well as external radiation hazards. Internal exposure is due to the alpha decay of ^{234}U, ^{235}U, and ^{238}U and their daughter products. In contrast to UF_6 based enrichment technologies, uranium metal will oxidize during maintenance activities. Uranium oxides are produced during the variety of AVLIS maintenance activities and create a potential airborne hazard.

An external radiation hazard is created by photons and x-rays generated from the electron beam impingement on the uranium metal; from the high voltage equipment utilized in the laser, electron beam heating, and ion collection systems; and by the possibility of an inadvertent criticality event following the enrichment process. Uranium metal and its compounds also present a beta radiation hazard [4,5]. These hazards and potential controls to mitigate the hazard are summarized in subsequent discussion.

3.4.4 Laser Enrichment Health Physics and Other Hazards

There are unique health physics hazards associated with laser enrichment. The unique hazards arise for a variety of reasons that include the use of uranium metal in the AVLIS process, vaporization of uranium, use of lasers to create ions and excited molecules, and collection of ^{235}U ions and $^{235}UF_5$ molecules. This section discusses the specific health physics issues that are unique to uranium laser isotope separation technologies. Traditional uranium enrichment hazards encountered in gaseous diffusion and gas centrifuge facilities that were previously addressed are not specifically repeated.

3.4.4.1 X-ray Production

X-Rays are produced from stray currents in the high voltage power supplies supporting the various laser systems and the AVLIS product collection system. The AVLIS vapor generation system also produces x-rays if it utilizes an electron beam to heat the uranium metal. The collection system is unique to the AVLIS technology that extracts ^{235}U ions using electromagnetic fields.

X-ray hazards can be minimized using shielding and locating equipment in low occupancy locations.

Shielding should be added to all high-voltage power supplies. High voltage equipment should be located in areas not usually occupied or in areas of restricted access. The AVLIS vaporization unit should also be shielded to minimize the x-ray hazard, and have restricted access during operations to minimize worker doses.

3.4.4.2 Airborne Radioactive Material

Gaseous diffusion and gas centrifuge enrichment facilities have numerous components (e.g., valves, compressors, and instrument lines) that leak and lead to surface contamination and airborne radioactive material. These hazards also exist in laser enrichment facilities. The AVLIS facility vaporizes uranium metal that will coat the process vessel with a fine particulate coating. If the AVLIS separation unit is breached during operations (e.g. by a mechanical impingement accident, chemical reaction, thermal excursion, overpressure event, or laser induced damage) this particulate material will be released. Since uranium is pyrophoric, the fine particulate material will ignite and disperse oxidized uranium throughout the enrichment facility. As such is presents a unique airborne hazard. Airborne uranium can also be created if air is rapidly introduced into the AVLIS reaction chamber during maintenance operations.

Maintenance operations should proceed by slowly drawing air into the AVLIS separation unit. A controlled transition from vacuum pressures to normal pressures will minimize the phrophoric reaction and its contribution to airborne radioactive material.

Airborne hazards can also be minimized using traditional health physics controls. Airflow and ventilation systems should be designed and located to minimize airborne radioactive materials. Localized ventilation should be used to supplement installed systems to minimize airborne activity. In addition, exhaust air should be HEPA filtered and not recirculated from higher airborne concentration areas to lower airborne concentration areas. Alarming air monitors should be installed in areas where uranium dust may be present. These monitors warn personnel to exit process areas that minimizes the potential for an intake of uranium. The system design should consider integral glove boxes or other confinement structures to facilitate maintenance and repair operations within the separation unit. These engineering controls provide a needed barrier to limit internal intake of radioactive materials.

The airborne hazard becomes more significant if reprocessed uranium is used as the feed material. Dust and debris resulting from maintenance operations may present disposal problems due to the quantity of transuranium elements present. This hazard will only exist if the uranium feed includes recycled material derived from a fuel cycle that uses reprocessed uranium. The control measures noted previously will require careful review to ensure their adequacy if plutonium and minor actinides are present in the feed and product material.

3.4.4.3 Nuclear Criticality

The high separation factor expected in a laser enrichment facility suggests that highly enriched uranium can be achieved in a single separation unit. This contention is supported by a recent study by the American Physical Society [13]. Higher ^{235}U enrichments increase the likelihood of a criticality event.

Neutron and gamma rays are produced as a result of the criticality. A criticality event can occur with either the uranium metal or UF_5 product forms. The proper sizing and arrangement of transfer lines and storage containers can minimize the probability of a criticality. Criticality alarms should be installed with detectors properly located in enriched materials storage areas or near enriched material transport areas. Since lethal doses can be produced in a criticality, alarm systems can significantly reduce worker doses if personnel rapidly exit the separation unit area.

3.4.4.4 Laser Hazards

Laser radiation is normally directed into the separation unit. However, an abnormal event (facility accident, beam misalignment, or failure of the optical system) could redirect the laser radiation into occupied areas. This is a concern because high intensity (Class 4) laser radiation can damage the skin and eyes. In addition, reflected laser light from the photo-excitation process may damage the skin and eyes [4,5].

There are a number of controls that can mitigate the laser radiation concern. Beam tubes and optical transport systems should be designed to keep laser radiation out of occupied or accessible areas.

Interlocks and access controls should be used to preclude entry into areas having high-intensity laser radiation. The interlock would terminate the laser power supply that would preclude enrichment operations and eliminate the hazard.

3.4.4.5 Electromagnetic Hazards

High-strength EM fields associated with the AVLIS ^{235}U ion collection system may cause biological injury [4,5] and require controls to limit their effects. Areas with high-strength EM fields should be interlocked to preclude inadvertent personnel access or subjected to strict access controls.

3.4.4.6 Thermal Hazards

Heat buildup from the uranium AVLIS vaporizer presents a worker safety issue. Thermal insulation and vaporizer cooling water systems should ensure worker habitability conditions are met. However, cooling water systems must be carefully routed to avoid enriched uranium removal systems and preclude an inadvertent criticality event.

3.4.4.7 Noise Hazards

Noise hazards are created by high-energy systems transporting large quantities of matter. These systems include laser and enrichment process support equipment. The laser enrichment facility will process in a few units the equivalent material processed by thousands of gaseous diffusion stages or gas centrifuge machines. The smaller laser enrichment facility will magnify the expected noise hazard.

High noise areas should have restricted access. Noise levels should be reduced through the use of shielding or access controls. Personnel protective equipment provides a means to mitigate high noise levels.

3.4.4.8 Reduced Radiotoxicity

The elimination of ^{234}U enrichment is a positive aspect of laser isotope separation technology. The enriched product specific activity will be reduced relative to equivalent enrichments from gaseous diffusion and gas centrifuge facilities because only ^{235}U is enriched in a laser enrichment facility.

The $^{235}UF_5$ laser products will have the expected increase in neutron radiation as the ^{235}U enrichment increases. This neutron radiation will not be present in the AVLIS product. Somewhat higher beta radiation levels arise from uranium metal (2.33 mSv/h at 7 mg/cm^2) vice $^{235}UF_6$ (~1.8 mSv/h at 7 mg/cm^2). The beta, gamma, and neutron radiation levels associated with uranium materials require dose management and ALARA planning to ensure that worker doses are properly controlled.

4.0 Nuclear Proliferation

The nuclear non-proliferation treaty provides for nations to acquire nuclear technology (e.g., fission reactors, fuel reprocessing facilities, and uranium enrichment systems), and most of these facilities are subject to international monitoring. These facilities are monitored and inspected by the International Atomic Energy Agency, which ensures that material is not diverted for other purposes (e.g., military or criminal uses) [7,11,13,20].

Nuclear proliferation concerns arise from a number of fuel cycle activities including uranium enrichment, ^{239}Pu production through reactor operation, and reprocessing spent reactor fuel. The advanced centrifuges and laser enrichment technologies have the capability to produce highly enriched uranium that can be used for nuclear weapons production.

4.1 Advanced Enrichment Technologies

Traditional uranium enrichment technologies (e.g., gaseous diffusion and gas centrifuge) require facilities that are difficult to hide. These facilities also have noticeable electric power requirements. Advanced centrifuge facilities utilizing higher output machines and laser enrichment techniques require significantly less space and electricity that further facilitates clandestine operation. The efficiency of advanced enrichment technologies increases the likelihood of their use to produce highly enriched uranium (HEU) which is an integral component of a uranium nuclear weapon.

These advanced uranium enrichment technologies have the potential to lower the fuel and associated generating cost for nuclear power plants, but also pose increased proliferation risks. The proliferation risks of a uranium enrichment process increase as the technology becomes more efficient. If the size of an enrichment facility decreases, its construction may no longer be visible through aerial surveillance. In addition, electrical efficiency precludes the necessity for an observable dedicated power facility and may preclude a heat signature observable through satellite imaging. Therefore, an extremely efficient uranium enrichment facility could be clandestinely constructed and operated to produce weapons grade uranium and not be detected. This would create a significant security risk and associated nuclear proliferation concern.

4.2 Advanced Centrifuge

Glaser [11] notes that the production of weapon-grade uranium can be accomplished with natural uranium feed material in an advanced centrifuge. Using standard formulae for separative work (Eq. 3), Glaser [11] determined that only about 280 kg of natural uranium feed is needed to produce one kilogram of ^{235}U having an enrichment of $\geq$ 90 wt %. This proliferation scenario assumes batch recycling, no material is discarded, and no mixing occurs.

Using pre-enriched feedstock and batch recycling presents an additional proliferation example. Results published by Glaser [11] predict that more than 100 kg of weapons grade uranium can be produced in one year with 3.5% preenriched feed material in an enrichment facility with a capacity of 5000 SWU/yr, which is equivalent to about 2,000 P-1 centrifuges. Without international inspections, an existing uranium enrichment facility could produce weapons grade material if higher enrichments are used as feed material. This can be accomplished using existing enriched material or altering the enrichment cascade to recycle product material to enrich it to higher levels. By repeating this process, weapons grade material can be produced over time. These examples illustrate the inherent proliferation risk of advanced enrichment technologies.

Operating data from various facility systems could also be used to detect the production or diversion of highly enriched uranium. These monitoring activities could be implemented through international safeguards efforts, but would not be applicable for a clandestine facility or a facility that was not open to international inspection.

4.3 Laser Enrichment

The American Physical Society (APS) raised concerns [13] regarding the proliferation risk of the SILEX uranium enrichment process described in Section 3.4.2. In its 2010 petition to the NRC [13], the APS argued that the SILEX technology could increase the global risk of a nation clandestinely acquiring nuclear material of sufficient enrichment to increase their nuclear weapons capability. The APS noted that the SILEX technology is up to 16 times more efficient than centrifuge technology. This efficiency permits a SILEX enrichment facility to be smaller and more easily concealed than gaseous diffusion or gas centrifuge facilities.

In view of the projected separation factors and performance characteristics, a single laser isotope separation unit would likely exceed the 5000 SWU/y weapons criterion to obtain 100 kg of highly enriched uranium noted by Glaser [11] in Section 4.2. This means that a single laser isotope separation unit could replace thousands of conventional centrifuges or hundreds of more advanced machines. This equivalency illustrates the increased proliferation potential that results from laser technology.

The companies operating SILEX, argue that a facility utilizing this technology has no greater proliferation potential than a gas centrifuge plant. They also argue that the level of technology required to construct and operate a SILEX facility is well beyond the capabilities of nations that are attempting to acquire nuclear weapons [15-17].

The APS did not fully concur with these contentions, and raised the additional concern that over time process information will be acquired by nations seeking nuclear weapons. APS concerns also include the commercial availability of baseline SILEX components including the carbon dioxide lasers used in the separation process.

Although the NRC has issued a license for the SILEX Process, the concerns noted by the APS illustrate the need for strong controls to limit the dissemination of process specific information and sale of process related equipment. Historically, these controls have not been completely successful in limiting the spread of nuclear weapons technology. The most obvious example of the failure of these controls is the acquisition of centrifuge technology and supporting hardware. Failure to control centrifuge technology has led to the expansion of this enrichment method to nations that have developed or are attempting to develop nuclear weapons capability.

The development of centrifuge enrichment capability by North Korea and Iran has focused worldwide attention on the proliferation issue. Health physicists have a significant role in the proliferation arena since the detection of ^{239}Pu and ^{235}U are tasks well within their capability. The diversion of nuclear material and aspects of nuclear forensics [20] also require significant health physics resources to ensure radioactive materials are detected and their origins identified.

Detecting the diversion of enriched material or enriching material beyond facility limits is a complex task. Higher enrichments can be detected by monitoring process lines or uranium materials entering the facility as feed or exiting as product. In an MLIS facility, the ^{235}UF$_5$ product or UF$_6$ feed could be monitored for their neutron radiation levels since these levels were previously noted to be a function of the ^{235}U enrichment. An AVLIS facility could include gamma spectroscopy as a method to assess the ^{235}U enrichment.

5.0 Conclusions

Laser isotope separation presents unique health physics concerns since it has the potential for high enrichment factors. The possibility of producing significant quantities of weapons grade uranium is a consequence of the large separation factors and efficiency of the laser enrichment process. The capability to produce highly enriched uranium leads to unique health physics issues and proliferation challenges.

Laser isotope separation is unique because only ^{235}U is enriched without increasing the ^{234}U content. Criticality safety becomes a more significant concern because highly enriched ^{235}U can be produced in a single separation unit. The laser enrichment technique also introduces a number of unique ionizing, nonionizing, and industrial hazards. These hazards arise from the feed production, laser irradiation, and product collection mechanisms that are unique to the laser isotope separation technologies.

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Table 1. Estimated Design Characteristics of Selected Centrifuge Generations [a]

Type	Original Machine Designation	Deployment Period	Rotor Characteristics				
			Material	Speed (m/s)	Diameter (cm)	Length (m)	Separative Power (SWU/y)
----	Zippe	1940s-50s	Aluminum	350	7.4	0.3	0.44
P-1	SNOR/CNOR	1960s-70s	Aluminum	350	10	2.0	2 – 3
P-2	G-2	1960s-70s	Maraging Steel	485	15	1.0	5 – 6
P-3	4-M[c]	Early 1980s	Maraging Steel	485	[b]	2.0	12
P-4	SLM (TC-10)[c]	Late 1980s	Maraging Steel	500	15	3.2	21
---	TC-11[c]	Late 1980s	Carbon Fiber	600	[b]	3.0	[b]
---	TC-12[c]	1990s	Carbon Fiber	620	20[a]	3.0	40
---	TC-21[c]	2000s	Carbon Fiber	770	20[a]	5.0	100
---	AC100[d]	2000s	Carbon Fiber	900	60[a]	12.0	330

[a] Derived from Glaser (2008).
[b] Not provided by Glaser (2008).
[c] URENCO designation.
[d] USEC, American Centrifuge designation.

Table 2. Comparison of Potential Commercial Enrichment Technologies[a]

Enrichment Process	Separation factor	Number of Equipment Units	Energy Consumption (kWh/SWU)	Capital Costs
Gaseous Diffusion	1.004	Thousands	2400	Reference Cost
Advanced Gas Centrifuge	1.3	Thousands	~100	Higher than Diffusion
MLIS	2-6	<4	~100	Lower than Diffusion
AVLIS	2-6	<4	~100	Lower than Diffusion

[a] Consolidation of Refs 1-17.