ANSWER KEY

MODULE 1.0: INTRODUCTION TO URANIUM ENRICHMENT

1-1 Self-Check Questions

1. The United States accounts for approximately 25 % of the world's energy consumption, and represents about 25 % of the world's economy.

2. Energy used to produce electricity corresponds to about 50 % of total energy consumed.

3. Nuclear power supplies about 20 % of electricity generated in the United States.

4. Nuclear energy generally produces more than 30 times the energy used in the creation of fuel and the manufacture of the plant (the so-called energy ratio).

1-2 Self-Check Questions

1. List the first five steps of the nuclear fuel cycle.

   The first five steps of the nuclear fuel cycle are mining, recovery, processing/conversion, enrichment, and fuel fabrication.

2. Identify three uranium mining techniques.

   Three uranium mining techniques are open pit, underground, and in-situ leaching.

3. What is a uranium recovery designed to accomplish?

   A uranium recovery is designed to extract uranium from ore.

4. What is the final product produced from a uranium recovery facility?

   The final product of uranium milling is triuranium octoxide (U_3O_8), which is also known as "yellowcake" or "uranium ore concentrate."

5. What is the final product of a processing/conversion plant?

   The final product of a processing/conversion plant is pure uranium hexafluoride (UF_6).

6. What isotope of uranium is preferred for enrichment and why?

   Uranium-235 is the preferred isotope for enrichment because of its ability to fission.

7. During fuel fabrication, enriched UF_6 is converted to what uranium compound for fuel pellets manufacturing?

   During fuel fabrication, enriched UF_6 is converted to uranium dioxide (UO_2) for fuel pellets manufacturing.

8. What are the final products at a fuel fabrication facility, and where are they shipped?

   The final products at a fuel fabrication facility are fuel assemblies, which are shipped to nuclear reactor power plants.

9. Describe the three basic steps for the fabrication of light water reactor fuel.

   The three basic steps for the fabrication of light water reactor fuel are as follows:
   - chemical conversion of UF_6 to uranium dioxide (UO_2) powder
   - ceramic process that converts UO_2 powder to pellets
   - mechanical process that loads the fuel pellets into rods and constructs finished fuel assemblies

10. What is spent nuclear fuel?

    Spent nuclear fuel is irradiated reactor fuel that is no longer useful as fuel.

11. How is spent fuel stored?

    Spent fuel is stored in water pools at the reactor site or off-site in a dry storage cask.

12. What is high-level waste?

    High-level waste includes irradiated reactor fuel, liquid wastes resulting from the operation of the first cycle solvent extraction system, the concentrated wastes from subsequent extraction cycles, and solids into which such liquid wastes have been converted.

1-3 Self-Check Questions

Fill in the missing words or numbers in each statement. Choose from the following words or numbers:

actinium	chain	compounds	different	enrichment	equilibrium
exposures	feeding	fluorinated	gaseous	half-life	hazard
higher	isotopes	lead	liquid	long-lived	materials
prevention	radium	safety	smaller	specific	transuranic
transportation	uranium	U-234	U-235	U-236	uranyl

1. Naturally occurring uranium consists of three isotopes: uranium-238, uranium-235, and uranium-234.

2. The isotope U-235 is usually the desired material for use in reactors.

3. The U-234 and U-238 isotopes belong to one family, the uranium series, and the U-235 isotope is the first member of another series called the actinium series.

4. Each individual radioactive substance has a characteristic decay period or half-life.

5. Decay products can represent the most significant hazard from uranium ore in the mining and recovery stages of the fuel cycle.

6. Typically, the most radiologically significant isotopes in natural uranium are isotopes of radium and its decay products (radon and polonium).

7. The higher the enrichment, the smaller the mass required to sustain a chain reaction.

8. Nuclear criticality safety has been defined as the prevention or termination of an inadvertent nuclear chain reaction in nonreactor environments.

9. If a critical mass is accidentally assembled in an unprotected area, a release of energy will occur. The following may happen:

   - high radiation exposures to personnel
   - release of radioactive materials to the environment
   - contamination of facilities

10. The concentration of uranium products or by-product materials can result in higher specific activity.

11. What three characteristics do the uranium, actinium and thorium series have in common?

    - The first member of each series is very long-lived.
    - Each has a gaseous member, and the radioactive gas in each case is a different isotope of the element radon.
    - The end product in each case is a stable isotope of lead.

12. In newly purified uranium, the immediate decay products of Th-234, Pa-234m, and Th-231 will have grown to their equilibrium levels within a few weeks.

13. Specific activity increases with enrichment, not because of the replacement of U-238 with U-235, but primarily because of the increase in the amount of U-234 present.

14. The chemical processes by which recycled uranium is purified leave trace amounts of transuranic material (neptunium and plutonium) and fission products (technetium-99 [Tc-99]). Recycled uranium also contains small amounts of uranium isotopes not found in nature, such as U-236.

15. There are two reasons for using UF_6. First, it can conveniently be used as a gas for enrichment, as a liquid for feeding and withdrawing, and as a solid for storage and transportation. Each of these states is achievable at relatively low temperatures and pressures. Second, because fluorine has only one natural isotope, all the isotopic separative capacity of the enrichment plant is used to enrich the concentration of the lighter uranium isotopes.

16. Uranium hexafluoride will increase in volume by more than 30% as it changes from a solid to a liquid.

17. Uranium hexafluoride is reactive with water or moisture in the air to form uranyl fluoride and hydrogen fluoride.

18. Protective measures required for an enrichment plant are similar to those taken by other chemical industries concerned with the production of fluorinated chemicals.

19. Exposure of the UF_6 gas to the atmosphere can lead to the formation of other compounds, but any effects remain essentially chemical.

1-4 Self-Check Questions

1. Enriched uranium is uranium with a U-235 content that has been increased through the process of isotope separation.

2. Define separative work units (SWU).

   Separative work units (SWU) are the measure of physical effort in separation for enrichment plants.

1-5 Self-Check Questions

Match the enrichment technology in column A with the process description in column B.

Column A – Enrichment Technology

A. Gaseous diffusion

B. AVLIS

C. Gas centrifuge

D. Electromagnetic separation

E. Thermal diffusion

Column B – Process Description

This enrichment technology uses:

1. C a centrifugal force to separate lighter U-235 atoms from U-238 atoms

2. B process lasers to emit precise frequencies of light that differentiate between U-238 and U-235 isotopes to selectively ionize U-235 atoms

3. A a porous barrier to diffuse uranium hexafluoride

4. E a temperature difference

5. D a magnetic field

1-6 Self-Check Questions

Complete the following questions.

1. What three things did the Energy Policy Act of 1992 require the NRC to do?

   - The Act required that, within two years after enactment of the legislation, the NRC was to develop standards for the USEC's two operating gaseous diffusion plants to protect public health and safety from radiological hazards and to provide for the common defense and security.
   - The Act further directed the NRC to establish a process under which the two gaseous diffusion plants will be certified annually by the NRC for compliance with those standards.
   - The Act also required the NRC to report annually to Congress on the status of the gaseous diffusion plants.

2. What change occurred for the NRC when the president signed into law the "Federal Reports Elimination Act of 1998"?

   It modified the requirement for NRC to issue an annual report to Congress on the gaseous diffusion plants. The law now states that the report to Congress does not have to be annual but is to be issued "not later than the date on which a certificate of compliance is issued."

3. What two enrichment technologies have been used in the past but are not operating in the United States today?

   Gas centrifuge, electromagnetic separation and thermal diffusion.

1-7 Self-Check Questions

Complete the following questions.

1. What ANSI standard addresses design, fabrication, and certification standards for uranium hexafluoride cylinders?

   Design, fabrication and certification standards for uranium hexafluoride cylinders are addressed in ANSI N14.1, “American National Standard for Nuclear Materials – Uranium Hexaflouride – Packaging for Transport.”

2. What Title 10 CFR Parts address the transporting of UF_6 cylinders?

   Title 10 CFR Parts 50 (including Appendix B), 71, 76, and 830.

3. Why should empty cylinders remain free of impurities such as hydrogenous materials?

   Empty cylinders must be free of impurities, particularly hydrogenous materials, because they could contaminate or react with UF_6 added to the cylinder.

4. When should a UF_6 cylinder be removed from service?

   A UF_6 cylinder shall be removed from service when:

   - It is found to have leaks, excessive corrosion, cracks, bulges, dents, gouges, defective valves, damaged stiffening rings or skirts, or other conditions that, in the judgment of the qualified inspector, render it unsafe or unserviceable.
   - Its shell and/or head thicknesses have decreased below the values specified in ANSI N14.1.
   - Inspections show that any unauthorized repair or modification has been made to the cylinder.

5. Why is UF_6 always handled in leak-tight containers and processing equipment?

   To prevent it from reacting with water vapor in the air.

6. What happens when hydrocarbon oil is introduced into processing equipment or cylinders when uranium hexafluoride is in the liquid or gaseous phase?

   Uranium hexafluoride reacts rapidly with hydrocarbons. If the UF_6 is in the gas phase, the reaction forms a black residue of uranium-carbon compounds. In the liquid phase, the reaction proceeds at an accelerated rate and has been known to cause explosions in cylinders.

7. What happens to volume and density when UF_6 transforms from a solid to a liquid?

   When UF_6 is transformed from a solid to a liquid, volume increases and density decreases.

8. What precautions should be administered when large cylinders containing liquid UF_6 are moved?

   Movement of large cylinders containing liquid UF_6 should be minimized, especially with respect to lift height, and performed only with the valve protector correctly installed. Cylinders should also be allowed to cool before movement. A cylinder shall not be shipped until its contents have completely solidified and the pressure in the cylinder is below atmospheric pressure.

9. What type of action should be required if valves are damaged while handling full UF_6 cylinders?

   Valves that are damaged while handling full cylinders of UF_6 require immediate action. If the valve has been broken off, the release can usually be stopped by driving a tapered wood plug into the opening.

10. What routine procedure should be administered after cylinder hookup?

    After cylinder hookup, all connections should be pressure tested and vacuum leak rated before use.

11. Should water be streamed directly into a cylinder opening?

    In no case should water be streamed directly into a cylinder opening.

12. What could be used effectively to stop a UF_6 release?

    A wet towel or rag wrapped around the release area can be very effective in stopping leaks. Dry ice or pressurized CO_2 from large-capacity fire extinguishers may be used safely with any enrichment to stop leaks.

13. When UF_6 is vaporized from a cylinder, what usually remains behind? What is emitted?

    When UF_6 is vaporized from a cylinder, the decay products usually remain behind. The decay products of uranium include isotopes that emit mildly penetrating beta rays and highly penetrating gamma rays.

14. How can radiation exposures of employees working around UF_6 cylinders be controlled?

    Radiation exposures of employees working around UF_6 cylinders are easily controlled at very low levels through conventional distance-time limitations.

15. How is the goal of preventing an inadvertent criticality with one or more cylinders accomplished?

    This goal is accomplished by employing, individually or collectively, specific limits on uranium-235 enrichment, mass, volume, geometry, moderation, and spacing, and in some instances, utilizing the neutron absorption characteristics of the steel cylinder walls.

16. For shipment of UF_6 above 5.0% U-235 enrichment, what controls or limits are employed?

    For shipment of UF_6 above 5.0% uranium-235 enrichment, geometry or mass limits are employed.

MODULE 2.0: GASEOUS DIFFUSION

2-1 Self-Check Questions

1. What is gaseous diffusion?

   Gaseous diffusion is an enrichment process based on the difference in rates at which uranium isotopes in the form of gaseous uranium hexafluoride diffuse through a porous barrier.

2. Name USEC's two gaseous diffusion plants and their operational status.

   Paducah, Kentucky, is currently operating; and Piketon, Ohio (Portsmouth GDP), is in "cold standby."

3. What are the three basic requirements needed to apply the gaseous diffusion process?

   The three basic requirements needed to apply the gaseous diffusion process are a stable process gas (UF_6), a porous membrane, and a driving force to cause selective diffusion of the molecules through the porous membrane.

Activity 1 - UF_6 Feed Storage and Feed Supply Autoclave

1. What is an autoclave?

   An autoclave is a containment shell that opens to accept a cylinder inside for heating.

2. What are the parameters used to ensure that autoclave heating is proceeding properly and that cylinder integrity is maintained?

   Pressure, temperature, and conductivity are the parameters used to ensure proper autoclave heating and cylinder integrity.

3. What assurances should occur before a UF_6 cylinder is heated in an autoclave?

   Material should meet feed composition and weight specifications. An external inspection on each cylinder to detect any physical damage should also be performed.

4. What should happen before drawing a liquid sample for chemical purity and isotopic concentration?

   The UF_6 should be liquefied and homogenized for approximately 10 hours.

5. Following the sample withdrawal, and before opening the sampling system to the atmosphere and removing the sample bottles, what should occur?

   The system should be purged of UF_6 and evacuated to about 1 psia or as low a vacuum as possible.

6. What form of UF_6 (solid, liquid, or gas) is fed to the cascade?

   UF_6 is fed to the cascade as a gas.

7. How is a cylinder connected to a manifold?

   A cylinder is connected to a manifold with a pigtail.

8. After pigtail and valve testing, what does a cylinder pressure less than or equal to 10 psia indicate?

   A pressure less than or equal to 10 psia indicates that the cylinder does not contain significant amounts of impurities and is acceptable for feed.

9. What does a cylinder pressure greater than 10 psia indicate?

   A cylinder pressure greater than 10 psia indicates noncondensibles (oxygen, nitrogen, etc.) or impurities (such as FREON) in the cylinder.

10. What is each autoclave provided with to protect against overpressurization?

    As a protection against overpressurization, each autoclave is provided with a rupture disc backed by a 3-inch by 4-inch pressure relief valve.

Activity 2 - Calculating the Required Cascade Length

Purpose: Demonstrate an understanding of the relationship between cascade stages and percent enrichment.

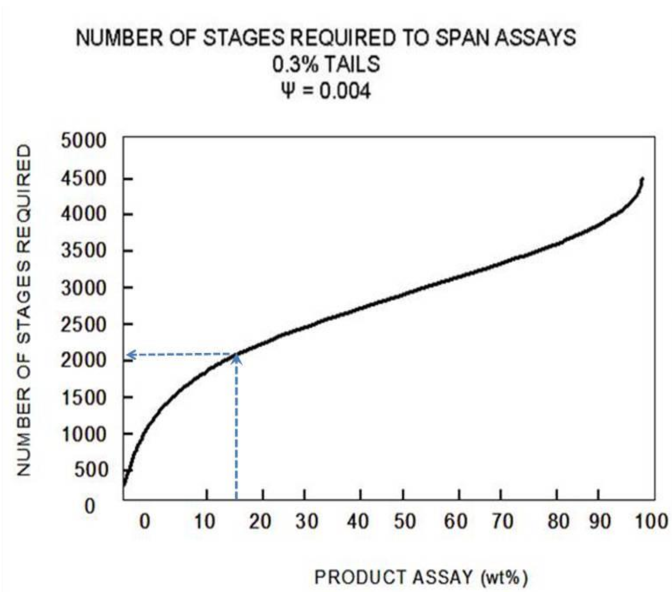
Instructions: Using the formula for ideal number of stages in Figure 2-15, calculate the required number of stages to enrich normal feed (0.711%) to 15% assay assuming a 0.3% tails assay and a separation factor of 1.004. Using Figure 2-15, check your answer with the plot of stages versus product assay.

$$R_T = \frac{U_{235}\ Top\ Concentration}{(1 - U_{235}\ Top\ Concentration)} = \frac{0.15}{1 - 0.15} = 0.176$$

$$R_B = \frac{U_{235}\ Bottom\ Concentration}{(1 - U_{235}\ Bottom\ Concentration)} = \frac{0.003}{1 - 0.003} = 0.003$$

$$N_{min} = \ln\left(\frac{\mathrm{R_T}}{\mathrm{R_B}}\right)/\Psi = \ln\left(\frac{0.176}{0.003}\right)/0.004 = 1020$$

$$Ideal\ Number\ of\ Stages\ = 2N_{min}\ = 2(1020) = 2040\ stages$$



Activity 3 - Cascade Configuration

1. A schematic representation of an efficient cascade is usually drawn with a diamond shape. What does this shape illustrate?

   A diamond shape indicates the relative physical size of the stages, the relative operating pressures, and the relative flow rates of UF_6 in the stages. The larger equipment, higher pressures, and higher flow rates can be found in the wider portion of the cascade diamond. The small equipment, lower pressures, and lower flow rates are found in the smaller portions of the diamond.

2. What determines the required length of the cascade (number of stages)?

   The length of the cascade is determined by the needed enrichment. For example, a 4% enrichment requires many more stages than a 2.6% enrichment.

   Knowing the needed enrichment in the product (top concentration 3% to 5% assay) and the programmed enrichment for the tails (bottom concentration 0.2% to 0.4% assay) sets the theoretical minimum number of stages needed, as well as the ideal number of stages.

3. What is a cell?

   A cell is a configuration of several stages in series. A cell usually contains 8 to 10 stages, coolant condensers to remove the heat of compression, and block valves to isolate the cell from the rest of the cascade. It is the smallest section of the cascade that can be isolated from the rest of the enrichment plant operations.

4. What constitutes a unit, and how does it constitute a cascade?

   A group of cells constitutes a unit, while several units constitute a cascade.

5. A cascade is operated under several large divisions called <u>areas</u>. (Fill in the blank.)

6. What are the "A" and "B" streams?

   The enriching flow path is called the "A" stream, and the depleting flow path is called the "B" stream.

7. Provide a brief description of the following valves.

AB1 and AB2.

The valves that isolate the "A" stream are AB1 (A stream block valve no. 1 - inlet) and AB2 (A stream block valve no. 2 - outlet).

BB1 and BB2.

The valves that isolate the "B" stream are BB1 (B stream block valve no. 1 - inlet) and BB2 (B stream block valve no. 2 - outlet).

ABP and BBP

ABP and BBP are bypass valves.
ABP (A stream block valves bypass).
BBP (B stream block valves bypass).

8. If given stages 1 through 8, how do the A stream and B stream flow?

The A stream flows up from stage 1 through stage 8, and the B stream flows down from stage 8 through stage 1.

9. What are area control rooms (ACRs)?

In the area control rooms, there are controls for the cells in each unit as well as auxiliary support systems associated with each unit. The ACR also controls the systems of piping and valves that interconnect the various units and cells. The ACR is the primary operating location and emergency response location for the cascade.

10. What are local control centers (LCCs)?

Local control centers assist the area control room by providing additional indicators for each cell and its associated stages. The LCC contains controls and indications for electrical breakers for valves and compressor motors, stage pressures, cell coolant systems, and sampling connections.

11. What are the components of a stage?

A stage has one converter, one compressor, one stage control valve, and associated piping and indications.

12. In what are converters, compressors, and connecting process gas piping enclosed to keep the temperature high enough so that no process gas will condense or desublime (freeze)?

    They are enclosed in insulated cell housings.

13. What piece of equipment must be provided for moving the process gas through the converter and to maintain required pressure differential across the barrier in the converter?

    A compressor moves the process gas through the converter.

14. What makes up an axial flow compressor?

    An axial flow compressor consists mainly of a rotor, stator, blades, and casing.

15. What do stator blades do in the compressor?

    The stator blades act as straighteners and direct the gas at the desired angle into the next row of rotor blades. If there were no stator blades in the compressor, the gas would merely rotate with the rotor.

16. What are three zones of a seal and what purpose do they serve?

    There are three zones of a seal; the process gland, the intermediate gland, and the atmospheric gland. The process gland is the first barrier to the escape of UF_6 from the cascade from around the compressor shaft. If UF_6 does escape the process gland, it travels to the intermediate gland where the seal exhaust system is connected to remove any UF_6 and nitrogen that passes through the intermediate gland seal before coming in contact with the atmospheric gland. The atmospheric gland seal is maintained by a back pressure of dry air applied to the gland gap at a significantly higher pressure than the UF_6 that may have escaped from the intermediate gland.

17. What is the purpose of connecting pipe headers?

    Connecting pipe headers called interbuilding tie lines are used to move UF_6 between buildings.

18. If a stage control valve is opened more because of a need to slightly lower the pressure on the B stream outlet from a converter, what happens to the pressure at the B stream inlet of the compressor of the previous stage?

    The pressure increases slightly.

19. What happens to the A stream inlet of that same compressor?

    Less A stream flow enters the compressor because of the higher pressure from the B stream inlet that enters the middle of the compressor.

20. What happens to the output of the compressor?

    No change should be experienced at the outlet of the compressor.

Activity 4 – Coolant, Freezer-Sublime, Unit Lube Oil and Ventilation Systems

1. What is the purpose of the cell coolant system and why is it important?

   The purpose of the cell coolant system is to remove unwanted heat from the cell using a cooling coil that is internal to the converter A stream outlet chamber. This cooling is important to the proper operation of the barrier material and the compressor. Maintaining the proper temperature increases the performance of the barrier and the lifetime of the compressor.

2. Why was Freon-114 the original choice for a coolant medium?

   The choice of Freon-114 was originally based on its high thermal conductivity, high thermal capacity, and good phase-change characteristics over a wide range of temperatures and pressures.

3. What is the purpose of the freezer–sublimer system? Give an example of when it could be used.

   The freezer–sublimer system is designed to be a nuclear-criticality–safe storage of UF_6 in key locations in the cascade process. An example is when there is a need to reduce power consumption in the cascade, UF_6 can be diverted to a freezer–sublimer instead of pushing it up the A stream, which consumes power. When the reduced power need has passed, then the UF_6 can be removed from the freezer-sublimer and placed back in the A stream.

4. Why is lubrication oil used in the cascade?

   Fire hazards as well as explosions may occur as a result of overpressure of isolated equipment, the ignition of explosive gas mixtures, or exothermic reactions.

5. What is the purpose of a ventilation system in a gaseous diffusion facility?

   The ventilation system is provided to rapidly change the air in the building on a continuous basis as a form of heat removal.

Activity 5 - Tails

1. What form(s) of UF_6 make(s) up tail material and what size cylinders are used for tails storage?

   UF_6 gas is compressed and condensed as liquid UF_6 and drained as a hot liquid at greater than atmospheric pressure into 10-ton or 14-ton tails storage cylinders. The filled tailed cylinders are weighed and moved outside the building where they are permitted to cool at ambient conditions until their contents are solidified.

2. What is the typical assay of tails material?

   The typical assay of the tails material is between 0.2% and 0.4%.

3. How is actual tails assay chosen?

   The actual tails assay that is chosen is a programmed value based upon the economics of the optimum match of cascade configuration, cost of normal feed (0.711% assay), cost of power, operating pressures, and enriched product market price.

4. What size cylinders are typically used for tails storage?

   Tails material is typically stored in 14-ton cylinders.

5. How are cylinder movements and stacking accomplished?

   Cylinder movements and stacking are accomplished with large-capacity mobile equipment specifically designed to safely handle the large 14-ton and 10-ton cylinders filled with solid UF_6.

6. Is mobile equipment used to transport liquid UF_6 cylinders?

   No!

Activity 6 - Product Withdrawal and Storage

1. UF_6 product in the gaseous state is <u>removed</u> from the enrichment cascade through heated piping to the <u>product withdrawal facilities</u> where it is further compressed to a pressure of <u>approximately 30 psia</u> and cooled for condensation to the liquid phase.

2. What are two methods that could be used to assay the contents of product cylinders?

   A UF_6 sample can be collected by an automatic sampler during cylinder-filling operations or by an approved method such as in-line mass spectrometers.

3. Why are accumulators located in the liquid withdrawal line?

   Accumulators are located in the liquid withdrawal line to provide storage of liquid UF_6 during withdrawal interruptions.

4. To ensure compliance with accumulator assay limitations, what do administrative controls require?

   To ensure compliance with the accumulator assay limitations, administrative controls require frequent, periodic laboratory-analysis verification of continuous mass-spectrometer assay determination and physical lockout of withdrawal header valves.

5. Laboratory analysis of new assay materials is performed before condensing is started by circulating the new assay for <u>30</u> minutes before pulling the sample from the withdrawal station sample manifold.

6. What size cylinders are used for product withdrawal from the cascade?

   10-ton cylinders are used for product withdrawal from the cascade.

7. What size cylinders are used for transfer of product to customers?

   2.5-ton cylinders are used for transfer of product to customers.

8. What is the purpose of overpacks?

   Overpacks provide additional transport protection for the product cylinder as well as an additional barrier to the potential spread of contamination should contamination leach from the metal surfaces of the cylinder.

2-2 Self-Check Questions

Fill in the missing words in each statement. Choose from the following words:

barrier	feed	rotor
blades	Freon R-114	seal
block	freezer–sublimer	size
cell housings	headers	stage
compressors	heat	stage control
configuration	motor	stator
centrifugal	oil	subatmospheric
converter	parallel	UF_6
corrosion	process gland	ventilation

1. The number of separative work units required to enrich a given amount of uranium is dependent on the enrichment of the final product, the tails assay, and the feed enrichment.

2. The basic stage configuration is one converter, one compressor, one stage control valve, and associated piping and indications.

3. A means must be provided for moving the process gas through the converters and maintaining required pressure differential across the barrier in the converter. This is accomplished by means of gas compressors, one for each converter in the cascade.

4. The barrier material is constructed in tubes, many of which are arranged in a tube bundle and installed in a converter.

5. The gas that enters the converter contains an excess amount of heat imparted to it by the compressor.

6. All of the converters, compressors, and connecting process gas piping are enclosed in insulated cell housings so that they are at all times surrounded by heated air, which helps to keep the temperature high enough so that no process gas will desublime (plate-out and "freeze").

7. The axial flow compressor consists mainly of a rotor, stator, blades, and casing.

8. The rotor is a cylindrical metal drum with a shaft through its axis.

9. The stator is cone-shaped and fits just outside the tips of the rotor blades.

10. The axial flow compressor is called "axial" because the gas flow is parallel to the axis of the rotor.

11. The <u>centrifugal</u> compressor consists mainly of rotating wheels or impellers with attached vanes, and a casing.

12. It is necessary to <u>seal</u> the shafts of both axial and centrifugal compressors where they enter the compressor casings.

13. The <u>process gland</u> is the first barrier to the escape of UF_6 from the cascade from around the compressor shaft.

14. The <u>motor</u> and its associated connections are always located outside the cell enclosure.

15. Process piping, with its associated flanges, valves, and expansion joints, is the massive transportation system that moves the <u>UF_6</u> from compressor to converter, cell to cell, and building to building.

16. UF_6 piping is nickel-plated internally to reduce <u>corrosion</u>.

17. Connecting pipe <u>headers</u> called interbuilding tie lines are used to move UF_6 between buildings.

18. The function of the <u>block</u> valves in the system is to isolate cells or other major UF_6-containing process equipment, allowing the equipment to be taken out of service for repairs.

19. Motor operated valve (MOV) closure time is dependent upon valve <u>size</u>.

20. A <u>stage control</u> valve automatically controls the process gas pressure in the converter. It operates as a throttling or back-pressure valve.

21. The primary methods of system control are <u>configuration</u> and pressure.

22. The purpose of the cell coolant system is to remove unwanted <u>heat</u> from the cell using a cooling coil that is internal to the converter A stream outlet chamber.

23. The coolant medium is a refrigerant called <u>Freon R-114</u>.

24. The <u>freezer–sublimer</u> system is designed to be a nuclear-criticality–safe storage of UF_6 in key locations in the cascade process.

25. Lubricating <u>oil</u> is used in the cascade to lubricate compressor bearings and compressor motor bearings, and to provide a source for hydraulic operating oil for the stage control valves.

26. The <u>ventilation</u> system is provided to rapidly change the air in the building on a continuous basis as a form of heat removal.

2-3 Self-Check Questions

Complete the following questions.

1. What are the locations and operating status of the two gaseous diffusion plants in the United States?

   The Portsmouth Gaseous Diffusion Plant is located in Piketon, Ohio, and the Paducah Gaseous Diffusion Plant is located in Paducah, Kentucky. The Paducah GDP is currently operating and the Portsmouth GDP is in "cold standby."

2. Which gaseous diffusion plant has produced feed material for other gaseous diffusion plants?

   The Paducah Gaseous Diffusion Plant has produced feed material for the Portsmouth plant. It also supplied feed material for the Oak Ridge Gaseous Diffusion Plant.

3. Who is responsible for managing the environmental legacy left from prior operations at the two plants?

   The Department of Energy has retained the responsibility for managing the environmental legacy left from prior operations.

4. What overseas corporation operates gaseous diffusion enrichment facilities in a consortium with Spain, Italy, and Belgium?

   AREVA operates gaseous diffusion enrichment facilities in Eurodif, a consortium with Spain, Italy, and Belgium. Eurodif is a corporation formed and administered under French law, although its ownership is held over a broad international base.

5. Eurodif gaseous diffusion plant represents a good example of this type of configuration.

   Vertical configuration.

6. In the Eurodif configuration, approximately how many stages are in each cell?

   The Eurodif configuration has 20 stages in each cell.

7. The Pierrelatte facility in France has a separative capacity that is generally reported as how many tonne SWU per year?

   The Pierrelatte facility in France has a plant separative capacity generally reported as 400 tonne SWU per year.

8. The Eurodif Tricastin gaseous diffusion plant has what separative capacity per year?

   The Tricastin GDP has a total separative capacity of 10,800 tonne SWU per year.

9. Besides the United States and the Eurodif consortium, what other countries have enriched uranium via gaseous diffusion?

   China and Russia join the U.S. and Eurodif consortium with gaseous diffusion capabilites.

2-4 Self-Check Questions

Complete the following questions.

1. What is the primary concern of the systems analyzed in the gaseous diffusion process?

   The primary concern of the systems analyzed in the gaseous diffusion process is atmospheric releases of UF_6, HF, and F_2.

2. The probability of massive releases is greater when UF_6 is in a (solid, liquid, or gaseous) state.

   The probability of massive releases is greater when UF_6 is in the liquid state.

3. Where is the most vulnerable equipment in the UF_6 feed, withdrawal, sampling, handling, and cylinder storage operations?

   The most vulnerable equipment in the UF_6 feed, withdrawal, sampling, handling, and cylinder storage operations is the pigtail connection between the piping manifolds and the cylinders.

4. Place a "Y" for "Yes" or an "N" for "No" if liquid releases of UF_6 can occur in the following areas in the gaseous diffusion facility:

   Y Feed
   Y Withdrawal
   Y Cylinder sampling
   Y Cylinder-to-cylinder transfer facilities

5. The potential exists for UF_6 reaction with H_2O in the autoclaves, resulting in formation of <u>HF</u> and <u>UO_2F_2</u> and an increase in pressure.

6. <u>True</u> or False. Inleakage of lube oil could cause the formation of a solid mass of uranium compound large enough to become critical.

7. <u>True</u> or False. Exothermic reactions could result in friction heat and melting of aluminum.

8. What uranium deposit treatment gases could workers be exposed to during enrichment operations?

   Workers could be exposed to barrier treatment gases ClF_3 and F_2.

9. The risks in UF_6 handling and storage are caused primarily by <u>operator error</u>.

10. Give three examples of operator error in handling and storing UF_6 cylinders.

    Some examples:

    - Dropping a liquid-filled UF_6 cylinder (operator error, or equipment failure).
    - Moving a liquid-filled UF_6 cylinder while the cylinder is still connected to the feed, withdrawal, or autoclave manifold (operator error).
    - Handling a liquid-filled UF_6 cylinder with straddle carrier (operator error).
    - Moving a UF_6 cylinder with mobile equipment before the UF_6 solidifies (operator error).
    - Using an uncertified pigtail, which could result in rupture (operator error and equipment failure).
    - Not leak testing pigtails after hookup (operator error).
    - Stacking UF_6 cylinders to form a critical mass and geometry (operator error).

11. Mixtures of F_2, ClF_3, and R-114 are explosive in certain concentrations if an ignition source is available, such as friction heat created by rubbing equipment from some compressor failures. The areas of most concern are in the <u>purge</u> cascade or in <u>off-stream cells</u> where an explosion may release UF_6. Explosions are also produced when ClF_3 comes in contact with materials containing <u>carbon</u> and hydrogen.

12. The possibility of fires occurring in the compression and/or liquefaction withdrawal system is high because of the lube oil presence and possible ignition source (hot compressor bearing).

13. To reduce the probability of a criticality, temperatures and pressures are maintained at values to prevent solidification of UF_6.

14. Radiation monitoring is conducted throughout the cascade to locate any accumulation of solid uranium mass.

15. During maintenance and equipment removal, all equipment should be covered with plastic sheeting to protect the uranium compounds from loss, protect the maintenance personnel at the scene, and prevent water from entering the equipment.

16. In general, any contaminant of higher molecular weight than uranium (for example, transuranics) will concentrate at or slightly below the UF_6 feed point. Those contaminants with molecular weight lower than that of uranium (for example, technetium) will travel up the diffusion cascade and concentrate at the UF_6 "front" (the break point between UF_6 and low-density gases such as O_2 and N_2).

17. In general, the presence of uranium decay products or fission products poses no significant hazard while confined within the process equipment. The primary hazard occurs when the equipment is opened and removed for maintenance or replacement.

18. Operations using uranium hexafluoride will not generally present a hazard from penetrating radiation, except in the handling of empty UF_6 cylinders and the maintenance and decontamination of process equipment. However, internal exposures may be of significant concern from the standpoint of both acute and chronic exposures.

19. What are some examples of materials that may be used in auxiliary support processes that could have adverse health effects on humans?

    Chlorine, natural gas, and gasoline are examples of materials used in auxiliary support processes that could have adverse health effects on humans.

20. How are chlorine trifluoride, hydrogen fluoride, and fluorine used in the gaseous diffusion process? What are some of the hazards associated with their use? List two substances that chlorine trifluoride can react with to produce a violent reaction.

    Chlorine trifluoride is used as a drying agent. Chlorine trifluoride reacts violently with water, organic matter, glass, asbestos, sand, chlorofluorocarbons, acids, alkalis, halogens, salts, and metal oxides, as well as many other materials.

21. What are the three primary reasons why UF_6 poses a potential health risk?

    UF_6 can pose a potential health risk because:

    - Uranium is radioactive and can therefore increase the likelihood of cancer in exposed individuals.
    - Uranium is a heavy metal that can have toxic effects (primarily on the kidneys) if it enters the bloodstream through ingestion or inhalation.
    - UF_6 can react with moisture in the air to produce HF, a corrosive gas that can damage the lungs if inhaled. HF can also penetrate the skin. In addition to severe burns, it can react with calcium, affecting bones and the electrolyte balance (the latter can result in cardiac effects).

Activity 7 - United States Enrichment Corporation's Facilities

Instructions: Complete the activity questions and take the electronic tours for Paducah and Portsmouth by using the following steps:

1. Through your internet provider, access the USEC World Wide Web address by keying in www.usec.com

2. Select Uranium Enrichment, then Gaseous Diffusion.

3. Select the Paducah and Portsmouth site information.

4. Review background and facts information for each site and answer activity questions.

5. Take an electronic tour for each site and answer the remaining activity questions.

Answer Key

1. Review the plant history of the Paducah Gaseous Diffusion Plant. When did the following events occur?

Event:	Date:
First production cells go "onstream."	September 1952
Plant shifts from military mission to commercial application to supply enriched uranium to electric utilities operating nuclear power plants.	Mid 1960s
Energy Policy Act creates USEC to take over government's uranium enrichment enterprise.	November 1992
USEC assumes responsibility for the Paducah and Portsmouth uranium enrichment plants.	July 1993
NRC grants certificates of compliance for USEC's two enrichment plants.	November 1996
Regulatory oversight of enrichment plants officially transfers from DOE to NRC.	March 1997

2. How many process buildings are at the Paducah site?

   There are 4 process buildings at Paducah.

   How many enrichment stages?

   There are 1,760 enrichment stages at the Paducah site.

3. How many process buildings are at the Portsmouth site?

   There are 3 process buildings at Portsmouth.

   How many enrichment stages?

   Approximately 1,700 enrichment stages are involved at Portsmouth.

4. Access the Paducah electronic tour. The following questions are each related to a specific tour section that is noted at the beginning of each question. Note: Not all sections have a question. However, you are encouraged to view each section. [http://www.globalsecurity.org/wmd/facility/paducah-facility.htm]

   a. The Central Control Center. In addition to the shift superintendent and his/her staff monitoring plant functions around the clock, what other center is based here?

      The Emergency Operations Center.

   b. The Process Buildings. The four enrichment process buildings are each supported by what?

      Each process building is supported by its own switchyard and cooling towers.

   c. The Product Withdrawal Facility. What happens to enriched UF_6 at the product withdrawal facility?

      Enriched UF_6 is removed from the process at the product withdrawal facility. It is cooled to convert the gas back to a liquid, and then drained into the cylinders. The liquid is allowed to cool and return to a solid form before it is transported.

   d. Cooling Towers. What is the purpose of the cooling towers, and how many gallons of water are lost each day through steam-off from the cooling towers?

      The cooling towers remove the heat generated through the enrichment process. Each tower loses up to 12 million gallons of water each day through steam-off from the cooling towers.

5. Access the Portsmouth electronic tour. The following questions are each related to a specific tour section that is noted at the beginning of each question. Note: Not all sections have a question. However, you are encouraged to view each section. [http://www.globalsecurity.org/wmd/facility/portsmouth_oh.htm]

   a. Delivery of Slightly Enriched Uranium. The Paducah Tiger rail cars deliver slightly enriched UF_6 from the Paducah Gaseous Diffusion Plant in Kentucky to which facility at the Portsmouth plant?

      Feed vaporization and sampling facility.

b. Production Feed Cylinder. What happens to production feed cylinders?

   Cylinders are weighed and selectively sampled for purity and adherence to specifications.

c. Process Cell. What are the components that make up process cells?

   Each cell has eight stages and consists of one converter, one motor, and one compressor.

d. Withdrawing Product. Product is withdrawn from the cascade in 10-ton USEC-owned cylinders. The product is then transferred into what size customer-owned cylinders?

   Product is transferred into 2.5-ton customer-owned cylinders.

e. Product Preparation Shipping Facility. Approximately how many customer cylinders are filled each year at the Portsmouth site?

   Approximately 1,800 customer cylinders are filled each year at Portsmouth.

f. Control Room Instrumentation. Which level (upper or bottom) instrumentation of the control room provides power operations monitoring and control of the switchyards?

   Bottom level

g. Control Room Instrumentation. Which level (upper or bottom) instrumentation of the control room provides monitoring and control instrumentation for portions of the process buildings?

   Upper level

MODULE 3.0: LASER ENRICHMENT METHODS (AVLIS AND MLIS)

Activity 1 - Principles of the AVLIS process

Instructions: Complete the following activity.

1. Natural uranium is composed of three isotopes:

   uranium-238, uranium-235 and uranium-234.

2. Of which characteristic does the AVLIS program take advantage?

   The AVLIS program takes advantage of the difference in the absorption spectrums of the two uranium atoms (uranium-235 and uranium-238).

3. Six general conditions must be met to use laser isotope separation. Fill in the missing word(s) for each condition.

   - The initial energy level configuration must allow the selective excitation of the desired isotope.
   - The absorption spectrum of the material must contain at least one well-defined shift in an absorption line attributable to isotopic effects.
   - The exciting laser light source must be precisely tunable to the wavelength of the shifted line (that is, atoms and molecules absorb light only at well-defined wavelengths; the wavelengths of the laser beam must coincide with the absorption wavelength), be stable at that wavelength, and have a line width that is narrow compared to the magnitude of the isotopic shift effect.
   - The laser must be sufficiently efficient and powerful to provide a reasonable yield without excessive energy demand.
   - The energy and/or charge exchange losses between the excited component and the rest of the system should be small.
   - The separation process should be sufficiently selective and capable of producing a good yield of the desired isotope.

4. Number the following basic steps as they occur in the AVLIS process.

   __5__ Excitation of vaporized metal

   __3__ Solid-state laser and dye laser generation

   __2__ Conversion of UF_4 to a uranium-iron alloy

   __4__ Uranium metal vaporization

   __7__ Conversion of metal product to UO_2

   __1__ Conversion of U_3O_8 into UF_4

   __6__ Collection of product and tails

5. A single dye can produce many shades of red and orange light so the wavelength must be "tuned" to the desired wavelength within the frequency band by using optical components.

3-1 Self-Check Questions

1. AVLIS is an enrichment process in which lasers are used to selectively ionize uranium-235 in a photochemical process to allow it to be separated from ____________________.

   a. uranium-234
   b. uranium-236
   * c. uranium-238
   d. uranium hexafluoride

2. Which uranium isotope is capable of sustaining fission?

   a. uranium-234
   * b. uranium-235
   c. uranium-236
   d. uranium-238

3. AVLIS is a quantum process based on ______________________ and offers the possibility of a higher degree of enrichment in a single step than do such processes as gaseous diffusion and the gas centrifuge, which depend on ______________________.

   a. large mass differences between the isotopes; differences in atomic or molecular structure
   b. differences in atomic or molecular structure; large mass differences between the isotopes
   c. small mass differences between the isotopes; differences in atomic or molecular structure
   * d. differences in atomic or molecular structure; small mass differences between the isotopes

4. In AVLIS, the dye laser is tuned to a frequency that will cause the uranium-235 to ionize but not other uranium isotopes; thus, not only is the enrichment of uranium-234 avoided, but its isotopic ratio is ____.

   a. lower in the feed material than in the product.
   b. higher in the product than in the feed material.

Answer Key

∗ c. lower in the product than in the feed material.
d. the same in the product and in the feed material.

5. In the AVLIS process, what is the range of product concentrations of uranium-235 obtained from natural uranium in a single pass through the separator device?

a. .1% to .3%
b. .3% to .5%
c. 1% to 3%
∗ d. 3% to 5%

6. Which of the following devices can produce large numbers of photons, all having almost precisely the same frequency?

∗ a. laser
b. cyclotron
c. separator
d. gas centrifuge

7. Which uranium enrichment process uses metallic uranium vapor as the feed material?

∗ a. AVLIS
b. gas centrifuge
c. thermal diffusion
d. gaseous diffusion

8. For isotopes of every element, what is defined by the colors of light absorbed by their atoms?

The unique spectroscopic "signatures" are defined by the colors of light absorbed by their atoms.

9. What does the pump laser do in the AVLIS process?

It converts electrical energy into light energy.

10. What does the process laser provide in the AVLIS process?

The process laser provides the specific frequency light needed to photoionize uranium-235 vapor in the ALVIS process.

11. The molten uranium is extremely ____________________, and elaborate systems are required to keep it from contacting the support structures and to prevent rapid dissipation of heat supplied to the uranium ingot.

    a. hot
    b. emollient
*   c. corrosive
    d. radioactive

12. The uranium atoms move undisturbed through the lower portion of the chamber and lose much of the excess energy they received during their evaporation .

13. What percentage of the evaporated atoms reach the photoionization zone?

    a. 40%
    b. 45%
*   c. 50%
    d. 60%

Activity 2 - Components of the AVLIS Process

Instructions: Complete the following activity.

1. What is contained in the separator system?

   The separator system contains a vaporizer and a collector.

2. List some of the components of the laser system.

   pump lasers
   dye lasers
   dye amplifiers
   beam propagation optics
   thyratrons/magnetic switches
   high-voltage energy storage capacitor

3. Which regulation addresses the export and import of nuclear equipment and material?

∗ a. 10 CFR Part 110
 b. 15 CFR Part 774
 c. 29 CFR Part 1910
 d. 47 CFR Part 1

3-2 Self-Check Questions

Complete the following questions.

1. What are the two major subsystems of the AVLIS process?

 Separator system
 Laser system

2. The uranium metal alloy feedstock is vaporized by an electron beam and bombarded by a laser beam to ionize the uranium-235 atoms and separate them from the uranium-238 in an electrostatic field. What is the outcome of the process?

 This process produces an enriched product stream and a depleted tails stream.

3. What drives the ionized uranium-235 to the product collector plates?

 An electromagnetic field drives the ionized uranium-235 to the product collector plates.

4. What happens to the uranium atoms that do not absorb the light from the laser beam?

 They remain nonionized and largely pass through the product collector system to the tailings collector.

5. What is the duration of each pulse of the laser?

 a. Less than one-hundredth of a second.
 b. Less than one-thousandth of a second.
∗ c. Less than one-millionth of a second.
 d. Less than a ten-millionth of a second.

Answer Key

6. An Illustrative list of laser-based enrichment plant equipment and components is provided in which of the following?

   a. Appendix C to Part 110
   b. Appendix D to Part 110
   c. Appendix E to Part 110
* d. Appendix F to Part 110

3-3 Self-Check Questions

Complete the following questions.

1. The U-AVLIS program in the United States began at what national laboratory?

   Lawrence Livermore National Laboratory began the U.S. U-AVLIS.

2. What act granted USEC exclusive commercial rights to deploy AVLIS?

   The Energy Policy Act of 1992 granted USEC exclusive commercial rights to deploy AVLIS.

3. Although conceptually simple, the actual implementation of the AVLIS process is likely to be difficult and expensive because of what requirement?

   The AVLIS process requires much sophisticated hardware constructed of specialized materials that must be capable of reliable operation for extended periods of time.

3-4 Self-Check Questions

Complete the following questions.

1. What is the basis for MLIS?

   Laser energy excites molecular bonds causing isotope-specific reactions or decomposition.

2. Why do MLIS processes often use cryogenic temperatures?

   Rotational and vibrational transition spectra are clearer transition spectra peaks and transition energies.

3. What uranium compound is often used in MLIS?

   UF_6

4. What is a typical U-235 reaction product or intermediate in MLIS?

   UF_5

5. Why is a carrier gas used?

   For temperature control and easier separation, a carrier gas is used.

6. What does a scavenger gas do?

   Prevents refluorination of the enriched UF_5.

3-5 Self-Check Questions

Complete the following questions.

1. Match the enrichment process (Column A) with the appropriate country (Column B).

Enrichment Process Column A		Country Column B	
___D___	U-AVLIS	A.	Australia
___C___	RIMLIS	B.	France
___A___	SILEX	C.	Japan
___B___	SILVA	D.	United States

2. What are some typical enrichment levels achieved overseas by LIS?

   Overseas developers of LIS have achieved assay levels ranging from power reactor LEU (3% to 5%) up to HEU (50% to 70%).

Activity 3 - Hazards of the AVLIS Process

Instructions: Complete the following activity.

1. What is the most serious potential health physics problem associated with the AVLIS process?

   The most serious potential health physics problem associated with the AVLIS process is inadvertent exposure to the extremely high x-ray fields generated within the vacuum vessel.

2. If AVLIS containment systems fail, what two processes produce hydrogen gas?

   The following two processes produce hydrogen gas:

   - Fire in the separator containment vessel where molten uranium reacts in air to form hydrogen gas.
   - Breach of the water cooling system in the presence of molten uranium generates an exothermic reaction that produces hydrogen gas.

3. Using the code provided, identify the hazard category for each hazard description.

   C = chemical and chemical reaction hazards
   P = physical/mechanical hazards
   R = radiological/criticality hazards
   F = fire and explosion hazards
   E = environmental and natural disasters

__F__ Solutions of organic dye and solvent, high flammability and explosion potential

__C, F__ Breach of separator containment vessel

__R__ Low-level alpha respiratory hazard

__P__ High-energy system on laser beam, electron beam

__C, F__ Propane/natural gas

__P__ Physically hot materials

__E__ Normal seismic hazards, tornado, or flood

__C, F_ Breach of sealed water cooling system for separation equipment

__R___ Low-level gamma emissions

__C, F_ Hydrogen gas (H_2)

__P___ Connecting/disconnecting sealed product and tails stream collection pots

__C___ Hydrofluoric acid - liquid and fumes

__P___ High voltage on electrical beam power supply 10-kV to 100-kV range

__P___ Heat stress, lifting with cranes/hoists

__F___ Explosion potential if breach in water cooling system inside separator

__C, F_ Diesel and gasoline

__P___ Laser electrical exciter 40-kV range high power

__C___ Alcohol

__R___ Continued maintenance to refurbish pods

__R___ Loss of borated water in the separator

3-6 Self-Check Questions

Complete the following questions.

1. What are the common characteristics of uranium hexafluoride (UF_6)?

   a. UF_6 is a very stable compound.
   b. UF_6 is an unstable but nonreactive compound.
   c. UF_6 is a highly corrosive but mordant compound.
   * d. UF_6 is a highly corrosive and reactive compound.

2. What are unique hazards of the AVLIS system?

   a. HF, UF_6
   b. lasers, UF_6
* c. lasers, x-rays
   d. x-rays, high-speed components

3. What protective clothing is worn by individuals handling UF_6 cylinders?

   a. Gloves only are needed.
   b. Respirators are mandatory.
   c. Protective clothing is unnecessary.
* d. Face masks and protective clothing are worn.

4. All interconnected process piping, valves, pumps, and compressors must be free from moisture, oils, and lubricants to prevent exothermic reaction. After being exposed to the atmosphere, what is used to purge them?

   a. dry ice
* b. dry nitrogen
   c. lime solutions
   d. compressed air

5. The most serious potential health physics problem associated with this process is inadvertent exposure to the extremely high ______________________ generated within the vacuum vessel.

   a. gamma rays
* b. x-ray fields
   c. concentration of nitric acid
   d. voltage on the electrical beam power supply

MODULE 4.0: GAS CENTRIFUGE

4-1 Self-Check Questions

Complete the following questions.

1. What is the feed material for the gas centrifuge enrichment process?

   Uranium hexafluoride (UF_6) is the feed material for the gas centrifuge enrichment process.

2. The centrifuge separation process uses the principle of centrifugal force to create what?

   The centrifuge separation process uses the principle of centrifugal force to create a density gradient in gaseous uranium hexafluoride (UF_6) that contains components of different molecular weights.

3. What happens to U-235 and U-238 atoms in the centrifuge process?

   UF_6 molecules with the heavier U-238 atoms tend to move toward the outer wall of the cylinder and the UF_6 molecules with the lighter U-235 atoms move toward the axis, thus partially separating the uranium isotopes.

4. What increases separation?

   Separation is increased by a relatively slow axial countercurrent flow of gas within the centrifuge that concentrates enriched gas at one end and depleted gas at the other.

5. What are the major components of a gas centrifuge?

   The major components of a gas centrifuge include center post, scoops, rotor, baffle, end caps, molecular pump (optional), top and bottom suspension systems, electric motor, and casing.

6. How and through what component is the feed stream introduced into the rotor?

   The feed stream is introduced at a constant rate into the rotor through the center post.

7. Why and how can multiple rotors be joined together?

   Multiple rotors can be joined together by bellows to extend the length of the centrifuge.

8. How is a rotor driven?

   A rotor is driven by an electric motor.

9. What is the purpose of a baffle?

   A baffle allows the gas to leak from the main rotor cavity into the area near the scoop. It is needed at one end to keep the scoop from imposing a vertical flow that would counteract the circulatory flow generated by the scoop at the other end.

10. How are end caps used?

    End caps are used to close the rotor at the top and bottom so that the UF_6 cannot escape from the rotor.

11. Why is an optional molecular pump used?

    A molecular pump may be used to maintain a low pressure between the rotor and the casing.

12. What are the three functions of the top and bottom suspension systems?

    Top and bottom suspension systems serve the following functions: (1) reliably support the rotor at full speed, (2) control the rotor at startup and run-down speeds, and (3) allow the rotor to rotate about its center of mass.

13. What is the purpose of the casing?

    The casing provides a vacuum-tight enclosure for the rotor to minimize the drag on the rotating parts and thus reduce power consumption resulting from gas friction when the rotor is spinning. It also provides a physical barrier for protection from flying debris in the event of a machine failure.

14. What factors influence the separative capacity of a gas centrifuge?

    The separative capacity of a gas centrifuge is greatly influenced by its rotational speed and the length of the rotor.

15. What is limited by the strength-to-density ratio of the rotor construction materials?

    The peripheral speed of the rotor is limited by the strength-to-density ratio of the rotor construction materials.

16. What are some major factors that affect the rotor dynamics?

    Major factors affecting the rotor dynamics include the straightness of the rotor, the uniformity of the wall, and the damping characteristics of the bottom bearing system.

17. What concern exists with centrifuges that have a large length-to-diameter ratio?

    A concern with centrifuges that have a large length-to-diameter ratio is the problem of bringing them to operating speed.

18. One of the key components of a gas centrifuge enrichment plant is the power supply (frequency converter) for the gas centrifuge machines. How should the power supply operate?

    The power supply must operate at high efficiency, provide low harmonic distortion, and provide precise control of the output frequency.

19. List two differences between a gas centrifuge facility and a gaseous diffusion facility.

    Possible answers for differences between a gas centrifuge facility and a gaseous diffusion facility may include any of the following:

    - Enrichment process theories show that a higher degree of U-235 enrichment can be obtained from a single unit gas centrifuge than from a single unit gaseous diffusion barrier.
    - The separation factor available from a single centrifuge is about 1 to 2 as compared to 0.004 for a gaseous diffusion stage. However, the throughput rate of UF_6 that can be processed by a single centrifuge is very small compared to a gaseous diffusion stage.
    - Although they differ in the type and function of the enrichment equipment used to process the UF_6, gas centrifuge and gaseous diffusion enrichment plants use essentially the same process, equipment, and safety systems for UF_6 feed and withdrawal of product and tails.
    - The electrical consumption of a gas centrifuge facility is much less than that of a gaseous diffusion plant. Consequently, a centrifuge plant will not have the easily identified electrical and cooling systems typically required by a gaseous diffusion plant.

4-2 Self-Check Questions

Complete the following questions.

1. What usually happens to UF_6 feed cylinders upon receipt at the enrichment plant?

    Upon receipt at the enrichment plant, UF_6 feed cylinders may be weighed, inspected, and liquid sampled (optional) to establish nuclear materials accountability values (via destructive analysis) and to verify specifications by the enricher and customer. The cylinders are then placed in a storage area. When it is time for the contents of a full feed cylinder to be fed into the process, the cylinder is moved from the storage area to the feed area.

2. What is cold purification?

   Cold purification involves venting the cylinder while the UF_6 is solid at ambient temperature. During cold purification, the feed autoclave door is left open to automatically disable the feed autoclave heater and prevent inadvertent heating of the cylinder. The vented light gases pass through a desublimer and chemical traps to remove uranium and HF before being released to a gaseous effluent vent system. This provides assurance of contaminant control by filtering the vent gases through cold feed high efficiency particulate air filters and activated carbon filters before releasing the gas to the atmosphere. This purification process is repeated until the desired purity is achieved.

3. What is hot purification?

   Hot purification involves heating the UF_6 cylinder until the contents are liquefied. The UF_6 is liquefied by heating the exterior of the feed cylinder with hot air within the autoclave. The air temperature is controlled to maintain specific pressure as the UF_6 is liquefied. The cylinder is again vented to the desublimer to remove light gas contaminants that may have been trapped in the solid UF_6. Typically, only one hot purification cycle is performed for each cylinder. Once the desired purity is reached, the feed cylinder vent valve is closed and the cylinder is maintained in a standby mode with the UF_6 still in the liquid state.

4. What happens to the feed cylinder when it is almost empty?

   When the feed cylinder is almost empty, it is isolated from the feed header. The cylinder is then vented to the purification desublimer to evacuate residual UF_6 (cylinder heel). After removal of the residual UF_6, the cylinder is allowed to cool.

5. What happens when the desublimer reaches its UF_6 operational fill limit?

   When the desublimer reaches its UF_6 operational fill limit, it is heated by Freon supplied by a hot refrigerant system to sublime the trapped UF_6 for gaseous transfer and collection in a feed purification cylinder. The gaseous UF_6 recovered is desublimed by spraying the cylinder with cooled water at 4 °C (39 °F). Cooling water is supplied by a spray cooling water system.

6. After feed purification, how is gaseous UF_6 transferred from the feed cylinder to the cascade?

   After feed purification, a valve in the line from the cylinder to the cascade is opened and gaseous UF_6 flows from the cylinder to the cascade. This is accomplished as the gaseous UF_6 passes through piping to a pressure-reduction station and is drawn through pipes leading to the cascade system. The pressure-reduction station and the piping leading to it are heated to prevent the gaseous UF_6 from cooling and solidifying in the pipes and valves. Heating is not required downstream from this station because the UF_6 is at low pressures and remains gaseous at ambient temperatures.

7. Why are centrifuges connected in series?

   Centrifuges are connected in series to achieve the concentration range desired for the plant.

8. Why are centrifuges connected in parallel to form stages?

   Centrifuges are connected in parallel groups called stages to provide the desired material flow rate.

9. What are the stages between the points where the feed is introduced and the product is withdrawn called?

   The stages between the points where the feed is introduced and the product is withdrawn are called the "enriching stages," or more simply, the "enricher."

10. What are "stripping stages" or the "stripper"?

    The stages between the points where the feed is introduced and the depleted stream is withdrawn are called the "stripping stages" or the "stripper."

11. The number of stages that are connected in series to form a cascade depends on what?

    The number of stages that are connected in series to form a cascade depends on the desired U-235 concentration of the feed, product, and tails streams and on the magnitude of the stage separation factor.

12. What is the advantage of blending streams with identical isotopic concentration?

    Blending streams of identical isotopic concentration minimizes separative work losses.

Answer Key

13. Why are the material flow rates different for each stage?

    The material flow rates (and the number of centrifuges connected in parallel) are different for each stage to ensure that the streams between stages match concentrations.

14. What is the material feed rate to a specific stage dependent on?

    The material feed rate to a specific stage is dependent on the separation factor, the isotopic concentrations of the streams, and the flow rates of the exiting streams.

15. Which stage has the largest material flow rate and has the greatest number of centrifuges connected in parallel?

    The feed stage to the cascade has the largest material flow rate and, therefore, has the greatest number of centrifuges connected in parallel.

16. Are the centrifuges located at the product end of the cascade physically different from those at the tails end?

    No, they are not different. All individual centrifuges in a cascade are physically identical. From visual observation, one cannot distinguish the isotopic concentrations or flow rate of the process gas contained within a centrifuge, stage, or cascade.

17. What are the advantages of using multiple small cascades connected in parallel?

    The advantages of multiple parallel cascades are easier maintenance (e.g., a single cascade can be taken off-stream for repairs) and production flexibility (e.g., a variety of product enrichments can be produced).

18. What happens after the enriched and depleted streams leave the cascades?

    After the enriched and depleted streams leave the cascades, they are collected in desublimers where the gas solidifies. When full, the desublimers are heated and the UF_6 is transferred, either as a gas or liquid (depending on the system), to empty cylinders where it solidifies. At some facilities, a compressor system may be used instead of desublimers to collect the product and/or tails material.

19. What typically happens to filled tails cylinders?

    Tails cylinders containing the depleted material are weighed and then moved to an on-site storage yard for long-term storage.

20. What typically happens to filled product cylinders?

The product cylinders containing the enriched material are weighed, liquid sampled, possibly blended or rebatched, and then transferred to a storage area to await shipment off-site.

21. What is a secondary function of the product and tails removal systems?

A secondary function of the product and tails removal systems is to provide a rapid means of evacuation of UF_6 from the centrifuge cascades to avoid damages to the centrifuges produced from abnormal operating conditions, such as high or low temperature, high pressure, or loss of drive to the centrifuges.

22. What is a contingency dump system composed of, and how does it work?

Dumping of a cascade to the product or tails removal system is effected through bypassing of the cascade terminal control valve, which allows elevated flow rates of UF_6 to the product or tails cylinders. In the event of loss of electrical power or instrument calibration, dumping of the cascades to the product or tails removal system is not possible. In this case, the contents of the cascades may be dumped to a contingency dump system. The contingency dump system comprises multiple trains of NaF absorber beds, surge vessels, and vacuum pumps. One train of contingency dump equipment is provided for each cascade. When the cascade gas is vented through this system, UF_6 is bound to the NaF absorber, and the remaining light gases are released to a gaseous effluent vent system.

23. When are evacuation and sampling ports used?

Sampling ports are used to remove process samples from the cascade while it is operating. Evacuation and sampling ports are used to evacuate the process system before operation begins, to remove process samples from the cascade while it is operating, and to remove process gas before maintenance activities.

24. When is the recycle mode of operation generally used?

The recycle mode of operation is generally used to permit a cascade to reach the design product and tails concentrations (e.g., initial startup or restart following maintenance) before the cascade output is introduced to the process system and when the cascade is in standby mode.

25. Why is fill weight controlled on product cylinders?

    The fill weight is controlled to prevent cylinder rupture during product sampling when the cylinder is heated, causing the solid UF_6 to expand during transformation to the liquid state.

26. What standard analyses are performed on samples?

    Standard analyses performed on a sample include (1) the determination of the uranium concentration by the gravimetric method, (2) the determination of the isotopic abundances and U-235 content by gas-phase mass spectrometry, and (3) the determination of impurity content by a variety of techniques.

27. Where in the gas centrifuge process might samples be required for analyses?

    Samples that may require analyses include UF_6 samples from feed, product, and tails cylinders; process gas samples from the cascades; and other uranium-bearing samples from scrap materials.

28. How can product blending be achieved?

    Blending is achieved by melting and vaporizing the UF_6 in two donor autoclaves, and then transferring the desired amount from each donor cylinder to air-cooled receiver cylinders. Flow control is used to achieve the desired mixture. Unblended heels are collected in a heels cylinder.

29. How are product cylinders stored?

    Product cylinders are stored resting on chocks. Cylinders are not stacked, and adequate clearance should be provided for mobile carrier access.

30. What are some typical waste materials at a gas centrifuge facility?

    Typical materials include contaminated burnable and nonburnable wastes; alumina and/or sodium fluoride from chemical traps; decontamination solutions, other solutions, oils, and sludge from the decontamination and maintenance areas; and samples and analytical wastes from an analytical laboratory.

31. How often should sampling of sewage sludge for possible uranium accumulation be done?

    Sampling of sewage sludge for possible uranium accumulation should be done on a semiannual basis.

Activity 1 - Gas Centrifuge World Wide Web Sites

Instructions: Access the Internet. Search the World Wide Web by keying in one of the following addresses:

http://www.urenco.com (URENCO - check out the locations and associated facility pictures)

http://www.jnfl.co.jp (Japan Nuclear Fuel Limited)

∗ This is an optional activity and is not required for module completion.

1. On the URENCO Web site, go to the About URENCO section. Complete the following statement.

   With its industry-leading centrifuge technology and around <u>27%</u> global market share, URENCO is firmly positioned in the <u>enrichment stage</u>.

2. On the Japan Nuclear Fuel Limited Web site, choose "English Here" on the top right of the page. From the About Us section, list the first two Main Activities and Services.

   a. Uranium enrichment

   b. Reprocessing of spent nuclear fuel

4-3 Self-Check Questions

Complete the following questions.

1. Is there a gas centrifuge enrichment facility operating in the United States?

   Domestically, only one commercial GC is operational; the LES's NEF facility in New Mexico.

2. What countries presently have gas centrifuges in operation?

   The United Kingdom, the Netherlands, Germany, Japan, Russia, and China have gas centrifuges in operation.

3. How are the centrifuge cascades at the Almelo plant in the Netherlands mounted?

   The centrifuge cascades at the Almelo plant are individually mounted machines (i.e., machines with a single rotor in each vacuum casing). Each machine requires three small process lines: one each for the feed, product, and waste. These lines connect to the three main piping headers (for feed, product, and tails) running the length of the cascade.

4. What type of centrifuge cascade design is used in Gronau, Germany?

   The centrifuge cascades at Gronau, Germany, are an example of block-mounted design (i.e., centrifuges composed of a number of rotors mounted in a common vacuum housing). Gronau also has a large number of the newer, higher capacity, individually mounted centrifuges.

4-4 Self-Check Questions

Complete the following questions.

Fill in the missing words in each statement. Choose from the following words:

autoclaves	empty	liquefied	pH
Bremsstrahlung	enrichment	manifold	piping
cleaning	excesses	mass control	procedures
compounds	F_2	material	public
controlled	5 wt%	mechanical	radioisotopes
critical	geometry equipment	mobile	rotor
criticality	hydrofluoric acid	moderation control	seal
decontaminate	inhalation	moderators	solvents
density	kidney	nitrogen	uranium hexafluoride

1. The primary hazard at a gas centrifuge facility is uranium hexafluoride.

2. A secondary potential hazard is stored quantities of chlorinated compounds, primarily refrigerants.

3. The largest impact could occur following a catastrophic failure of a hot cylinder containing liquefied UF_6.

4. A gas centrifuge unit operating at high speeds could generate flying pieces of equipment and material as a result of the destruction of the rotor and other spinning components.

5. Nitrogen is used for purging, blanketing, and drying vessels and lines to make sure that uranium does not react with trapped moisture in the system and deposit on surfaces.

6. Sodium hydroxide (NaOH) is used to adjust the pH of wastewater from decontamination facilities.

7. Citric acid ($C_6H_8O_7$) is used to decontaminate equipment.

8. Chlorofluorocarbons (CFCs) are used to cool water and air and to improve the enrichment process efficiency. They are also used as solvents for degreasing equipment.

9. The gaseous chemical effluent of major concern is hydrofluoric acid produced by the hydrolysis of UF_6.

10. The predominant radioactive material used at a gas centrifuge site will be natural, low-enriched, and depleted uranium primarily in the form of uranium hexafluoride.

11. A primary concern for gas centrifuge operations is incidental or accidental inhalation of uranium, which can cause nonstochastic chemical damage to the kidney (nephrotoxicity) if intakes exceed a threshold within a specified period of time.

12. Significant releases of UF_6 in work areas are unlikely because the entire centrifuge system, with the exception of the autoclaves, is operated in a partial vacuum so that leaks are into the system, not into the work areas.

13. Most of the radioisotopes that could be encountered emit alpha and beta particles, which are nonpenetrating forms of radiation that would be shielded from workers by UF_6 storage cylinders and primary containment systems (i.e., process lines).

14. Because of the high density of UF_6 when stored as a solid, the material would also provide considerable self-attenuation of x-rays and gamma rays from the uranium series nuclides present.

15. A significant portion of the direct radiation encountered would be in the form of Bremsstrahlung radiation, which would be generated by the interaction of beta radiation with high atomic number atoms, such as uranium in UF_6 and, to a lesser extent, iron in UF_6 cylinders.

16. Abnormal operations that could affect nuclear criticality safety include the presence of moderating material in an empty product cylinder, and the production of enrichments above 5 wt % U-235.

17. Product cylinders containing UF_6 enriched to 5.020 wt % U-235 are critically safe if moderators are limited and controlled.

18. If a filled cylinder at ambient temperature were punctured, enough water could enter the cylinder and moderate enough enriched uranium to form a critical mass.

19. Loss of containment of the UF_6 gas does not provide a significant criticality hazard or risk because the density of the gas below atmospheric pressure is very low and only a few grams of uranium are in any centrifuge.

20. The use of moderators such as water and hydrocarbon oils in the UF_6 process areas must be controlled.

21. A general approach to nuclear criticality safety is to prevent enrichment excesses; use favorable geometry equipment when practicable; provide moderation control within the UF_6 enrichment process; and use strict mass control on solutions.

22. Fire and explosion hazards may include the presence of flammable cleaning solutions, HF and F_2 presence in the feed process, and potential explosive reactions during mechanical failures.

23. Enrichment plants are designed to protect equipment, the workforce, and the public in the cases of weather and seismic events.

24. Past incidents indicate that leaks from disconnecting piping and from pump seal failures are the most frequent events that lead to UF_6 releases.

25. Line disconnection losses have occurred with mobile pump set equipment, with pump maintenance, and with sampling manifold handling.

26. Responses to the in-plant leaks have included revision of operating procedures and training of workers.

Complete the following questions.

27. What happens during a centrifuge containment failure?

    In a centrifuge failure, the following occurs:

    - Rotational energy is converted to heat.
    - The rotor disintegrates.
    - A quantity of gas generated in the disintegration process subsequently reacts with UF_6.
    - A pressure pulse occurring during the crash closes isolation valves and separates the failed centrifuge from the balance of the cascade.
    - Solid reaction products accumulate in the bottom of the failed centrifuge, and over a period of weeks, the reaction gases leak into the cascade header and are removed through the gaseous effluent vent system.

28. List three contributing factors that may cause a UF_6 cylinder failure.

    Possible answers:

    - Introduction of reactive hydrocarbons into a cylinder.
    - Impact of a liquid-filled cylinder against or from an object.
    - Valve or pigtail failure due to movement of a connected cylinder containing UF_6.
    - Hydraulic rupture of a cylinder exposed to fire.
    - Hydraulic rupture of an overheated cylinder.
    - Hydraulic rupture of an overfilled cylinder.
    - Heating or filling a defective cylinder.
    - Heating a cylinder containing excessive volatile and/or gaseous contaminants.
    - Dropping a liquid-filled cylinder.

29. List three contributing factors that may cause a UF_6 process system failure.

    Possible answers:

    - Excessive heating of process equipment containing solidified UF_6.
    - Fatigue failure of a process system.
    - Impact of an object on a process system containing UF_6.
    - Valve failure of a cylinder or a system containing UF_6.
    - Pigtail failure.

- ◙ Process system loss of containment caused by natural phenomena.
- ◙ Heating a cold trap containing excessive volatile and/or gaseous contaminants.
- ◙ Heating an overfilled cold trap.
- ◙ Overheating a cold trap.
- ◙ Cold trap failure caused by corrosion, fatigue, or thermal shock.
- ◙ Venting of UF_6 through a hydrolyzer.

30. Have leaks occurred when a take-up cylinder is connected to the transfer piping using flexible pipe?

    Yes, leaks have been experienced.

4-5 Self-Check Questions

1. What are the three commercial GC facilities that have undergone licensing reviews at the NRC, and who are the licensees?

    LES-1/CEC, LES-2/NEF, ACP, and USEC

2. Where are the proposed facilities located?

    - ◙ LES-1/Homer, Louisiana
    - ◙ LES-2/Hobbs, New Mexico (moved from Hartsville, Tennessee)
    - ◙ ACP/Portsmouth (Piketon), Ohio

3. Describe DU disposition plans.

    The enrichment facilities generate considerable quantities of DU. The NRC requires disposition of the DU. LES-1 was required to have a sinking fund for DU disposition, most likely as a waste. LES-2 will maintain a DU fund for disposition either via private deconvertor and disposal companies or pay DOE for acceptance of the DU. USEC will maintain a DU fund and disposition via DOE, with an option for private disposition.

4. What is the current status of these facilities?

    LES-1 – Final Safety Evaluation Report (FSER) and Final Environmental Impact Statement (FEIS) found no undue safety risks from the proposed facility. The application was withdrawn after concerns about the nonsafety focus of the Commission/ASLB reviews.

    LES-2 - The license was issued with conditions. Construction has commenced.

ACP - The license was issued with conditions. Preliminary construction has commenced.

5. What was used as the basis for the GC facility license reviews?

The NRC staff used NUREG-1520, the SRP for fuel cycle facilities.

6. What were some of the issues surrounding LES-1?

Criticality, liquid UF_6, DU management, and Natural Phenomena Hazards (NPH) were the principal safety issues. Controls were identified to address these. The Commission and ASLB reviews focused on DU and environmental justice primarily, and on need, contracts, and financing as other issues.

7. Discuss the conditions on the LES-2 license.

The conditions relate to the design of the digital I&C system, which will require further review during construction and before startup.

8. Discuss the conditions on the ACP license.

There are several conditions related to financing and criticality safety (e.g., not to exceed 5% assay), and additional reviews needed before startup.

9. What are the planned assay limits for these facilities?

LES-1 planned to produce circa 3.5% assay, but was designed to accommodate up to 5% assay.

LES-2 plans to produce up to 5% assay and is licensed for 5% assay, but is designed to accommodate 6% assay. Some modifications would be needed to go up to 10% assay.

ACP plans to produce 5% assay initially and is licensed for 5%, but is designed for 10% assay. NRC approval is needed to exceed 5% assay.

10. What are some of the issues with exceeding 5% assay?

The standard 30B cylinder and its transportation package are not licensed for above 5% assay. The existing fuel fabrication plants are not licensed for above 5% assay. Criticality can occur without a moderator above approximately 7% assay; moderator exclusion can no longer be used as a control above this.

11. What are the projected routine doses associated with these facilities?

    A maximum of a few tens of millirems.

12. What are the main hazards?

    liquid UF_6 handling, Natural Phenomena Hazards (NPH), and criticality

13. Would liquid UF_6 be present in these facilities, and would it contribute to hazards and risks?

    LES-1; yes, several 48Y liquid UF_6 cylinders could be present in the feed autoclaves and sampling operations.

    LES-2; yes, but in small quantities—liquid UF_6 would be present only during the sampling of product (30B) cylinders that would not be moved outside of the autoclave until the contents had solidified. Subliming/desubliming would be used for all feed and removal operations.

    ACP; yes, but in moderate quantities—liquid UF_6 would be present in product cylinder (30B cylinders) sampling, and for transfer and blending operations (48X and 30B cylinders).

MODULE 5.0: ELECTROMAGNETIC SEPARATION (CALUTRON) AND THERMAL DIFFUSION

5-1 Self-Check Questions

Complete the following questions.

1. Describe the principle of the electromagnetic separation (calutron) uranium enrichment process.

   Basically, electromagnetic separation methods use magnetic and electronic forces to manipulate charged isotopic species.

   - Uranium tetrachloride (UCl_4), a uranium chloride salt, is electrically heated to produce UCl_4 vapor in an evacuated tank and ionized to give each molecule an electrical charge.
   - These ions (uranium metal and chlorides) are passed through electrically charged slits to create a beam of charged particles that is passed through a very strong magnetic field.

- The magnetic field introduces a force on each ion, causing it to travel in a circular path, the radius of which is proportional to the momentum of the ion.
- The heavy U-238 metal ions have a greater momentum than the U-235 metal ions, and their beam is bent less than the lighter ions.
- With this very strong magnetic field, beam separation is sufficient to permit individual collectors to be located to accumulate the light and heavy isotopes.

2. What are the advantages of calutrons?

   They can separate almost any stable isotope, separate different isotopes simultaneously, and they may be used to ionize and separate compounds.

3. Which responds more readily to a magnetic field, light or heavy ions?

   Lighter ions respond slightly more readily to a magnetic field than the heavier ions.

4. What were some of the technical problems associated with the electromagnetic process?

   The beams, though small, could melt the collectors during long hours of operation; the staff, therefore, installed water cooling for the collectors and tank liner.

   They contrived electric arcs to ionize the uranium chloride feed.

   They devised ways to extract the enriched uranium that collected at the receiver, and the still valuable feed material that condensed along with chloride "gunk" (to use their technical term) all over the inside of the tank.

   They made scrapers to clean the exit slits of the feed sources regularly lest the accumulated "crud" (another word of art) cut down beam strength.

5-2 Self-Check Questions

Complete the following questions.

1. How were the calutrons physically arranged at the Oak Ridge Y-12 plant?

   The calutrons were arranged in continuous oval or rectangular arrays called race tracks or simply, tracks. In these arrangements, separator tanks alternated with electromagnetic units.

2. What were some of the major problems encountered in the Y-12 calutron project?

   The major problems encountered in the Y-12 calutron project were the severe limitations on ion beam strength created by space charge effects, and the inability to convert more than a small fraction of the feed material into product in a single run. Also, sources had to be redesigned, and there were difficulties in recovering BETA feed that was strewn throughout the calutron. Process efficiencies stayed low; only 4% or 5% of the U-235 in the feed ended up in the output.

5-3 Self-Check Questions

Complete the following questions.

1. When did the United States produce the first kilogram of highly enriched uranium via the Y-12 calutrons?

   In 1944, Y-12 calutrons produce the first kilogram of highly enriched uranium in the U.S.

2. What Tennessee facility supplemented the efforts of the United States calutron process?

   The thermal diffusion plant at the K-25 site supplemented the calutron process; this plant was designated the S-50 plant.

3. Why were the Y-12 calutrons shut down in 1946?

   Because of the lower cost of the gaseous diffusion process, the Y-12 calutrons were shut down in 1946 after all sections of K-25 were operational.

4. For uranium enrichment, the production rate of the calutron process was proportional to what?

   For uranium enrichment, the production rate of the calutron process was proportional to the feed assay of the ALPHA stage. Thus, if the ALPHA stage assay was increased from the natural assay of 0.711% U-235 to 3% U-235, then the production rate was approximately quadrupled.

5. What happened to the Y-12 calutrons after their shutdown in 1946?

   In the fall of 1959, Oak Ridge National Laboratory took over operation of the calutrons at Y-12 in Building 9204-3 for its stable isotope production program. ORNL produced thallium-203 until 1991 when its customers turned to Russia because it was selling the isotope for 10% to 20% less.

   In 1994 a contract was signed between the Department of Energy and Trace Sciences International of Ontario, Canada, to buy stable isotopes in large quantities. Eight units of the calutrons were initially restarted when operations resumed on January 3, 1995. Over the years it has operated 30 calutrons for 4 million hours, producing a total of 250 kilograms (550 pounds) of material enriched in 232 different stable isotopes.

   The Y-12 calutrons were once again shut down in 1998 because of declining sales.

6. How were calutron devices used in Iraq?

   Iraq used the calutron technology for development of its nuclear weapons program.

5-4 Self-Check Questions

1. What are some of the disadvantages of the electromagnetic process?

   Following are some of the disadvantages:

   - Calutron enrichment is a batch process, which limits its output and requires considerable maintenance.
   - The collectors must be removed regularly so that the enriched uranium product can be scraped out of them.
   - The calutron tanks and other equipment must be periodically washed and cleaned to recover accumulated uranium from their surfaces.
   - Uranium chloride salt oxidizes readily when exposed to air, which creates chemical processing problems in the calutron feed and product material.

2. What chemical hazard was of concern for the electromagnetic process?

   Uranium chloride salt oxidizes readily when exposed to air, which creates chemical processing problems in the calutron feed and product material.

3. List at least two physical/mechanical hazards for the electromagnetic process.

   Physical/mechanical hazards include:

   - Magnetic field energy sources.
   - Normal industrial hazards due to moving heavy components.
   - High-voltage, high power sources.

4. What radiological or criticality hazards were associated with the electromagnetic process?

   Radiological/criticality hazards include:

   - Possible ingestion of alpha particles.
   - Very low criticality probability due to favorable geometry containment; criticality concerns related particularly to BETA tracks.

5. Name at least five mechanical incidents that occurred in the electromagnetic process.

   Mechanical incidents include:

   - Vacuum tanks leaked or loose vacuum tanks moved out of line.
   - Welds in magnets gave way and spilled oil on the operating floor.
   - Rectifier tubes and other electrical equipment failed.
   - Magnet coils had shorts caused by millscale, rust, and other sediment in the cooling oil.
   - Chemical equipment broke down.
   - Receivers and insulators were damaged.
   - Accelerating slits were clogged.
   - Vacuum spoiled by a dead mouse.
   - Chemical tank were corroded.

5-5 Self-Check Questions

Complete the following questions.

1. Briefly explain how enrichment of uranium hexafluoride can be obtained through the thermal diffusion process.

   A temperature difference is created across an annular region between two long, vertical cylindrical pipes. The inner pipe carries high-temperature steam, while the outer is cooled by circulating water. Uranium hexafluoride is kept in liquid form under high pressure in the region between the pipes, and in a very slow process, the lighter isotope tends to move towards the hot inner wall and then rise to the top of the tube. The thermal gradient causes the light UF_6 stream containing more U-235 to diffuse towards the hot wall (inner pipe) and move upward by convection. The heavy UF_6 stream containing more U-238 tends to diffuse towards the cold wall (outer water jacket) and move downward by convection. The heavier isotope diffuses outward and is collected at the bottom.

2. What affects the degree of separation in thermal diffusion?

   The degree of separation obtained depends in part on the magnitude of the temperature gradient across the fluid mixture.

3. Between gas-phase mixtures and liquid phase mixtures, which one usually has more thermal stability?

   Gas-phase mixtures usually have more thermal stability than liquid mixtures.

4. What device did Clusius and Dickel invent to make thermal diffusion for the separation of isotopes possible?

   A device called a "thermogravitational column."

5-6 Self-Check Questions

Complete the following questions.

1. What were some of the problems incurred in the building of thermal diffusion facilities in the 1940s?

   Some of the problems that were incurred in the building of thermal diffusion facilities were
   - obtaining sufficient steam pressure, and
   - procuring columns that met specifications.

2. When using two 48-foot columns, how many kilograms of hexafluoride per day were processed?

   About two grams of hexafluoride were produced per day.

3. True or False. Early plants had no moving parts and no valves in the hexafluoride system.

   True. The process liquid moved by natural convection.

4. Why was the S-50 thermal diffusion plant built in Oak Ridge, Tennessee?

   The S-50 plant was constructed to provide low-enriched feed (0.86% to 0.89% U-235) for the Y-12 electromagnetic spectrometers (calutrons).

5-7 Self-Check Questions

Complete the following questions.

1. Why is thermal diffusion no longer used as a uranium enrichment process?

   The main reasons are the long plant equilibrium time if liquid UF_6 is used as the process fluid, and the extremely low thermodynamic efficiency of the process.

2. What enrichment amount did the S-50 plant in Oak Ridge produce, and how was it used?

   During its operation, the S-50 plant enriched normal assay UF_6 to about 0.85 weight percent uranium-235. The resulting product was used as feed for the electromagnetic separators at the Y-12 plant.

3. How has gas-phase thermal diffusion been used in the past?

   Isotope separation using gas-phase thermal diffusion has been widely practiced in the United States and abroad. U.S. applications have included separation of both stable and radioactive isotopes. These applications were uniformly restricted to very low production amounts (gram per day amounts).

5-8 Self-Check Questions

Complete the following questions.

1. What happens to UF_6 in the presence of moisture?

   In the presence of moisture, UF_6 is immediately hydrolyzed, forming the solid uranium oxyfluoride (UO_2F_2) and hydrogen fluoride (HF).

2. What problems can UO_2F_2 and HF cause in the UF_6 process system?

   Hydrogen fluoride gas is very toxic. UO_2F_2 is less dense than UF_6 and hence occupies more space than the UF_6 that produced it. If this reaction occurs in a confined space, process equipment can rupture hydrostatically. This problem is particularly acute when the UF_6 is present in solid form, which is essentially incompressible. Water cooling of process equipment must therefore be carefully engineered to ensure isolation of the cooling water from the UF_6 process fluid.

3. What is a main mechanical/physical hazard related to the thermal diffusion process?

   Mechanical/physical hazards for the thermal diffusion process mainly relate to the use of steam.

MODULE 6.0 REGULATIONS APPLICABLE TO ENRICHMENT FACILITIES

6-1 Self-Check Questions

1. The NRC is the principal regulator of commercial activities involving radioactive materials. List the two overall objectives.

   a. Protect the health and safety of the public and workers, and protect the environment, from radiological and certain chemical hazards.

   b. Safeguard nuclear facilities and materials from loss, theft, or diversion.

2. NRC regulates the following areas of chemical safety:

   a. Hazardous chemical effects from licensed radioactive materials; an example is the chemical effects of UF_6. This is codified in 10 CFR Parts 70.61, 70.62, and 70.64. There is no radiological dose requirement; the effect may be entirely from the chemical hazard.

   b. Hazardous chemicals and their effects, produced from licensed radioactive materials; examples are hydrogen fluoride released by the UF_6 reactions or NOx released from nitric acid reacting with UO_2 or uranium metal. This is codified in 10 CFR Parts 70.61, 70.62, and 70.64. There is no radiological dose requirement; the effect may be entirely from the chemical hazard.

   c. Hazardous chemicals and their effects that affect the safe handling of licensed radioactive materials; examples are nitric acid fumes corroding or adversely impacting the operation of safety equipment (or electronics), inerting gases depressing operator reaction times (or even operator asphyxiation), or hazardous gases incapacitating or hindering operator egress from radiological areas. In general, there is some increase in radiation risk or dose although the principal hazard is chemical in origin. This is codified in 10 CFR Parts 70.62 and 70.64 regulations, and while the guidance is nonspecific, the increase in radiation risk is usually associated with very small doses of “mrem.”

6-2 Self-Check Questions

1. The NRC oversees two gaseous diffusion plants. List the two plants.

   a. The Honeywell facility located at Paducah, Kentucky
   b. The Portsmouth plant located in Piketon, Ohio

2. 10 CFR Part 76, Subpart – Safety, describes the <u>use and transfer</u> of radioactive materials, sets the scope of <u>accident</u> assessment, technical safety requirements, <u>criticality accident</u> requirements, emergency planning, quality assurance, and <u>training</u>.

3. 10 CFR 76.68 covers plant changes and requires <u>safety</u> analysis to show there is no <u>undue</u> risk or <u>decrease</u> in safety, safeguards, or security.

Answer Key

Activity 1 - Event Report

Purpose: To identify the general event reporting requirements for gaseous diffusion plants.

Instructions: Access 10 CFR 76 - Certification of Gaseous Diffusion Plants in the Appendix. Match the correct event reporting category in column A to each event listed in column B by placing the proper letter in each blank.

Column A

A. Immediate report (within 1 hour after discovery)

B. Four-hour report

C. Twenty-four-hour report

Column B

1. __C__ An unplanned contamination event that involves a quantity of material greater than five times the lowest annual limit on uptake

2. __C__ An explosion of a 2S sample container containing 3.5% U-235

3. __A__ A criticality event

4. __B__ A radiological release in a building that prevents immediate protective actions necessary to avoid exposures that could exceed regulatory limits

5. __A__ A site area emergency

6. __C__ A worker injury that requires unplanned medical treatment where the worker is found to have skin contamination

7. __C__ A criticality alarm system detector is found to be inoperable during routine surveillance.

8. __A__ A U-tube sample containing UF_6 is found in a contractor vehicle outside the protected area of the plant.

9. _A__ A monthly inventory of a locked cage of enriched uranium-bearing containers shows a loss of two containers.

6-3 Self-Check Questions

Complete the following questions.

1. A revision of 10 CFR Part 70 resulted in a major performance-based requirement that takes into consideration probable risks, consequences, likelihoods of occurrence, and integration of hazards. What is this new requirement?

   An integrated safety analysis (ISA) is the major performance-based requirement resulting from the 10 CFR Part 70 2001 revision.

2. List the chemical consequence AEGLs:

   AEGL-1 The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation or certain asymptomatic, nonsensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

   AEGL-2 The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects, or an impaired ability to escape.

   AEGL-3 The airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

3. List the chemical consequence ERPGs:

ERPG-1 The maximum airborne concentration of a substance below which it is believed nearly all individuals could be exposed for up to one hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.

ERPG-2 The maximum airborne concentration of a substance below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective actions.

ERPG-3 The maximum airborne concentration of a substance below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects.

ERPGs are normalized to a one-hour nominal acute exposure to the chemicals.

4. What are the limitations of chemical consequences?

Only limited data exist for human exposure to chemicals. Usually human test subjects are healthy young male volunteers, and only low exposures are used in testing. Usually, there are no test data on women. Chemical exposures during incidents and accidents are not usually measured, or if they are, the measurements are often inaccurate. Animal data may be manipulated by unrealistic modifying factors.

5. Match the subparts of 10 CFR Part 76 in Column A with the appropriate requirements in Column B.

Column A

A. General provisions

B. Application

C. Certification

D. Safety

E. Safeguards and security

F. Reports and inspections

G. Enforcement

Column B

1. ___D___ Scope of acceptable technical safety requirements

2. __A__ Completeness and accuracy of information in the application and certification process

3. ___D___ Limiting control settings

4. ___F___ Event reporting and NRC inspection processes

5. ___B___ Sets annual renewal requirements

6. ___C___ Describes the procedure for plant changes

7. ___E___ Sets the specific requirements for physical security

8. ___G___ Sets the scope of violations and penalties allowed

6-4 Self-Check Questions

1. List the regulations that 10 CFR Part 110 prescribes.

   This Part prescribes regulations on licensing, enforcement, and rulemaking procedures and criteria, under the Atomic Energy Act, for the export of nuclear equipment and material, and the import of nuclear equipment and material.

2. List three of the facilities and equipment that are subject to export/import control.

   Any three from this list are acceptable.

   a. Nuclear reactors and especially designed or prepared equipment and components for nuclear reactors.

b. Plants for the separation of isotopes of uranium (source material or special nuclear material) including gas centrifuge plants, gaseous diffusion plants, aerodynamic enrichment plants, chemical exchange or ion exchange enrichment plants, laser based enrichment plants, plasma separation enrichment plants, electromagnetic enrichment plants, and especially designed or prepared equipment, other than analytical instruments, for the separation of isotopes of uranium.

c. Plants for the separation of isotopes of lithium and especially designed or prepared assemblies and components for these plants.

d. Plants for the reprocessing of irradiated nuclear reactor fuel elements and especially designed or prepared assemblies and components for these plants.

e. Plants for the fabrication of nuclear reactor fuel elements and especially designed or prepared assemblies and components for these plants.

f. Plants for the conversion of uranium and plutonium and especially designed or prepared assemblies and components for these plants.

g. Plants for the production, separation, or purification of heavy water, deuterium, and deuterium compounds and especially designed or prepared assemblies and components for these plants.

h. Plants for the production of special nuclear material using accelerator-driven subcritical assembly systems capable of continuous operation above 5 MWe thermal.

3. The <u>auxiliary</u> systems, equipment and components for a gas centrifuge enrichment plant are the systems of the plant needed to feed <u>UF_6</u>, to the centrifuges to <u>link</u> the individual centrifuges to each other to form cascades (or stages) to allow for progressively higher enrichments and to <u>extract</u> the product and tails of UF_6 from the centrifuges, together with the equipment required to drive the centrifuges or to control the plant.

4. In the gaseous diffusion method of uranium isotope separation, the main technological assembly is a special <u>porous</u> gaseous diffusion barrier, heat exchanger for cooling the gas (which is heated by the process of <u>compression</u>), seal valves and control valves, and pipelines. Inasmuch as gaseous diffusion technology uses UF_6, all equipment, pipeline, and instrumentation surfaces (that come in contract with the gas) must be made of materials that remain <u>stable</u> in contact with UF_6.

5. For laser-based enrichment items, the materials resistant to corrosion by the vapor or liquid of uranium metal or uranium alloys include yttria-coated graphite and tantalum; and the materials resistant to corrosion by UF_6 include copper, stainless steel, aluminum, aluminum alloys, nickel or alloys containing 60% or more nickel and UF_6-resistant fully fluorinated hydrocarbon polymers.

6-5 Self-Check Questions

1. A worker is defined as an individual engaged in activities licensed by the Commission and controlled by a licensee (e.g., a company), but does not include the licensee itself.

2. Part 19.12 lists instructions for workers. Individuals who in the course of employment are likely to receive an occupational dose in excess of 100 mrem in a year shall be (list the requirements)

   a. kept informed of the storage, transfer, or use of radiation and/or radioactive material;

   b. instructed in the health protection problems associated with exposure to radiation and/or radioactive material, in precautions or procedures to minimize exposure, and in the purposes and functions of protective devices employed;

   c. instructed in, and required to observe, to the extent within the worker’s control, the applicable provisions of Commission regulations and licenses for the protection of personnel from exposure to radiation and/or radioactive material;

   d. instructed of their responsibility to report promptly to the licensee any condition that may lead to or cause a violation of Commission regulations and licenses or unnecessary exposure to radiation and/or radioactive material;

   e. instructed in the appropriate response to warnings made in the event of any unusual occurrence or malfunction that may involve exposure to radiation and/or radioactive material; and

   f. advised as to the radiation exposure reports that workers may request pursuant to Part 19.13.

3. 10 CFR 20.1201 provides the annual occupational dose limit.

4. What do the 10 CFR Part 61 regulations establish?

   10 CFR Part 61 regulations establish requirements for land disposal of radioactive waste, the procedures, criteria, and terms and conditions upon which the NRC issues licenses for the disposal of radioactive wastes containing byproduct, source and special nuclear material received from other persons.

5. 10 CFR 71 establishes requirements for packaging, preparation for shipment, and transportation of licensed material, and procedures and standards for NRC approval of packaging and shipping procedures for fissile material and for a quantity of other licensed material in excess of a Type A quantity.

6. According to 10 CFR 73, what capabilities does the physical protection system need to include?

   This regulation prescribes requirements for the establishment and maintenance of a physical protection system that will have capabilities for the protection of special nuclear material at fixed sites and in transit and of plants in which special nuclear material is used. It identifies design-basis threats for use to design safeguards systems to protect against acts of radiological sabotage and to prevent the theft or diversion of special nuclear material.

7. 10 CFR 74 controls and accounts for special nuclear material at fixed sites, whose transfer is documented. Source material is also tracked.

MODULE 7.0 DEPLETED URANIUM

7-1 Self-Check Questions

1. What is depleted uranium (DU)?

   DU is uranium with less than the natural assay (0.711%) of isotope U-235. DU does not contain special nuclear material.

2. Describe plans for DU disposition in the U.S.

   Both LES and USEC plan to store DU outside in 48G cylinders, with two differences relative to current GDP operations. First, the cylinders would be filled with DU via a desublimation process, where the DUF_6 vapor is directly condensed into the solid. This avoids liquid UF_6 and its associated ES&H concerns. Second, storage would be an interim step before shipment for deconversion and disposition.

3. Is DU source material?

   Yes, it contains >0.05% uranium.

7-2 Self-Check Questions

1. Is DU predominantly a radiation or a chemical toxicity hazard?

   DU is predominantly a chemical toxicity hazard.

2. Describe the consequences of damage to a liquefied cylinder.

   Any incident or accident that can damage a liquefied cylinder would have significant consequences due to the pressurized nature of the release (20 psia or more), typical liquid DUF_6 temperatures (approximately 140 °F), and the reactive nature of liquid DUF_6 upon a loss of confinement (i.e., the rapid formation of HF, explosive reactions with oils and organic material).

7-3 Self-Check Questions

1. What are the three disposition pathways for DU?

   Store, reuse, dispose.

2. DU is currently stored as the <u>hexafluoride</u>.

3. Describe contamination control for DU disposal.

   A preferable DU form for disposal incorporates multiple barriers such as the DU chemical form, DU physical form, coatings, binders, encapsulants, containers, disposal site location, disposal site construction, or other means to address contamination or ES&H concerns.

7-4 Self-Check Questions

1. Match the reuse alternatives in Column A with the reuse amounts in Column B.

Column A	Column B
_A_ 1. Re-enrichment	A. Partial reuse
_A_ 2. Semiconductor applications	B. Substantial or total reuse
_B_ 3. Shielding	
_A_ 4. MOX fuel	
_A_ 5. Catalysis	

7-5 Self-Check Questions

1. Identify the three program paths developed by DOE to address DU disposition.

Path 1: Surveillance and maintenance of current cylinder storage.

Path 2: Technology development, primarily for reuse applications.

Path 3: Large-scale deconversion of DUF_6 into uranium oxide (essentially U_3O_8).

7-6 Self-Check Questions

1. At the AREVA/Eurodif GDP in Tricastin, France, GDP operations are being phased out and replaced with what technology?

   Centrifuge technology

2. Identify three NRC rulings in DU from January 2005.

   - DU is an LLW. The Commission used the 10 CFR 61.2 definition for LLW in its considerations. The Commission noted that LLW is generally acceptable for near-surface disposal and that disposal as LLW was a plausible strategy.
   - DU is subject to the 1996 USEC Privatization Act. Section 3113 requires DOE to accept for disposition DU from any NRC-licensed enrichment facility for a fee covering the costs of such disposition.
   - The FY 2005 Energy Policy Act requires DOE to take title and possession of such DU at an existing DU storage or processing facility.

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