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## SYSTEMS AND METHODS FOR PRODUCTION OF XENON-133

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### Abstract

A coil assembly for separation of Xenon-133 from an off gas stream includes a coil flange having first and second sides and defining a flange inlet and outlet. The coil assembly further includes a coil positioned on the first side of the coil flange. The coil includes inlet and outlet portions and a helical portion having a double-helix configuration. The helical portion has a top positioned a first distance from the first side of the coil flange. The inlet portion extends through the flange inlet, the outlet portion extends through the flange outlet, and the helical portion is fluidly connected to the inlet and outlet portions. The coil assembly further includes a fluid control assembly attached to the second side of the coil flange, including inlet and outlet assemblies. The inlet portion is fluidly connected to the inlet assembly and the outlet portion is fluidly connected to the outlet assembly.

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## **Background/Summary**

**CROSS-REFERENCE TO RELATED APPLICATIONS [0001]** This application is a continuation application of U.S. application Ser. No. 18/312,989, filed on May 5, 2023, which is a divisional application of U.S. application Ser. No. 16/405,703 filed on May 7, 2019, now U.S. Pat. No. 11,679,979, which claims priority to U.S. Provisional Patent Application Ser. No. 62/668,688, filed on May 8, 2018, the disclosures of each of which are hereby incorporated by reference in their entirety.

### **FIELD**

[0002] The field of the disclosure relates generally to production of radioactive isotopes and, more particularly, to systems and methods for producing Xenon-133.

### **BACKGROUND**

[0003] Radioactive isotopes are used in nuclear medicine for diagnostic and therapeutic purposes. Xenon-133 (“Xe-133”) is one such isotope, used as an inhalation diagnostic agent. In at least some radioisotope production processes, such as Molybdenum-99 (“Mo-99”) production processes, Xe-133 is produced as a by-product. For example, during production of Mo-99, enriched uranium targets are irradiated to produce various fission products including, among others, Mo-99, Xe-133, Iodine-131, and Krypton-85 (“Kr-85”). Previous methods and techniques for producing and purifying Xe-133 are not satisfactory for isolating and purifying Xe-133 from other off gasses produced during the Mo-99 production process, such that Xe-133 is typically discarded in conventional Mo-99 production processes. Accordingly, a need exists for systems and methods for separating and purifying Xe-133 from the off gas generated during dissolution of irradiated enriched uranium targets.

[0004] This Background section is intended to introduce the reader to various aspects of art that may be related to various aspects of the present disclosure, which are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the present disclosure. Accordingly, it should be understood that these statements are to be read in this light, and not as admissions of prior art.

### **BRIEF SUMMARY**

[0005] In one aspect, a coil assembly for separation of Xenon-133 from an off gas stream includes a coil flange having a first side and a second side, the coil flange defining a flange inlet and a flange outlet. The coil assembly further includes a coil positioned on the first side of the coil flange and includes an inlet portion, an outlet portion, and a helical portion having a double-helix configuration. The helical portion has a top positioned a first distance from the first side of the coil flange. The inlet portion extends through the flange inlet, the outlet portion extends through the flange outlet, and the helical portion is fluidly connected to the inlet portion and the outlet portion. The coil assembly further includes a fluid control assembly attached to the second side of the coil flange. The fluid control assembly includes an inlet assembly and an outlet assembly. The inlet portion is fluidly connected to the inlet assembly and the outlet portion is fluidly connected to the outlet assembly.

[0006] In another aspect, a transportation vessel for transportation of Xenon-133 includes a coil

assembly, a first nuclear radiation shield, and a second nuclear radiation shield. The coil assembly includes a coil flange having a first side and a second side, the coil flange defining a flange inlet and a flange outlet. The coil assembly further includes a coil positioned on the first side of the coil flange and includes an inlet portion, an outlet portion, and a helical portion having a double-helix configuration. The helical portion has a top positioned a first distance from the first side of the coil flange. The inlet portion extends through the flange inlet, the outlet portion extends through the flange outlet, and the helical portion is fluidly connected to the inlet portion and the outlet portion. The coil assembly further includes a fluid control assembly attached to the second side of the coil flange. The fluid control assembly includes an inlet assembly and an outlet assembly. The inlet portion is fluidly connected to the inlet assembly and the outlet portion is fluidly connected to the outlet assembly. The first nuclear radiation shield is removably attached to the first side of the coil flange. The first shield defines a first shield cavity and the coil assembly is positioned within the first shield cavity. The second nuclear radiation shield is removably attached to the second side of the coil flange. The second shield defines a second shield cavity and the fluid control assembly is positioned within the second shield cavity. The first and second shields completely enclose the coil assembly.

[0007] In yet another aspect, a system for producing Xenon-133 from an off gas produced during a Molybdenum-99 production process includes at least one nuclear radiation shielded enclosure, a storage tank for containing the off gas from the Molybdenum-99 production process, the off gas including Xenon-133 and Krypton-85, and a coil assembly positioned within the at least one nuclear radiation shielded enclosure. The coil assembly includes a coil including an inlet portion, an outlet portion, and a helical portion having a double-helix configuration. The helical portion fluidly connected to the inlet portion and the outlet portion. The coil assembly further includes a fluid control assembly including an inlet assembly and an outlet assembly. The inlet portion is fluidly connected to the inlet assembly and the outlet portion is fluidly connected to the outlet assembly.

[0008] Various refinements exist of the features noted in relation to the above-mentioned aspects. Further features may also be incorporated in the above-mentioned aspects as well. These refinements and additional features may exist individually or in any combination. For instance, various features discussed below in relation to any of the illustrated embodiments may be incorporated into any of the above-described aspects, alone or in any combination.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. 1 is a schematic view of an example system for producing Xe-133.

[0010] FIG. 2 is a perspective view of an example glovebox suitable for use in the system shown in FIG. 1 and Xe-133 production processes described herein.

[0011] FIG. 3 is another perspective view of the example glovebox shown in FIG. 2 with a hot cell door of the glove box in an opened position.

[0012] FIG. 4 is a front view of the example glovebox shown in FIG. 2.

[0013] FIG. 5 is another front view of the example glovebox shown in FIG. 2 with the hot cell door in the opened position.

[0014] FIG. 6 is a perspective view of an example hot cell within the example glovebox shown in FIG. 2.

[0015] FIG. 7 is a side sectional view of the example glovebox taken along line 7-7 in FIG. 4.

[0016] FIG. 8 is another side sectional view of the example glovebox taken along line 8-8 in FIG. 5 with the hot cell door in the opened position.

[0017] FIG. 9 is a top sectional view of the example glovebox taken along line 9-9 in FIG. 5.

[0018] FIG. **10** is a top sectional view of the example glovebox shown in FIG. **2**.

[0019] FIG. **11** is a top perspective view of an example charcoal column assembly suitable for use in the system shown in FIG. **1** and the Xe-133 production processes described herein.

[0020] FIG. **12** is a bottom perspective view of the example charcoal column assembly shown in FIG. **11**.

[0021] FIG. **13** is a top view of the example charcoal column assembly shown in FIG. **11**.

[0022] FIG. **14** is a side view of the example charcoal column assembly shown in FIG. **11**.

[0023] FIG. **15** is a side sectional view of the example charcoal column assembly taken along line **15-15** in FIG. **13**.

[0024] FIG. **16** is a perspective view of an example column transportation vessel suitable for use with the charcoal column assembly shown in FIG. **11**.

[0025] FIG. **17** is a perspective sectional view of the example column transportation vessel taken along line **17-17** in FIG. **16**.

[0026] FIG. **18** is a sectional view of the example column transportation vessel taken along line **18-18** in FIG. **16**.

[0027] FIG. **19** is a top perspective view of an example coil assembly suitable for use in the system shown in FIG. **1** and the Xe-133 production processes described herein.

[0028] FIG. **20** is a bottom perspective view of the example coil assembly shown in FIG. **19**.

[0029] FIG. **21** is a top view of the example coil assembly shown in FIG. **19**.

[0030] FIG. **22** is a side sectional view of the example coil assembly taken along line **23-23** in FIG. **21**.

[0031] FIG. **23** is a side sectional view of the example coil assembly shown in FIG. **19**.

[0032] FIG. **24** is a perspective view of an example coil transportation vessel suitable for use with the coil assembly shown in FIG. **19**.

[0033] FIG. **25** is a perspective sectional view of the example coil transportation vessel taken along line **25-25** in FIG. **24**.

[0034] FIG. **26** is a schematic sectional view of the example coil transportation vessel taken along line **26-26** in FIG. **24**.

[0035] Corresponding reference characters indicate corresponding parts throughout the several views of the drawings.

#### DETAILED DESCRIPTION

[0036] The present disclosure is generally directed to the production of radioactive isotopes and, more particularly, to systems and methods for producing Xenon-133 (“Xe-133”). Radioactive isotopes are used, for example, in nuclear medicine for diagnostic and therapeutic purposes by introducing a small dose of the radioactive material into a patient. Among other possible uses, the isotope Xe-133 is a suitable inhalation diagnostic agent that is used to help diagnose lung diseases and to check blood flow in the brain.

[0037] Xe-133 is one fission product among over **300** other nuclides produced during the thermal neutron induced fission of Uranium-235 (“U-235”). Xe-133 is commonly produced as a by-product of other radionuclide production processes, such as Mo-99. In previous Mo-99 production processes, Xe-133 was disposed of or discarded. Systems and methods of the present disclosure facilitate production of Xe-133 from an off gas produced by dissolution of enriched Uranium targets. Particular embodiments of the present disclosure provide systems and methods for isolating and purifying Xe-133 from a Mo-99 production process in which low-enriched Uranium (LEU) targets are irradiated. Although systems and methods are described herein as suitable for use with LEU, embodiments of the present disclosure are not limited to use with LEU and may be used with other forms of enriched Uranium, such as highly enriched Uranium (HEU). As compared to previous Xe-133 production systems and methods, embodiments of the systems and methods described herein provide improved yield of Xe-133 from off gases, enabling production of Xe-133 from raw gases having an initially lower concentration of Xe-133 (e.g., from irradiated LEU).

[0038] In an example method, bombarded uranium targets, such as LEU targets, are processed by dissolving the targets in alkaline or acid media to release fission products. The off gas (i.e., all fission gasses) produced by dissolution of the LEU targets is collected in a gas tank. During dissolution of the uranium targets in a Mo-99 production process, Xe-133 is released from the metallic matrix, removed from the process, and stored in the gas tank. Other gasses are also released from the target dissolution, such as Hydrogen (H.sub.2), water vapor (H.sub.2O), nitrogen gas (N.sub.2), and carbon dioxide (CO.sub.2), as well as other radioactive fission gasses, such as other Xe isotopes (e.g., Xe-135) and Krypton (Kr) isotopes (e.g., Kr-85). These gasses, along with a process carrier gas, such as Helium (He), are stored in the same gas tank(s) as the Xe-133. This gas mixture is the “off gas” produced during dissolution of enriched Uranium targets (i.e., during the Mo-99 production process), and may be interchangeably referred to as the “raw Xe gas”. Thus, the off gas includes the radioactive isotopes Xe-133 and Kr-85, among others, as well as other, non-radioactive gases, such as Hydrogen (H.sub.2), Helium (He), water vapor (H.sub.2O), nitrogen gas (N.sub.2), and carbon dioxide (CO.sub.2).

[0039] In some embodiments, the off gas is collected in one or more vacuum tanks. The vacuum tank may have any suitable volume that enables the methods to be carried out as described herein. In some embodiments, the vacuum tank has a volume in the range of 50 liters (L) to 500 L, 100 L to 400 L, 200 L to 450 L, 300 L to 550 L, 100 L to 200 L, 200 L to 300 L, 300 L to 400 L, and 400 L to 500 L. Further, in some embodiments, the off gas is allowed to cool within the gas tank(s) for a period of at least 24 hours following the end of irradiation (EOI) of the Uranium targets. In some embodiments, the off gas is allowed to cool within the gas tank(s) for a period of up to 36 hours, up to 48 hours, up to 60 hours, or up to 72 hours.

[0040] The off gas is then processed to purify and concentrate Xe-133 gas. The example method includes selectively adsorbing Xe-133 from the off gas onto a charcoal column assembly such that Xe-133 is preferentially or selectively adsorbed onto the charcoal column assembly relative to Kr-85, desorbing the Xe-133 from the charcoal column assembly, and condensing the desorbed Xe-133 within a cooled coil assembly.

[0041] To selectively adsorb Xe-133 from the off gas onto a charcoal column assembly, the charcoal column assembly is cooled to a temperature at which Xe-133 is preferentially adsorbed onto an activated charcoal material within the charcoal column assembly, and at which the carrier gas (e.g., He) and Krypton isotopes (e.g., Kr-85) are not measurably adsorbed. In some embodiments, the charcoal column assembly is cooled to a temperature in the range of  $-10^{\circ}\text{C.}$  to  $10^{\circ}\text{C.}$ ,  $-10^{\circ}\text{C.}$  to  $5^{\circ}\text{C.}$ ,  $-5^{\circ}\text{C.}$  to  $10^{\circ}\text{C.}$ ,  $-5^{\circ}\text{C.}$  to  $5^{\circ}\text{C.}$ ,  $0^{\circ}\text{C.}$  to  $10^{\circ}\text{C.}$ , or  $0^{\circ}\text{C.}$  to  $6^{\circ}\text{C.}$  Once the charcoal column assembly is cooled to the desired temperature, the off gas is directed through the cooled charcoal column assembly such that Xe-133 is preferentially or selectively adsorbed onto the activated charcoal material. Gases not adsorbed onto the activated charcoal material (e.g., Kr-85 and He) pass through the charcoal column assembly and are directed to post-processing and air cleaning systems (e.g., gas delay filters) for disposal. Activated charcoal materials suitable for use in the charcoal column assemblies described herein include, for example and without limitation, chromatographic grade activated charcoal, such as activated charcoal Norit® RB1, sold by Cabot Corporation.

[0042] In some embodiments, the activated charcoal may be pre-treated or pre-processed to facilitate maximizing the yield of Xe-133 during the adsorption step. For example, the activated charcoal may be subjected to a vacuum drying process prior to the adsorption step. Additionally or alternatively, the activated charcoal may be heated and subjected to a flow of inert gas (e.g., He) for a period of between 2 hours and 16 hours, between 4 hours and 12 hours, or between 4 hours and 8 hours. The activated charcoal may be heated to a temperature of between  $50^{\circ}\text{C.}$  and  $120^{\circ}\text{C.}$ , between  $60^{\circ}\text{C.}$  and  $100^{\circ}\text{C.}$ , or between  $70^{\circ}\text{C.}$  and  $90^{\circ}\text{C.}$  while subjected to the inert gas flow.

[0043] During the adsorption process, the flow of off gas through the charcoal column assembly may be regulated with suitable flow regulating devices (e.g., vacuum pumps, flow controllers,

valves, etc.) to achieve target flow rates, gas velocities, and/or pressures. In some embodiments, for example, the off gas is directed through the cooled charcoal column assembly at a target flow rate while the charcoal column assembly is held at a cooled temperature, such as within one of the temperature ranges described above. The target flow rate may generally be any suitable flow rate that enables the Xe-133 production methods to be carried out as described herein, and may be selected or based on, for example, the temperature of the charcoal column assembly during the adsorption process, the physical dimensions of the charcoal column assembly (e.g., length and cross-sectional area), and the Xe-133 concentration (absolute or relative) of the off gas. In some embodiments, the target flow rate is in the range of 1.0 normal liters per minute (NL/min) to 2.0 NL/min, 1.0 NL/min to 1.6 NL/min, 1.2 NL/min to 1.8 NL/min, 1.4 NL/min to 2.0 NL/min, 1.1 NL/min to 1.5 NL/min, 1.3 NL/min to 1.7 NL/min, 1.5 NL/min to 1.9 NL/min, and 1.35 NL/min to 1.65 NL/min.

[0044] Further, in some embodiments, the off gas is directed through the cooled charcoal column assembly at a target flow velocity while the charcoal column assembly is held at a cooled temperature, such as within one of the temperature ranges described above. The target flow velocity may generally be any suitable flow velocity that enables the Xe-133 production methods to be carried out as described herein, and may be selected or based on, for example, the temperature of the charcoal column assembly during the adsorption process, the physical dimensions of the charcoal column assembly (e.g., length and cross-sectional area), and the Xe-133 concentration (absolute or relative) of the off gas. In some embodiments, the target flow velocity is in the range of 3 centimeters per second (cm/s) to 14 cm/s, 3 cm/s to 12 cm/s, 5 cm/s to 14 cm/s, 3 cm/s to 10 cm/s, 5 cm/s to 10 cm/s, 7 cm/s to 14 cm/s, 5 cm/s to 8 cm/s, 6 cm/s to 9 cm/s, and 7 cm/s to 10 cm/s.

[0045] Following the adsorption process, the charcoal column assembly contains primarily Xenon isotopes. The relative amount of Xe-133 adsorbed onto the charcoal column assembly depends on the amount of time between the end of irradiation of the uranium targets and the end of adsorption. Xenon isotopes that may be present during the adsorption process include, for example and without limitation: Xe-128 (inactive), Xe-129 (inactive), Xe-129m (active), Xe-130 (inactive), Xe-131 (inactive), Xe-131m (active), Xe-132 (inactive), Xe-133 (active), Xe-133m (active), Xe-134 (inactive), Xe-135m (active), Xe-135 (active), and Xe-136 (inactive).

[0046] In the example method, after the Xe-133 is adsorbed onto the charcoal column assembly, the charcoal column assembly is disconnected from the off gas supply line and heated to a temperature at which the Xe-133 will desorb from the charcoal column assembly. Suitable temperatures to which the charcoal column assembly may be heated for the desorption process include, for example and without limitation, at least 60° C., at least 65° C., at least 70° C., at least 75° C., at least 80° C., at least 85° C., at least 90° C., and up to 120° C. In some embodiments, the charcoal column assembly is sealed after the adsorption process and prior to heating to inhibit the escape of Xe-133 from the charcoal column assembly.

[0047] In the example method, once the charcoal column assembly is heated to the target temperature, an inlet of the charcoal column assembly is connected to a carrier gas supply line (e.g., He), and an outlet of the charcoal column assembly is connected to a cooled Xe-133 collection device. In the example method, the Xe-133 collection device includes a helical coil assembly cooled to a suitable temperature at which Xe-133 gas condenses and/or crystallizes within the coil assembly when passed through the coil assembly. Suitable temperatures to which the coil assembly may be cooled during the desorption process include, for example and without limitation, less than -100° C., less than -125° C., less than -150° C., less than -170° C., less than -180° C., less than -190° C., less than -195° C., and down to -200° C.

[0048] In the example method, once the coil assembly is cooled to the desired temperature, the outlet of the charcoal column assembly is connected to an inlet of the coil assembly, and a carrier gas (e.g., He) is flowed through the heated charcoal column assembly such that Xe-133 is desorbed

from the charcoal column assembly and entrained in the carrier gas flow, and passed through the cooled coil assembly. As the carrier gas and Xe-133 flow through the cooled coil assembly, Xe-133 condenses and/or crystallizes on the interior walls of the coil assembly. The carrier gas is selected to have a boiling point and freezing point lower than the respective boiling point and freezing point of Xe-133 such that the carrier gas (e.g., He) passes through the cooled coil assembly without condensing and/or crystallizing. Trace amounts of Kr-85 remaining in the carrier gas flow (e.g., from being adsorbed and desorbed from the charcoal column assembly) similarly pass through the cooled coil assembly without significant condensation and/or crystallization because Kr-85 has a lower boiling point and freezing point than the respective boiling point and freezing point of Xe-133. Gases not condensed or crystallized within the coil assembly (e.g., Kr-85 and He) pass through the coil assembly and are directed to post-processing and air cleaning systems (e.g., gas delay filters) for disposal.

[0049] During the desorption process, the flow of off gas through the charcoal column assembly and the coil assembly may be regulated with suitable flow regulating devices (e.g., vacuum pumps, flow controllers, valves, etc.) to achieve target flow rates, gas velocities, and/or pressures. In some embodiments, for example, the carrier gas is directed through the charcoal column assembly and the coil assembly at a target flow rate while the column assembly is held at a heated temperature, such as within one of the temperature ranges described above, and while the coil assembly is held at a cooled temperature, such as within one of the temperature ranges described above. The target flow rate may generally be any suitable flow rate that enables the Xe-133 production methods to be carried out as described herein, and may be selected or based on, for example, the temperatures of the charcoal column assembly and the coil assembly during the desorption process, the physical dimensions of the charcoal column assembly and the coil assembly (e.g., length and cross-sectional area), and the Xe-133 concentration (absolute or relative) within the carrier gas. In some embodiments, the target flow rate is in the range of 50 normal-milliliters per minute (NmL/min) to 250 NmL/min, 80 NmL/min to 200 NmL/min, 120 NmL/min to 250 NmL/min, 100 NmL/min to 180 NmL/min, 120 NmL/min to 200 NmL/min, 120 NmL/min to 160 NmL/min, 140 NmL/min to 180 NmL/min, 160 NmL/min to 200 NmL/min, and 150 NmL/min to 170 NmL/min.

[0050] In the example method, the desorption process is carried out for a suitable amount of time to desorb substantially all of Xe-133 from the charcoal column assembly. The length of the desorption process may vary, for example, based on the temperatures of the charcoal column assembly and the coil assembly and the flow rate of carrier gas during the desorption step. In some embodiments, the carrier gas is flowed through the charcoal column assembly and the coil assembly during the desorption step for a period of at least 20 minutes, at least 30 minutes, at least 40 minutes, at least 50 minutes, at least 60 minutes, at least 70 minutes, at least 80 minutes, at least 90 minutes, and up to 120 minutes. In other embodiments, the desorption step may be performed for any suitable amount of time that enables the Xe-133 production methods to be carried out as described herein.

[0051] The example method further includes evacuating the coil assembly after the Xe-133 is condensed and/or crystallized within the coil to limit the internal pressure of the coil assembly resulting from evaporation of Xe-133 as the coil assembly is allowed to reach ambient temperature. In some embodiments, the coil is evacuated while the coil is held at a cooled temperature, such as within the temperature ranges described above, and/or while the Xe-133 is condensed and/or crystallized within the coil assembly (i.e., prior to the Xe-133 evaporating). Further, in some embodiments, the coil assembly is evacuated such that the pressure within the coil assembly is less than 500 milliBar (mBar), less than 450 mBar, less than 400 mBar, less than 350 mBar, less than 300 mBar, less than 250 mBar, less than 200 mBar, or less than 150 mBar, before the coil assembly is allowed to reach ambient temperature. Further, in some embodiments, the coil assembly is evacuated such that the pressure within the coil assembly at a temperature of 55° C. is less than 2.5 Bar, less than 2.0 Bar, less than 1.5 Bar, less than 1.25 Bar, and less than 1.0 Bar.

[0052] In some embodiments, the coil assembly is evacuated by sealing the inlet of the coil

assembly and connecting the outlet of the coil assembly to a vacuum source including, for example and without limitation, a vacuum pump or one or more evacuated containers. Further, in some embodiments, the flow rate of gas during the evacuation process is controlled to reduce or prevent evaporation and removal of Xe-133 gas from the coil assembly. In some embodiments, for example, a flow restrictor is fluidly connected to the coil assembly to limit the flow rate of gas out of the coil assembly during the evacuation process. In some embodiments, the flow restrictor is connected between the outlet of the coil assembly and the vacuum source. The flow restrictor may include, for example and without limitation, a restrictor orifice and a needle valve (e.g., a low flow metering valve).

[0053] Additionally, in some embodiments, the evacuation process is carried out in multiple steps or phases. In one embodiment, for example, the cooled coil assembly is connected to a first evacuated container, and the internal pressure of the coil assembly is allowed to reach equilibrium with the evacuated container. The coil assembly is then disconnected from the first evacuated container and sealed. A second evacuated container is then connected to the coil assembly, and the internal pressure of the coil assembly is allowed to reach equilibrium with the second evacuated container. The initial pressure within the evacuated containers may be less than 500 mBar, less than 400 mBar, less than 300 mBar, less than 200 mBar, and less than 100 Bar. In some embodiments, the initial pressure of the evacuated container and the flow rate of gas during the evacuation process are set such that the internal pressure within the coil assembly reaches equilibrium with the evacuated containers within 2 to 10 minutes, within 2 to 7 minutes, within 3 to 8 minutes, within 3 to 6 minutes, within 4 to 7 minutes, or within about 5 minutes.

[0054] In the example method, after the evacuation step is complete, the inlet and outlet of the coil assembly are sealed, and the coil assembly is allowed to reach ambient temperature such that condensed Xe-133 within the coil assembly evaporates into gaseous Xe-133 within the coil assembly. The activity of Xe-133 gas may then be measured and/or a sample of the Xe-133 gas may be collected for quality control analysis. The coil containing the Xe-133 API gas will be packed in a secondary transport container, and prepared for shipment.

[0055] In some embodiments, the method further includes filtering out or otherwise removing contaminants from the off gas, for example, prior to the selective adsorption step. In some embodiments, for example, the method includes passing the off gas through a series of filters and/or chromatographic columns to filter out and remove particles and contaminants from the off gas. In some embodiments, the method includes removing particles and other contaminants from the off gas prior the selective adsorption step by passing the off gas through a particle filter. Further, in some embodiments, the method includes removing water vapor from the off gas prior the selective adsorption step by passing the off gas through a zeolite column assembly. Additionally, in some embodiments, the method further includes removing carbon dioxide from the off gas prior to the selective adsorption step by passing the off gas through a column assembly containing sodium-hydroxide coated silicon dioxide (e.g., Ascarite® sodium hydroxide-coated silica, sold by MilliporeSigma). Removing gases, such as water vapor and carbon dioxide, from the off gas prior to the adsorption and desorption steps facilitates reducing the pressure within the coil assembly following the desorption step.

[0056] The methods described herein may be carried out in one or more nuclear radiation shielded enclosures, such as a hot cell and/or a glove box. The methods may be carried out in a single shielded enclosure or, as described in more detail herein, in multiple shielded enclosures. Further, the different steps of the methods described herein may be carried out in a single location or facility, or may be carried out in multiple locations or facilities. In one embodiment, for example, the adsorption process is carried out at a first location or facility, and the desorption and Xe-133 collection steps are carried out at a second location or facility. In such an embodiment, the loaded charcoal column assembly (i.e., charged with Xe-133) may be transported to a second location or facility where subsequent processing (e.g., desorption and/or Xe-133 collection) is carried out.



[0057] With reference now to the figures, an example system **100** for producing Xe-133 is shown schematically in FIG. **1**. The system **100** shown in FIG. **1** may be used to produce Xe-133 from a variety of sources (i.e., raw gases). The system **100** of FIG. **1** is particularly suited for producing Xe-133 from an off gas produced during a Mo-99 production process, although the system **100** is not limited to use with only off gas produced during a Mo-99 production process.

[0058] As shown in FIG. **1**, the system **100** generally includes a plurality of stations. In the example embodiment, the system **100** includes a storage station **102**, a filtering station **104**, a pump station **106**, and a Xenon collection station **108**. The system **100** also includes a post-processing and air cleaning system **110** for processing and cleaning gas following the Xe-133 production process. In the illustrated embodiment, the system **100** includes two storage stations **102**, two filtering stations **104**, and two pump stations **106**. Each storage station **102**, each filtering station **104**, and each pump station **106** has an identical configuration in the illustrated embodiment. In the example embodiment, the Xenon collection station **108** is selectively connectable to the different storage stations **102**, filtering stations **104**, and pump stations **106** such that a single Xenon collection station **108** can receive and process off gas from multiple Mo-99 production lines.

[0059] The filtering station **104**, the pump station **106**, and the Xenon collection station **108** are enclosed in one more nuclear radiation shielded containment chambers. In the example embodiment, each station is enclosed within a separate containment chamber. In other embodiments, one or more of the filtering station **104**, the pump station **106**, and the Xenon collection station **108** may be located in the same containment chamber. In the example embodiment, the filtering station **104** is located within a hot cell **112** in which a Mo-99 production process is carried out. Further, the pump station **106** is located in a first glove box **114**, and the Xenon collection station **108** is located in a second glove box **116**.

[0060] Components of the different stations are fluidly connected to one another with suitable fluid conduits **118**. Fluid conduits that extend between or connect components between different stations are shielded with suitable nuclear radiation shielding to inhibit release of nuclear radiation in operator-occupied areas.

[0061] The storage station **102** includes a storage tank **120** for storing gas and other materials produced during dissolution of irradiated enriched uranium targets. In the example embodiment, the storage tank **120** is fluidly connected to a Mo-99 production process to receive the off gas generated during dissolution of irradiated enriched uranium targets. In some embodiments, the storage tank **120** is a vacuum tank. The storage tank **120** may have any suitable volume that enables the system **100** to function as described herein. In some embodiments, the storage tank **120** has a volume in the range of 50 L to 500 L, 100 L to 400 L, 200 L to 450 L, 300 L to 550 L, 100 L to 200 L, 200 L to 300 L, 300 L to 400 L, and 400 L to 500 L.

[0062] The filtering station **104** is connected downstream of the storage station **102** to receive the off gas from the storage tank **120**. The filtering station **104** includes a particle filter **122** and a first zeolite column assembly **124**. In the illustrated embodiment, the first zeolite column assembly **124** is separate from the particle filter **122**, and is connected downstream from the particle filter **122**. In other embodiments, the particle filter **122** may be integrated within the first zeolite column assembly **124**.

[0063] The particle filter **122** includes suitable filtering media to remove inhalable particulates from the off gas stream. The filtering media may include, for example and without limitation, porous sintered metal media (also known as “frits”). The porous sintered metal media may have a porosity of between 0.1 and 10 microns, between 0.1 and 5 microns, between 0.1 and 3 microns, or between 0.1 and 2 microns.

[0064] The first zeolite column assembly **124** includes an amount of zeolite to absorb water vapor within the off gas stream. Suitable forms of zeolite for use in the first zeolite column assembly **124** include, for example and without limitation, zeolite type 4A and zeolite type 13X. The first zeolite column assembly **124** may contain any suitable amount of zeolite that enables the system **100** to

function as described herein. In some embodiments, the first zeolite column assembly **124** contains a mass of zeolite of between 5 grams (g) and 30 g, between 8 g and 25 g, between 10 g and 30 g, between 10 g and 25 g, between 15 g and 30 g, between 12 g and 20 g, or between 15 g and 20 g. [0065] The pump station **106** includes one or more flow regulating devices for controlling the flow of the off gas through the system **100**. In some embodiments, for example, the pump station **106** includes at least one vacuum pump that is connected in fluid communication with the storage tank **120** and a charcoal column assembly **138**, and is operable to pump the off gas from the storage tank **120** and through the charcoal column assembly **138**.

[0066] In the illustrated embodiment, the pump station **106** includes a first vacuum pump **126**, a second vacuum pump **128**, and a pressure controller **130**. The first vacuum pump **126** is connected to the filtering station **104** and in fluid communication between the storage tank **120** and the charcoal column assembly **138**. The first vacuum pump **126** is operable to draw or pump off gas from the storage tank **120** through the filtering station **104**. The second vacuum pump **128** is fluidly connected downstream of the first vacuum pump **126** and the charcoal column assembly **138** through components of the Xenon collection station **108**, and is operable to draw or pump the off gas from the first vacuum pump **126**, through components of the Xenon collection station **108** (e.g., the charcoal column assembly **138**), and to the post-processing and air cleaning system **110** for disposal. As described further herein, the second vacuum pump **128** is also selectively connectable to an outlet of a coil assembly **140** within the Xe collection station **108** during the desorption step to direct a carrier gas through the charcoal column assembly **138** and the coil assembly **140**.

[0067] The pressure controller **130** is connected to the first vacuum pump **126** and/or the second vacuum pump **128**, and is operable to control or regulate the first vacuum pump **126** and/or the second vacuum pump **128** to maintain a set pressure of the off gas throughout the system **100** during the adsorption process.

[0068] In the illustrated embodiment, the pump station **106** further includes a water indicator **132** connected downstream from the first vacuum pump **126**, and a second zeolite column assembly **134** connected downstream from the water indicator **132**. The water indicator **132** is configured to detect the presence of water, particularly water vapor, within the off gas stream as it flows through the pump station **106**. The water indicator **132** is configured to provide a visual and/or audible indicator when water is detected in the off gas stream. The second zeolite column assembly **134** may have the same construction as the first zeolite column assembly **124**, and act as a backup or redundant zeolite column assembly to capture any water vapor remaining in the off gas stream after passing through the first zeolite column assembly **124**.

[0069] The Xenon collection station **108** includes a carbon dioxide (CO.sub.2) removal column assembly **136**, a charcoal column assembly **138**, a coil assembly **140**, a heating and cooling system **142**, and a flow controller **144**. In the illustrated embodiment, the Xenon collection station **108** also includes a carrier gas supply **146**, an evacuation device **148**, and a sample collection device **150**.

[0070] The CO.sub.2 removal column assembly **136** is connected upstream of the charcoal column assembly **138**, and is configured to remove or filter out carbon dioxide from the incoming off gas stream. The CO.sub.2 removal column assembly **136** contains a suitable CO.sub.2 scavenger or adsorbent including, for example and without limitation, sodium-hydroxide coated silicon dioxide (e.g., Ascarite® sodium hydroxide-coated silica, sold by MilliporeSigma). The CO.sub.2 removal column assembly **136** may contain any suitable amount of a CO.sub.2 scavenger or adsorbent that enables the system **100** to function as described herein. In some embodiments, the CO.sub.2 removal column assembly **136** contains a mass of CO.sub.2 scavenger or adsorbent of between 50 g and 200 g, between 60 g and 150 g, between 80 g and 170 g, between 100 g and 170 g, between 70 g and 140 g, between 90 g and 160 g, between 110 g and 180 g, between 90 g and 140 g, between 110 g and 160 g, between 130 g and 180 g, between 110 g and about 140 g, or about 130 g. Removing carbon dioxide from the off gas stream prior to the adsorption step (i.e., upstream of the charcoal column assembly **138**) facilitates maximizing the yield of Xe-133 during the production

process because the presence of carbon dioxide in the off gas stream would otherwise reduce the amount of Xenon adsorbed onto the charcoal column assembly (i.e., reduce the Xenon adsorption capacity of the charcoal column assembly **138**). Additionally, removing carbon dioxide from the off gas stream facilitates reducing the pressure within the coil assembly **140** following the desorption step.

[0071] The charcoal column assembly **138** is located downstream of the CO.sub.2 removal column assembly **136** and the carrier gas supply **146**. Further, the charcoal column assembly **138** is selectively connectable to the storage tank **120** (via the CO.sub.2 removal column assembly **136**) and the carrier gas supply **146** such that the gas supplied to the charcoal column assembly **138** can be changed between the off gas and the carrier gas. The charcoal column assembly **138** includes an activated charcoal material suitable for adsorbing Xe-133. Activated charcoal materials suitable for use in the charcoal column assembly **138** include, for example and without limitation, chromatographic grade activated charcoal, such as activated charcoal Norit® RB1, sold by Cabot Corporation. The charcoal column assembly **138** may contain any suitable amount of activated charcoal that enables the system **100** to function as described herein. In some embodiments, the charcoal column assembly **138** contains a mass of activated charcoal of between 10 g and 100 g, between 10 g and 80 g, between 10 g and 50 g, between 20 g and 60 g, between 30 g and 70 g, between 15 g and 45 g, between 25 g and 55 g, between 20 g and 40 g, between 30 g and 50 g, or about 30 g.

[0072] The heating and cooling system **142** is connected in thermal communication with the charcoal column assembly **138**, and is operable to heat and cool the charcoal column assembly **138** during the Xe-133 production process. The heating and cooling system **142** may generally include any combination of heating and/or cooling devices (e.g., electric heaters, cooling coils, etc.) that enables the system **100** to function as described herein. In one embodiment, for example, the heating and cooling system **142** is a heat exchanger in thermal communication with the charcoal column assembly **138** that receives a heating fluid or a cooling fluid to heat or cool the charcoal column assembly **138**, respectively.

[0073] The carrier gas supply **146** is selectively connectable to an inlet of the charcoal column assembly **138**, for example, to desorb Xenon-133 from the charcoal column assembly **138** during the desorption process, and includes suitable gas flow components for supplying a carrier gas to the charcoal column assembly **138**. In some embodiments, for example, the carrier gas supply **146** includes a carrier gas storage tank, a fluid conduit connecting the carrier gas storage tank to the charcoal column assembly **138**, and a control valve to control the flow of the carrier gas through the charcoal column assembly **138**. In one embodiment, the carrier gas is Helium, although the carrier gas may include any suitable inert gas that enables the system **100** to function as described herein. In the illustrated embodiment, the carrier gas supply **146** is located entirely within the Xenon collection station **108** and the associated second glove box **116**. In other embodiments, components of the carrier gas supply **146**, such as a carrier gas storage tank, is located outside the second glove box **116**.

[0074] The coil assembly **140** is located downstream from the charcoal column assembly **138**, and is selectively connectable to an outlet of the charcoal column assembly **138** for receiving the carrier gas and desorbed Xe-133 entrained in the carrier gas. The coil assembly **140** has a coil configuration suitable for heat exchange with the surrounding environment. The coil assembly **140** is located in a chamber or pocket (not shown in FIG. 1) within the second glove box **116** for receiving a volume of cooling fluid (e.g., liquid nitrogen) therein. In some embodiments, the chamber or pocket is defined by a vacuum flask (e.g., a Dewar flask) that contains a volume of cooling fluid. The coil assembly **140** has a volume for receiving Xe-133 gas therein. In some embodiments, the coil assembly **140** has a volume of between about 10 mL and about 100 mL, between about 10 mL and about 60 mL, between about 20 mL and about 80 mL, between about 10 mL and about 50 mL, between about 20 mL and about 60 mL, between about 10 mL and about 40

mL, between about 20 mL and about 50 mL, between about 20 mL and about 40 mL, or about 30 mL.

[0075] The flow controller **144** is operable to control or regulate the flow of gas through the Xenon collection station **108**, and may generally include any suitable flow regulating device or combination of devices that enables the system **100** to function as described herein. In some embodiments, for example, the flow controller **144** includes a mass flow controller operable to limit or regulate the flow of gas therethrough.

[0076] In operation, the system **100** is used to produce Xe-133 from an off gas produced during dissolution of enriched Uranium targets. In some embodiments, the Xe-133 is produced from an off gas produced during a Mo-99 production process. In some embodiments, the Xe-133 production process is carried out in multiple stages or “steps”. The general process flow of an Xe-133 production process is illustrated by directional arrows in FIG. 1, with the various steps labeled “Step 1,” “Step 2,” “Step 3,” and “Step 4”.

[0077] The off gas generated during dissolution of the enriched Uranium targets is collected in the storage tank **120**. In some embodiments, the off gas is allowed to cool or decay for a period of time following the end of irradiation of the enriched Uranium targets, such as 24 hours, 36 hours, 48 hours, or any other suitable period of time.

[0078] In the first or adsorption step of the example Xe-133 production process, once the off gas is allowed to cool or decay for a set amount of time, the off gas is drawn or pumped from the storage tank **120** by the first vacuum pump **126**. The off gas is directed through the particle filter **122** to filter out particulates from the off gas stream, and through the first zeolite column assembly **124** to remove water vapor from the off gas stream. The off gas is then directed through the pump station **106** and towards the Xenon collection station **108** via the second vacuum pump **128**. The pressure controller **130** controls or regulates the first vacuum pump **126** and/or the second vacuum pump **128** to maintain a set pressure, flow rate, and/or gas velocity of the off gas throughout the system **100** during the adsorption process.

[0079] The off gas is then directed through the CO.sub.2 removal column assembly, which removes CO.sub.2 from the off gas stream. The off gas is then directed through the charcoal column assembly **138**, which is held at a cooled temperature by the heating and cooling system **142**. In some embodiments, the charcoal column assembly **138** is cooled by the heating and cooling system **142** to a temperature in the range of  $-10^{\circ}\text{C.}$  to  $10^{\circ}\text{C.}$ ,  $-10^{\circ}\text{C.}$  to  $5^{\circ}\text{C.}$ ,  $-5^{\circ}\text{C.}$  to  $10^{\circ}\text{C.}$ ,  $-5^{\circ}\text{C.}$  to  $5^{\circ}\text{C.}$ ,  $0^{\circ}\text{C.}$  to  $10^{\circ}\text{C.}$ , or  $0^{\circ}\text{C.}$  to  $6^{\circ}\text{C.}$  As the off gas passes through the cooled charcoal column assembly **138**, Xe-133 is selectively or preferentially adsorbed onto the charcoal column assembly **138** relative to other gases (e.g., Kr-85) within the off gas. Other gases, such as He and Kr-85, pass through the charcoal column assembly **138**, and are directed to the post-processing and air cleaning system **110**, which includes, for example, gas delay filters **152**.

[0080] In the selective adsorption step (i.e., Step 1), the second vacuum pump **128** is connected to the outlet of the charcoal column assembly **138** to direct or draw the off gas through the charcoal column assembly **138** and towards the post-processing and air cleaning system **110**.

[0081] After adsorption of the Xe-133 onto the charcoal column assembly **138**, the charcoal column assembly **138** is disconnected from the off gas supply line (i.e., the storage tank **120**), and sealed. The charcoal column assembly **138** is then heated by the heating and cooling system **142** to a temperature at which the Xe-133 desorbs from the charcoal column assembly **138**. In some embodiments, the charcoal the charcoal column assembly **138** is heated to a temperature of at least  $60^{\circ}\text{C.}$ , at least  $65^{\circ}\text{C.}$ , at least  $70^{\circ}\text{C.}$ , at least  $75^{\circ}\text{C.}$ , at least  $80^{\circ}\text{C.}$ , at least  $85^{\circ}\text{C.}$ , at least  $90^{\circ}\text{C.}$ , and up to  $120^{\circ}\text{C.}$

[0082] Once the charcoal column assembly **138** reaches the desired temperature, the inlet of the charcoal column assembly **138** is connected to the carrier gas supply **146**, and the outlet of the charcoal column assembly **138** is connected to an inlet of the coil assembly **140**. The coil assembly **140** is submerged in a cooling fluid (e.g., liquid nitrogen) such that the coil assembly **140** is cooled

to a temperature at which Xe-133 gas condenses and/or crystallizes within the coil assembly **140**. Suitable temperatures to which the coil assembly **140** may be cooled during the desorption process include, for example and without limitation, less than  $-100^{\circ}\text{C}$ ., less than  $-125^{\circ}\text{C}$ ., less than  $-150^{\circ}\text{C}$ ., less than  $-170^{\circ}\text{C}$ ., less than  $-180^{\circ}\text{C}$ ., less than  $-190^{\circ}\text{C}$ ., less than  $-195^{\circ}\text{C}$ ., and down to  $-200^{\circ}\text{C}$ .

[0083] The carrier gas from the carrier gas supply **146** passes through the heated charcoal column assembly **138**, removing Xe-133 from the charcoal column assembly **138**. The carrier gas and Xe-133 then pass through the coil assembly **140**, where Xe-133 condenses and/or crystallizes within the coil assembly **140**. Other gases, such as Kr-85 and the carrier gas (e.g., He) pass through the coil assembly **140**. The outlet of the coil assembly **140** is connected to the second vacuum pump **128** such that gases not entrapped within the coil assembly **140** pass through the second vacuum pump **128** to the post-processing and air cleaning system **110**.

[0084] After the desorption step (i.e., Step 2), any non-condensed or non-solidified gas within the coil assembly **140** is evacuated (Step 3). The coil assembly **140** may be evacuated using the second vacuum pump **128**, or using a separate evacuation device **148** as shown in FIG. 1. In this embodiment, the evacuation device **148** includes at least one evacuated container that is selectively connectable to an outlet of the coil assembly **140** (e.g., following the desorption step to evacuate the coil assembly **140**). The evacuation device **148** also includes a fluid conduit and a flow restrictor. The coil assembly **140** is connected to the evacuated container using the fluid conduit such that the flow restrictor is fluidly connected between the coil assembly **140** and the evacuated container. The flow restrictor limits the flow rate of gas out of the coil assembly to prevent or inhibit evaporation and loss of Xe-133 within the coil assembly.

[0085] After the evacuation step (Step 3), the inlet and outlet valves of the coil assembly **140** are closed, and the coil assembly **140** is removed from the cooling fluid. The coil assembly **140** is allowed to reach ambient temperature, and the activity of Xe-133 gas is measured and a sample of the Xe-133 gas is taken using the sample collection device **150**. The coil assembly **140** containing the Xe-133 is then packed in a suitable shielded transport container, and prepared for shipment.

[0086] FIG. 2 is a perspective view of an example glovebox **1000** suitable for use with the system **100** shown in FIG. 1 and in the Xe-133 production processes described herein. FIG. 3 is another perspective view of the example glovebox **1000** shown in FIG. 2. While the glovebox **1000** is described herein with reference to the production of Xe-133, it is understood that the glovebox **1000** may be used to separate and produce gases from the production of Mo-99 other than Xe-133. Gloveboxes **1000** are typically used in the radiopharmaceutical and nuclear energy industries to shield and protect personnel from the radioactive material contained therein and radiation emitted therefrom. In some aspects, the glovebox **1000** prevents or mitigates contamination of the external environment with hazardous components from within the glovebox **1000**, such as radioactive material, chemical toxins and/or biological toxins. In some other aspects, the glovebox **1000** prevents or mitigates contamination of the glovebox **1000** with contaminants from the environment external to the glovebox **1000**, such as microbes that could compromise the sterility of material in the glovebox **1000**.

[0087] In the illustrated embodiment, the glovebox **1000** includes a shielded nuclear radiation containment chamber or shielded processing space **1002**, also referred to herein as a “hot cell”, a control panel **1004**, a hot cell door **1006**, and a filtration system **1008**. The hot cell **1002** includes an enclosure constructed of nuclear radiation shielding material **1010** (shown in FIGS. 6 and 9) designed to shield the surrounding environment from nuclear radiation. Suitable shielding materials **1010** from which hot cells **1002** may be constructed include, for example and without limitation, lead, depleted uranium, and tungsten. In some embodiments, hot cells **1002** are constructed of steel-clad lead walls.

[0088] The control panel **1004** is positioned above the hot cell door **1006**, and allows an operator to control the systems and processes within the glovebox **1000**. For example, the control panel **1004**

allows the operator to control the filtration system **1008** and the Xe-133 production processes described herein. The control panel **1004** may control any system, process, or device within the glovebox **1000** that allows the glovebox **1000** and/or the Xe-133 production process to operate as described herein.

[0089] FIG. **4** is a front view of the example glovebox **1000** shown in FIG. **2**. FIG. **5** is a front view of the example glovebox **1000** shown in FIG. **2** with portions of a front of the glovebox **1000** removed for clarity. The hot cell door **1006** is attached to the glovebox **1000** by a plurality of hinges **1012** and rotates about the hinges **1012**, allowing access to the hot cell **1002**. The hot cell door **1006** includes a viewing window **1007** constructed of a transparent shielding material. Suitable materials from which the viewing window **1007** may be constructed include, for example and without limitation, lead glass. The hot cell door **1006** defines a pair of glove ports **1014** configured to allow access to a pair of shielded gloves **1016** extending into the hot cell **1002**. A pair of glove port doors **1018** is attached by hinges to the hot cell door **1006**. Opening the glove port doors **1018** allows the operator to access the shielded gloves **1016** and operate equipment within the hot cell **1002**. In the example embodiment, the shielded gloves **1016** are made of a synthetic rubber (e.g., neoprene) loaded with lead to shield the operator's hands from nuclear radiation generated within the hot cell **1002**. In alternative embodiments, the shielded gloves **1016** are made of any material that allows the operator to safely operate equipment within the hot cell **1002**.

[0090] A transparent panel **1020** is positioned behind the hot cell door **1006** and partially defines a portion of the hot cell **1002**. The transparent panel **1020** defines a pair of panel glove ports **1022**. The shielded gloves **1016** are attached to the panel glove ports **1022** such that an air tight seal is formed at the attachment point. Additionally, the transparent panel **1020** is attached to the shielding material **1010** such that an air tight seal is formed around the transparent panel **1020**. In the illustrated embodiment, the transparent panel **1020** is made of a transparent, shatter resistant thermoplastic, such as, without limitation, Poly(methyl methacrylate). The transparent panel **1020** may be made of any transparent material that enables glovebox **1000** and/or the Xe-133 production process to operate as described herein.

[0091] In the illustrated embodiment, the filtration system **1008** is positioned on a top **1024** of glovebox **1000** and includes an air inlet **1026** and an air outlet **1028**. The filtration system **1008** is configured to supply the hot cell **1002** with air while simultaneously providing separation between a processing environment within the hot cell **1002** and the surrounding environment external to the hot cell **1002**. The filtration system **1008** of this embodiment is configured to channel a flow of air through the hot cell **1002**. In alternative embodiments, the filtration system **1008** may be configured to channel a flow of inert gas through the hot cell **1002**, creating an inert environment within the hot cell **1002**. In other embodiments, the filtration system **1008** is configured to partially remove air from the hot cell **1002**, creating a vacuum chamber within the hot cell **1002**.

[0092] In this embodiment, the air inlet **1026** and the air outlet **1028** each include a filter **1030** configured to remove contaminants from the flow of air before channeling the flow of air into or out of the hot cell **1002**. The filters **1030** are suitably High Efficiency Particulate Air (HEPA) filters. In addition to HEPA filters, the air inlet **1026** and the air outlet **1028** may each include an additional filter **1032** (shown in FIG. **8**) such as, without limitation, a charcoal filter. In alternative embodiments, the filter **1030** and the additional filter **1032** may be any filtration device that enables glovebox **1000** and/or the Xe-133 production process to operate as described herein.

[0093] The glovebox **1000** of this embodiment includes a drawer **1034** configured to allow equipment to enter and exit the hot cell **1002**. The drawer **1034** includes a drawer door **1036** attached to the glovebox **1000** by a plurality of drawer door hinges **1038** configured to rotate the drawer door **1036** between an open position and a closed position. The drawer **1036** also includes a bin **1040** attached to a pair of drawer slides **1042** configured to slide the bin **1040** into and out of the glovebox **1000**. The bin **1040** is sized and shaped to receive equipment for the Xe-133 production process. Specifically, the bin **1040** is sized and shaped to receive a charcoal column

assembly **2000** and a coil assembly **3000**, as further described herein.

[0094] In this example, the glovebox **1000** includes a plurality of process inlets **1044** and a plurality of process outlets **1046** positioned on the top **1024** of glovebox **1000**. The process inlets **1044** channel fluids from the Xe-133 production process into the hot cell **1002** and the process outlets **1046** channel fluids from the Xe-133 production process out of the hot cell **1002**. In the illustrated embodiments, the process inlets **1044** are configured to channel the off gas from a zeolite column into the glovebox **1000**. The process outlets **1046** are configured to channel the remaining off gas from the Xe-133 separation process to a plurality of Edel Gas Vertragings Filters (EGVF) within the Mo-99 production facility. In alternative embodiments, the process inlet **1044** and the process outlet **1046** are configured to channel any fluid into or out of the hot cell **1002** that enables the glovebox **1000** and/or the Xe-133 production process to operate as described herein.

[0095] The glovebox **1000** and/or the hot cell **1002** may be suitably maintained at a predetermined clean room grade (e.g., Grade B or Grade C). Unless otherwise indicated, references to clean room classifications refer to clean room classifications according to Annex **1** of the European Union Guidelines to Good Manufacturing Practice.

[0096] Additionally, the pressure within the glovebox **1000** and/or the hot cell **1002** may be controlled at a negative or positive pressure differential relative to the surrounding environment and/or relative to adjacent cells or stations. In some embodiments, for example, all of the gloveboxes **1000** and/or the hot cells **1002** are maintained at a negative pressure relative to the surrounding environment. Moreover, in some embodiments, the glovebox **1000** and/or the hot cell **1002** may be maintained at a positive pressure relative to other gloveboxes **1000** and/or hot cells **1002**.

[0097] FIG. **6** is a perspective view of the hot cell **1002** within the example glovebox **1000** shown in FIG. **2**. FIG. **7** is a side sectional view of the glovebox **1000** shown in FIG. **2** taken along sectional line **7-7**. FIG. **8** is a side sectional view of the glovebox **1000** shown in FIG. **2** taken along sectional line **8-8**. FIG. **9** is a top sectional view of the example glovebox **1000** shown in FIG. **2** taken along sectional line **9-9**. FIG. **10** is a top sectional view of the example glovebox **1000** shown in FIG. **2** taken along sectional line **10-10**. In the illustrated embodiment, a plurality of shield panels **1048** made of the shielding material **1010** define the hot cell **1002** and a drawer compartment **1050** within the glovebox **1000**. Additionally, the hot cell door **1006**, the drawer door **1036**, and glove port doors **1018** also include shield panels **1048** to shield the surrounding environment from nuclear radiation. The shield panels **1048** each have a shield panel thickness **1052**. In the illustrated embodiment, the shield panel thickness **1052** is in a range from about 10 mm to about 200 mm. More specifically, the shield panel thickness **1052** is in a range from about 40 mm to about 110 mm. More particularly, the shield panel thickness **1052** is either about 50 mm or about 100 mm. In the illustrated embodiment, the shield panels **1048** within the hot cell door **1006**, the drawer door **1036**, and glove port doors **1018** and the shield panels **1048** defining the hot cell **1002** and the drawer compartment **1050** have a shield panel thickness **1052** of about 50 mm.

[0098] The drawer compartment **1050** and the hot cell **1002** together define a drawer access opening **1054** which allows access to the drawer compartment **1050** from the hot cell **1002**. A drawer shield **1056** is slidably positioned over the drawer access opening **1054** and configured to provide shielding when the drawer door **1036** is open. That is, the drawer shield **1056** covers the drawer access opening **1054** when the drawer door **1036** is open during the process of loading and unloading equipment into the bin **1040** from the surrounding environment. The drawer shield **1056** does not cover the drawer access opening **1054** when the drawer door **1036** is closed during the process of loading and unloading equipment into the bin **1040** from the hot cell **1002**.

[0099] In the example embodiment, a plurality of processing stations **1058** is positioned within the hot cell **1002**. Each processing station **1058** includes equipment configured to perform a step in the Xe-133 production processes described herein. In the illustrated embodiment, the processing stations **1058** include a charcoal column process station **1060**, a coil processing station **1062**, and a

dose calibration station **1064**. The processing stations **1058** are wells or compartments defined within a bottom **1066** of the hot cell **1002**. Additionally, a plurality of instrumentation devices **1068** configured to measure and control the Xe-133 production process are positioned within the hot cell **1002**. The instrumentation devices **1068** include, for example and without limitation, pressure gauges, flow meters, temperature gauges, valves, and Geiger counters. In alternative embodiments, the instrumentation devices **1068** include any device configured to measure or control the Xe-133 production process.

[0100] In the illustrated embodiment, shield panels **1048** are arranged around the processing stations **1058** such that the processing stations **1058** are shielded. As shown in FIGS. 7 and 9, shield panels **1048** surround the charcoal column process station or charcoal column assembly receptacle **1060**, the coil processing station or coil assembly receptacle **1062**, and the dose calibration station **1064** such that the surrounding environment is shielded from nuclear radiation generated within the processing stations **1058**. Specifically, the dose calibration station **1064** is surrounded by two shield panels **1048** on each side such that a thickness **1070** of the shielding around the dose calibration station **1064** is between about 50-150 mm thick, or about 80-120 mm thick, or in one example about 100 mm thick.

[0101] The charcoal column process station **1060** includes a well or compartment configured to receive the charcoal column assembly **2000** described herein. Specifically, the charcoal column process station **1060** includes a heating and cooling system **1072** positioned within the charcoal column process station **1060** and configured to heat and/or cool the charcoal column assembly **2000**. In the example embodiment, the heating and cooling system **1072** is a heat exchanger that circumscribes the charcoal column assembly **2000**. The heating and cooling system receives a heating fluid or a cooling fluid (more broadly, a thermal transfer fluid) configured to heat or cool the charcoal column assembly **2000**. In alternative embodiments, the heating and cooling system **1072** may be any heating and/or cooling device that enables the glovebox **1000** and the Xe-133 production process to operate as described herein. The coil processing station **1062** includes a well or compartment configured to receive the coil assembly **3000**. Specifically, the coil processing station **1062** includes a Dewar flask **1074** positioned within the coil processing station **1062** and configured to cool the coil assembly **3000**. The Dewar flask **1074** is a vacuum flask or vessel configured to contain a predetermined volume of liquid nitrogen. The Dewar flask **1074** is filled with liquid nitrogen to a predetermined fill line configured to ensure that a coil **3002** of the coil assembly **3000** is completely submerged within the liquid nitrogen during the separation process.

[0102] During operation, an operator places a column transportation vessel, such as column transportation vessel **2500** (FIG. 16), and a coil transportation vessel, such as coil transportation vessel **3500** (FIG. 24), in the bin **1040** and transfers the transportation vessels and into the hot cell **1002** using the drawer **1034**. The transportation vessels are disassembled, and a charcoal column assembly, such as charcoal column assembly **2000** (FIG. 11), is removed from the column transportation vessel and placed into the charcoal column process station **1060**. A coil assembly, such as coil assembly **3000** (FIG. 19), is placed into the coil processing station **1062**. The charcoal column assembly is fluidly connected to an Ascarite® column and the coil assembly. The charcoal column assembly and the coil assembly are used in the Xe-133 production process as described herein. After the Xe-133 production process is complete, the transportation vessels are reassembled and the purified Xe-133 is transported to other facilities or manufacturing processes for further processing.

[0103] FIG. 11 is a top perspective view of an example charcoal column assembly **2000** suitable for use in the glovebox **1000** and the Xe-133 production processes described herein. FIG. 12 is a bottom perspective view of the example charcoal column assembly **2000** suitable for use in the glovebox **1000** and the Xe-133 production processes described herein. FIG. 13 is a top view of the example charcoal column assembly **2000** shown in FIG. 11. FIG. 14 is a side view of the example charcoal column assembly **2000** shown in FIG. 11. FIG. 15 is a side sectional view of the example



charcoal column assembly **2000** shown in FIG. **11** taken along sectional line **15-15**. The charcoal column assembly **2000** is configured to adsorb Xe-133 from an off gas stream generated from the production of Mo-99. The off gas stream includes Xe-133, Kr-85, other isotopes, and other non-radioactive components. The charcoal column assembly **2000** is specifically configured to separate Xe-133 from Kr-85 by adsorbing the Xe-133 while allowing the Kr-85 to pass through the charcoal column assembly **2000**. The Xe-133 is then desorbed and channeled to the Xe-133 production processes for further processing.

[0104] The charcoal column assembly **2000** includes a charcoal column **2002**, a column flange **2004**, a fluid control assembly **2006**, and an outlet tube **2008**. The charcoal column **2002** includes a charcoal column shell **2010** that defines a charcoal column bed **2012**, a charcoal column inlet **2014**, and a charcoal column outlet **2016**. The charcoal column **2002** also has a top **2020** and a bottom **2022**. The charcoal column bed **2012** is configured to contain a volume of activated charcoal **2018** configured to adsorb Xe-133. The charcoal column inlet **2014** is defined in the top **2020** of the charcoal column **2002**, and the charcoal column outlet **2016** is defined in the bottom **2022** of the charcoal column **2002**. The charcoal column bed **2012** has a bed diameter **2024**, a bed length **2026**, and a bed volume **2028**. In the example embodiment, the bed diameter **2024** is in a range from about 10 millimeters (mm) to about 30 mm. More specifically, the bed diameter **2024** is in a range from about 20 mm to about 25 mm. More particularly, the bed diameter **2024** is about 24 mm. In the example embodiment, the bed length **2026** is in a range from about 100 mm to about 200 mm. More specifically, the bed length **2026** is in a range about 120 mm to about 160 mm. More particularly, the bed length **2026** is about 145 mm. In the example embodiment, the bed volume **2028** is in a range from about 50 cubic centimeters (cc) to about 100 cc. More specifically, the bed volume **2028** is in a range from about 55 cc to about 70 cc. More particularly, the bed volume **2028** is about 65 cc.

[0105] The column flange **2004** includes a first side or a bottom side **2030**, a second side or a top side **2032**, a column flange diameter **2034**, and a column receiver **2036**. The column flange **2004** defines a column flange inlet **2038** and a column flange outlet **2040**. The column receiver **2036** extends from the first side **2030** of the column flange **2004** and is sized and shaped to receive the top **2020** of the charcoal column **2002** such that the charcoal column **2002** extends from the first side **2030** of the column flange **2004**. In the example embodiment, the column flange diameter **2034** is in a range from about 100 mm to about 200 mm. More specifically, the column flange diameter **2034** is in a range from about 150 mm to about 180 mm. More particularly, the column flange diameter **2034** is about 165 mm.

[0106] The fluid control assembly **2006** is positioned on the second side **2032** of the column flange **2004**. The fluid control assembly **2006** includes a column inlet assembly **2042** and a column outlet assembly **2044**. The column inlet assembly **2042** includes an inlet connector **2046**, an inlet tube **2048**, and an inlet valve **2050**. Similarly, the column outlet assembly **2044** includes an outlet connector **2052**, a control assembly outlet tube **2054**, and an outlet valve **2056**. The inlet connector **2046** and the outlet connector **2052** are configured to connect to an inlet conduit (not shown) and an outlet conduit (not shown) respectively. The inlet conduit is configured to channel a flow of off gas, including Xe-133 and Kr-85, to the inlet connector **2046** and the charcoal column assembly **2000**. The outlet conduit is configured to channel the unadsorbed flow of off gas from the outlet connector **2052** and the charcoal column assembly **2000**. The inlet tube **2048** is fluidly connected to the inlet connector **2046** and the charcoal column inlet **2014**. The inlet tube **2048** extends through the column flange inlet **2038** to the charcoal column inlet **2014**. The inlet valve **2050** is attached to the inlet tube **2048** and controls the flow of off gas into the charcoal column **2002**. The control assembly outlet tube **2054** is fluidly connected to the outlet connector **2052** and the outlet tube **2008**. The control assembly outlet tube **2054** extends through the column flange outlet **2040** to the outlet tube **2008**. The outlet valve **2056** is attached to the control assembly outlet tube **2054** and controls the flow of off gas from the charcoal column **2002**. In the example embodiment, both the

inlet valve **2050** and the outlet valve **2056** are plug valves. In alternative embodiments, the inlet valve **2050** and the outlet valve **2056** may be any type of valve that enables the charcoal column assembly **2000** and the Xe-133 production processes to operate as described herein.

[0107] The outlet tube **2008** is fluidly connected to the charcoal column outlet **2016** and the control assembly outlet tube **2054**. The outlet tube **2008** includes an outlet tube inlet **2058** fluidly connected to the charcoal column outlet **2016**, and an outlet tube outlet **2060** fluidly connected to the control assembly outlet tube **2054**. As such, the outlet tube inlet **2058** is positioned proximate the bottom **2022** of the charcoal column **2002** and the outlet tube outlet **2060** extends through the column flange outlet **2040**. The outlet tube **2008** is configured to channel the flow of off gas from the charcoal column **2002** to the column outlet assembly **2044**.

[0108] In the illustrated embodiment, the adsorption of Xe-133 into the activated charcoal **2018** is dependent upon the temperature of the adsorption process, the velocity of the off gas stream through the charcoal column bed **2012**, and the concentration of Xe-133 in the off gas stream. In the example embodiment, the temperature of the adsorption process is maintained in a range from about  $-5^{\circ}$  C. to about  $20^{\circ}$  C. More specifically, the temperature of the adsorption process is maintained in a range from about  $-5^{\circ}$  C. to about  $10^{\circ}$  C. More particularly, the temperature of the adsorption process is maintained at about  $3^{\circ}$  C., such that the heating and cooling system **1072** cools the charcoal column assembly **2000** to about  $3^{\circ}$  C. during the adsorption process. More Xe-133 is adsorbed into the activated charcoal **2018** at lower temperatures. However, more Kr-85 is also adsorbed into the activated charcoal **2018** at lower temperatures. As such, the operating temperature of  $3^{\circ}$  C. during the adsorption process is a temperature that balances adsorption of Xe-133 and Kr-85.

[0109] The velocity of the off gas stream through the charcoal column bed **2012** is determined by the bed diameter **2024** and the flow rate of the off gas in the charcoal column bed **2012**. The bed diameter **2024** is a constant determined by the geometry of the charcoal column bed **2012**. The flow rate of the off gas in the charcoal column bed **2012** is set such that the velocity of the off gas stream through the charcoal column bed **2012** is a predetermined velocity that promotes the selective adsorption of Xe-133. If the velocity of the off gas stream through the charcoal column bed **2012** is too high, the adsorption of Xe-133 will be too low. Conversely, if the velocity of the off gas stream through the charcoal column bed **2012** is too low, the adsorption of Xe-133 will increase, but the adsorption of Kr-85 also increases. As such, the predetermined velocity is designed to balance the adsorption of Xe-133 with the adsorption of Kr-85. In the example embodiment, the flow rate of the off gas in the charcoal column bed **2012** is in a range of about 1.2 normal liters per minute (NL/min) to about 1.8 NL/min. Additionally, the velocity of the off gas stream through the charcoal column bed **2012** is in a range of about 5 centimeters per second (cm/s) to about 10 cm/s. More particularly, the velocity of the off gas stream through the charcoal column bed **2012** is about 7 cm/s.

[0110] Higher concentrations of Xe-133 in the off gas stream generally increase the adsorption of Xe-133 into the activated charcoal **2018**. Accordingly, the geometry of the charcoal column bed **2012**, the temperature of the adsorption process, and the flow rate of the off gas in the charcoal column bed **2012** can be tuned to balance the selective adsorption of Xe-133 within the activated charcoal **2018**.

[0111] During operations, the inlet conduit (not shown) channels the flow of off gas to the column inlet assembly **2042** which channels the flow of off gas to the charcoal column **2002**. The off gas is channeled through the charcoal column bed **2012**, where Xe-133 is selectively adsorbed into the activated charcoal **2018**. The heating and cooling system **1072** maintains the temperature of the charcoal column assembly **2000** at  $3^{\circ}$  C. as the off gas is channeled through the charcoal column bed **2012**. The unadsorbed off gas is channeled from the charcoal column bed **2012** through the outlet tube **2008** to the column outlet assembly **2044**. The column outlet assembly **2044** channels the unadsorbed off gas to the outlet conduit (not shown).

[0112] After the entire volume of off gas has been channeled through the charcoal column **2002**, the inlet valve **2050** and the outlet valve **2056** are closed. The outlet conduit is fluidly connected to an inlet of a coil assembly, such as coil assembly **3000**. The inlet conduit is fluidly connected to a supply of carrier helium gas. The heating and cooling system **1072** heats the charcoal column assembly **2000** to about 80° C. and a flow of helium carrier gas is channeled through the charcoal column bed **2012**. The increased temperature causes the activated charcoal **2018** to desorb the Xe-133 into the flow of helium carrier gas. The desorbed Xe-133 and the flow of helium carrier gas are then channeled to the coil assembly for further processing.

[0113] In an alternative embodiment, the Xe-133 is stored within the activated charcoal **2018** rather than desorbing the Xe-133 and sending the desorbed Xe-133 to the coil assembly. In an example embodiment, the column assembly **2000** is incorporated into a column transportation vessel **2500**. FIG. **16** is a perspective view of an example column transportation vessel **2500** incorporating the charcoal column assembly **2000**. FIG. **17** is a perspective sectional view of the example column transportation vessel **2500** shown in FIG. **16**. FIG. **18** is a schematic sectional view of the example column transportation vessel **2500** shown in FIG. **16**. In addition to the column assembly **2000**, the column transportation vessel **2500** also includes a first or bottom nuclear radiation shield **2502** and a second or top nuclear radiation shield **2504**. In the example embodiment, the first nuclear radiation shield **2502** is removably attached to the first side **2030** of the column flange **2004**, and the second nuclear shield **2504** is removably attached to the second side **2032** of the column flange **2004** such that the first and second nuclear shields **2502** and **2504** completely enclose the column assembly **2000**.

[0114] The first nuclear radiation shield **2502** includes a first shielded portion **2506** and a first shield flange **2508**. The first shielded portion **2506** includes a first end **2510** and a second end **2512**. The first shield flange **2508** extends from the first end **2510** of the first shielded portion **2506** and defines a plurality of first shield fastener receptacles **2514**. The first shielded portion **2506** also includes a first shield inner shell **2516**, a first shield outer shell **2518**, and a first shield shielding **2520**. The first inner shield shell **2516** has a substantially cylindrical shape and defines a first shield inner shell diameter **2522** and a first shield inner cavity **2524** sized and shaped to receive the charcoal column **2002** and the outlet tube **2008** therein. The first shield outer shell **2518** has a substantially cylindrical shape and defines a first shield outer shell diameter **2526** and a first shield outer cavity **2528** sized and shaped to receive the first inner shield shell **2516** and the first shield shielding **2520** therein. The first shield outer shell diameter **2526** is larger than the first shield inner shell diameter **2522** such that a substantially cylindrical shielding volume **2530** is formed therebetween. The first shield shielding **2520** is positioned within the shielding volume **2530** and includes a first shield shielding thickness **2532**. In the example embodiment, the first shielding thickness **2532** is in a range from about 1 mm to about 100 mm. More specifically, the first shielding thickness **2532** is in a range from about 5 mm to about 25 mm. More particularly, the first shielding thickness **2532** is about 5 mm. The first shield shielding **2520** is configured to shield the surrounding environment from nuclear radiation generated within the charcoal column **2002** by the stored Xe-133. In the example embodiment, the first shield shielding **2520** is made of lead.

[0115] The second nuclear radiation shield **2504** includes a second shielded portion **2534** and a second shield flange **2536**. The second shielded portion **2534** includes a first end **2538** and a second end **2540**. The second shield flange **2536** extends from the second end **2540** of the second shielded portion **2534** and defines a plurality of second shield fastener receptacles **2542** (not labeled). The second shielded portion **2534** also includes a second shield inner shell **2544**, a second shield outer shell **2546**, and a second shield shielding **2548**. The second inner shield shell **2544** has a substantially cylindrical shape and defines a second shield inner shell diameter **2550** and a second shield inner cavity **2552** sized and shaped to receive the fluid control assembly **2006** therein. The second shield outer shell **2546** has a substantially cylindrical shape and defines a second shield outer shell diameter **2554** and a second shield outer cavity **2556** sized and shaped to receive the

second inner shield shell **2544** and the second shield shielding **2548** therein. The second shield outer shell diameter **2554** is larger than the second shield inner shell diameter **2550** such that a substantially cylindrical shielding volume **2558** is formed therebetween. The second shield shielding **2548** is positioned within the shielding volume **2558** and includes a second shield shielding thickness **2562**. In the example embodiment, the second shielding thickness **2562** is in a range from about 1 mm to about 100 mm. More specifically, the second shielding thickness **2562** is in a range from about 5 mm to about 25 mm. More particularly, the second shielding thickness **2562** is about 5 mm. The second shield shielding **2548** is configured to shield the surrounding environment from nuclear radiation generated within the charcoal column **2002** by the stored Xe-133. In the example embodiment, the second shield shielding **2548** is made of lead. The second nuclear radiation shield **2504** also includes a handle **2564** extending from the first end **2538** of the second nuclear radiation shield **2504**.

[0116] In the illustrated embodiment, the first nuclear radiation shield **2502** is positioned on the first side **2030** of the column flange **2004** such that the charcoal column **2002** and the outlet tube **2008** are completely enclosed in the first nuclear radiation shield **2502**. The second nuclear radiation shield **2504** is positioned on the second side **2032** of the column flange **2004** such that the fluid control assembly **2006** is completely enclosed within the second nuclear radiation shield **2504**. Additionally, the first nuclear radiation shield **2502** and the second nuclear radiation shield **2504** are positioned such that the first shield fastener receptacles **2514** and the second shield fastener receptacles **2542** align. A plurality of fasteners **2566** are inserted through the first shield fastener receptacles **2514**, the second shield fastener receptacles **2542**, and the column flange **2004** to secure the first nuclear radiation shield **2502**, the second nuclear radiation shield **2504**, and the column flange **2004** to form the column transportation vessel **2500**. The handle **2564** allows an operator to pick up and transport the column transportation vessel **2500**.

[0117] FIG. **19** is a perspective view of an example coil assembly **3000** suitable for use in the glovebox **1000** and the Xe-133 production processes described herein. FIG. **20** is another perspective view of the example coil assembly **3000**. FIG. **21** is a top view of the example coil assembly **3000** shown in FIG. **19**. FIG. **22** is a side view of the example coil assembly **3000** shown in FIG. **19**. FIG. **23** is a side sectional view of the example coil assembly **3000** shown in FIG. **19** taken along sectional line **23-23**. The coil assembly **3000** is configured to freeze and/or condense Xe-133 desorbed from the charcoal column assembly **2000**. The desorbed Xe-133 may also include Kr-85 and helium carrier gas. The coil assembly **3000** is specifically configured to separate the Xe-133 from the Kr-85 and the helium carrier gas by freezing and/or condensing the Xe-133, while allowing the Kr-85 and the helium carrier gas to pass through the coil assembly **3000**. The Xe-133 is then stored in the coil assembly **3000** for further processing.

[0118] The coil assembly **3000** includes a coil **3002**, a coil flange **3004**, and a fluid control assembly **3006**. The coil **3002** includes a coil tube **3008** that includes an inlet portion **3010**, an outlet portion **3012**, and a helical portion **3014**. In the example embodiment, the inlet portion **3010** and the outlet portion **3012** are straight portions of the coil tube **3008**. The helical portion **3014** includes an inlet or first helical portion **3016**, and an outlet or second helical portion **3018** arranged in a double-helix configuration. The inlet portion **3010** is fluidly connected to the inlet helical portion **3016**, which is fluidly connected to the outlet helical portion **3018**. The outlet helical portion **3018** is fluidly connected to the outlet portion **3012**. The inlet helical portion **3016** and the outlet helical portion **3018** are each individual helical tubes wound around the same central axis **3020** such that the inlet helical portion **3016** and the outlet helical portion **3018** form the double-helix configuration. The double-helix configuration increases the length of coil tube **3008** that is submerged within the liquid nitrogen. Accordingly, the double-helix configuration increases the volume of Xe-133 that may be stored and transported in the coil assembly **3000**.

[0119] In the illustrated embodiment, the coil tube **3008** has a coil tube diameter **3022**. In the example embodiment, the coil tube diameter **3022** is in a range from about 5 mm to about 10 mm.

The inlet portion **3010** and the outlet portion **3012** each extend a first distance **3024** from the coil flange **3004** such that a top **3026** of the helical portion **3018** is positioned the first distance **3024** from the coil flange **3004**. The first distance **3024** is long enough to maintain the helical portion **3018** submerged in liquid nitrogen in the Dewar flask **1074** during the desorption process. In the example embodiment, the first distance **3024** is in a range from about 20 mm to about 150 mm. More specifically, the first distance **3024** is in a range from about 50 mm to about 100 mm. More particularly, the first distance **3024** is about 75 mm.

[0120] The coil flange **3004** includes a first side or a bottom side **3030**, a second side or a top side **3032**, and a coil flange diameter **3034**. The coil flange **3004** defines a coil flange inlet **3038** and a coil flange outlet **3040**. The coil **3002** extends from the first side **3030** of the coil flange **3004**. In the example embodiment, the coil flange diameter **3034** is in a range from about 100 mm to about 200 mm. More specifically, the coil flange diameter **3034** is in a range from about 150 mm to about 180 mm. More particularly, the coil flange diameter **3034** is about 165 mm.

[0121] The fluid control assembly **3006** is positioned on the second side **3032** of the coil flange **3004**. The fluid control assembly **3006** includes a coil inlet assembly **3042** and a coil outlet assembly **3044**. The coil inlet assembly **3042** includes an inlet connector **3046**, an inlet tube **3048**, and an inlet valve **3050**. Similarly, the coil outlet assembly **3044** includes an outlet connector **3052**, a control assembly outlet tube **3054**, and an outlet valve **3056**. The inlet connector **3046** and the outlet connector **3052** are configured to connect to an inlet conduit (not shown) and an outlet conduit (not shown), respectively. The inlet conduit is configured to channel a flow of off gas, including Xe-133 and Kr-85, to the inlet connector **3046** and the coil assembly **3000**. The outlet conduit is configured to channel the remaining (i.e., uncondensed) flow of gas from the outlet connector **3052** and the coil assembly **3000**. The inlet tube **3048** is fluidly connected to the inlet connector **3046** and the inlet portion **3010**. The inlet tube **3048** extends through the coil flange inlet **3038** to the inlet portion **3010**. The inlet valve **3050** is attached to the inlet tube **3048** and controls the flow of off gas into the coil **3002**. The control assembly outlet tube **3054** is fluidly connected to the outlet connector **3052** and the outlet portion **3012**. The control assembly outlet tube **3054** extends through the coil flange outlet **3040** to the outlet portion **3012**. The outlet valve **3056** is attached to the control assembly outlet tube **3054** and controls the flow of off gas from the coil **3002**. In the example embodiment, both the inlet valve **3050** and the outlet valve **3056** are plug valves. In alternative embodiments, the inlet valve **3050** and the outlet valve **3056** may be any type of valve that enables the coil assembly **3000** and the Xe-133 production processes to operate as described herein.

[0122] During operations, the coil assembly **3000** is positioned in the Dewar flask **1074** such that the helical portion **3018** is completely submerged within liquid nitrogen. The liquid nitrogen lowers the temperature of the helical portion **3018** to within a range from about  $-220^{\circ}\text{C}$ . to about  $-180^{\circ}\text{C}$ . More particularly, the liquid nitrogen lowers the temperature of the helical portion **3018** to about  $-196^{\circ}\text{C}$ . The inlet conduit (not shown) channels the flow of desorbed Xe-133 to the coil inlet assembly **3042**, which channels the flow of desorbed Xe-133 to the coil **3002**. The desorbed Xe-133 is channeled through the coil **3002**, where Xe-133 condenses and/or freezes within helical portion **3014**. The unfrozen Kr-85 and helium carrier gases are channeled from the coil **3002** through the outlet portion **3014** to the coil outlet assembly **3044**. The coil outlet assembly **3044** channels the unfrozen Kr-85 and helium carrier gases to the outlet conduit (not shown).

[0123] After the entire volume of Xe-133 has been condensed and/or frozen in the coil **3002**, the inlet valve **3050** and the outlet valve **3056** are closed and the coil assembly **3000** is positioned within a coil transportation vessel, such as coil transportation vessel **3500**. FIG. 24 is a perspective view of an example coil transportation vessel **3500** with the coil assembly **3000** positioned therein. FIG. 25 is a perspective sectional view of the example coil transportation vessel **3500** shown in FIG. 24. FIG. 26 is a sectional view of the example coil transportation vessel **3500** shown in FIG. 24. The coil transportation vessel **3500** includes a first or bottom nuclear radiation shield **3502** and

a second or top nuclear radiation shield **3504**. In the example embodiment, the first nuclear radiation shield **3502** is removably attached to the first side **3030** of the coil flange **3004**, and the second nuclear shield **3504** is removably attached to the second side **3032** of the coil flange **3004** such that the first and second nuclear shields **3502** and **3504** completely enclose the coil assembly **3000**.

[0124] The first nuclear radiation shield **3502** includes a first shielded portion **3506** and a first shield flange **3508**. The first shielded portion **3506** includes a first end **3510** and a second end **3512**. The first shield flange **3508** extends from the first end **3510** of the first shielded portion **3506** and defines a plurality of first shield fastener receptacles **3514**. The first shielded portion **3506** also includes a first shield inner shell **3516**, a first shield outer shell **3518**, and a first shield shielding **3520**. The first inner shield shell **3516** has a substantially cylindrical shape and defines a first shield inner shell diameter **3522** and a first shield inner cavity **3524** sized and shaped to receive the coil **3002** therein. The first shield outer shell **3518** has a substantially cylindrical shape and defines a first shield outer shell diameter **3526** and a first shield outer cavity **3528** sized and shaped to receive the first inner shield shell **3516** and the first shield shielding **3520** therein. The first shield outer shell diameter **3526** is larger than the first shield inner shell diameter **3522** such that a substantially cylindrical shielding volume **3530** is formed therebetween. The first shield shielding **3520** is positioned within the shielding volume **3530** and includes a first shield shielding thickness **3532**. In the example embodiment, the first shielding thickness **3532** is in a range from about 10 mm to about 100 mm. More specifically, the first shielding thickness **3532** is in a range from about 25 mm to about 75 mm. More particularly, the first shielding thickness **3532** is about 50 mm. The first shield shielding **3520** is configured to shield the surrounding environment from nuclear radiation generated within the coil **3002** by the stored Xe-133. In the example embodiment, the first shield shielding **3520** is made of lead.

[0125] The second nuclear radiation shield **3504** includes a second shielded portion **3534** and a second shield flange **3536**. The second shielded portion **3534** includes a first end **3538** and a second end **3540**. The second shield flange **3536** extends from the second end **3540** of the second shielded portion **3534** and defines a plurality of second shield fastener receptacles (not labeled). The second shielded portion **3534** also includes a second shield inner shell **3544**, a second shield outer shell **3546**, and a second shield shielding **3548**. The second inner shield shell **3544** has a substantially cylindrical shape and defines a second shield inner shell diameter **3550** and a second shield inner cavity **3552** sized and shaped to receive the fluid control assembly **3006** therein. The second shield outer shell **3546** has a substantially cylindrical shape and defines a second shield outer shell diameter **3554** and a second shield outer cavity **3556** sized and shaped to receive the second inner shield shell **3544** and the second shield shielding **3548** therein. The second shield outer shell diameter **3554** is larger than the second shield inner shell diameter **3550** such that a substantially cylindrical shielding volume **3558** is formed therebetween. The second shield shielding **3548** is positioned within the shielding volume **3560** and includes a second shield shielding thickness **3562**. In the example embodiment, the second shielding thickness **3562** is in a range from about 10 mm to about 100 mm. More specifically, the second shielding thickness **3562** is in a range from about 25 mm to about 75 mm. More particularly, the second shielding thickness **3562** is about 50 mm. The second shield shielding **3548** is configured to shield the surrounding environment from nuclear radiation generated within the coil **3002** by the stored Xe-133. In the example embodiment, the second shield shielding **3548** is made of lead. The second nuclear radiation shield **3504** also includes a handle **3564** extending from the first end **3538** of the second nuclear radiation shield **3504**.

[0126] In the illustrated embodiment, the first nuclear radiation shield **3502** is positioned on the first side **3030** of the coil flange **3004** such that the coil **3002** is completely enclosed in the first nuclear radiation shield **3502**. The second nuclear radiation shield **3504** is positioned on the second side **3032** of the coil flange **3004** such that the fluid control assembly **3006** is completely enclosed

within the second nuclear radiation shield **3504**. Additionally, the first nuclear radiation shield **3502** and the second nuclear radiation shield **3504** are positioned such that the first shield fastener receptacles **3514** and the second shield fastener receptacles **3542** align. A plurality of fasteners **3566** are inserted through the first shield fastener receptacles **3514**, the second shield fastener receptacles **3542**, and the coil flange **3004** to secure the first nuclear radiation shield **3502**, the second nuclear radiation shield **3504**, and the coil flange **3004** to form the coil transportation vessel **3500**. The handle **3564** allows an operator to pick up and transport the coil transportation vessel **3500**.

[0127] Embodiments of the Xe-133 production systems and methods described herein provide several advantages over known systems, as described in the above examples.

## EXAMPLES

[0128] The following examples are non-limiting.

[0129] Six tests were carried out using a dry gas stream made up of 80 parts per million by volume (ppmV) Xenon gas and 16 ppmV Krypton gas. The remainder of the gas was made up of Helium, CO.sub.2, and N.sub.2. The composition of the dry gas stream was selected to simulate the off gas from a Mo-99 production process using LEU.

[0130] In each test, the gas mixture was directed through a system for producing Xe-133 substantially similar to the system **100** shown and described above with reference to FIG. **1** to separate and collect Xenon gas from the gas mixture. The final amount of Xenon recovered in the coil assembly was measured, and is reported in the below table. During testing, the gas stream was not directed through a zeolite column because the gas stream was dry (i.e., substantially free of water vapor). The system used in the tests included a charcoal column assembly containing 32 g of Norit® RB1 charcoal, and a CO.sub.2 removal column containing 130 g of Ascarite® sodium hydroxide-coated silica. The charcoal column assembly had substantially the same configuration as the charcoal column assembly **2000** shown and described above with reference to FIGS. **11-15**. Prior to the Xenon collection tests, the charcoal was subjected to a pre-treatment by heating the charcoal overnight at a temperature of 85° C. while subjecting the charcoal to a flow of Helium gas of 120 NmL/min.

[0131] Each test included an adsorption step and a desorption step. In the adsorption step for each test, the gas mixture was directed, in series, through the CO.sub.2 column assembly containing Ascarite® sodium hydroxide-coated silica and the charcoal column assembly. The Ascarite® sodium hydroxide-coated silica was at room temperature, and the temperature of the charcoal column assembly was regulated to a target temperature of 3° C. The gas mixture was directed through the CO.sub.2 column assembly and the charcoal column assembly at a flow rate of 1.5 NL/min.

[0132] In the desorption step for each test, the charcoal column assembly was disconnected from the supply of gas mixture, sealed, and heated to a temperature of 85° C. Following a pre-heating time of 40 minutes, the charcoal column assembly was connected to a coil assembly submerged in a liquid N.sub.2 bath within a Dewar vessel. The coil assembly was submerged in the liquid N.sub.2 bath for a pre-cooling period of 1 hour prior to being connected to the charcoal column assembly. The coil assembly used in testing had substantially the same configuration as the coil assembly **3000** shown and described above with reference to FIGS. **19-23**.

[0133] A Helium carrier gas was then directed, in series, through the heated charcoal column assembly and through the cooled coil assembly such that Xenon was desorbed from the charcoal column assembly and condensed in the cooled coil assembly. Each test used one of three different flow rates for the carrier gas: 140 NmL/min, 160 NmL/min, or 180 NmL/min. Two tests were carried out at each of the identified carrier gas flow rates. The carrier gas flow was carried out for no more than 80 minutes in each test. Results from each test are reported in the table below.

TABLE-US-00001 Charcoal capacity for Charcoal capacity for Kr Desorption Xe during adsorption during adsorption (NTP Flow Rate Test (NTP  $\mu$ moles/g charcoal)  $\mu$ moles/g charcoal)

(NmL/min) 1 9.7 0.23 140 2 9.8 0.23 160 3 9.6 0.23 180 4 9.9 0.23 140 5 9.8 0.23 160 6 9.0 0.23 180

TABLE-US-00002 Xe concentration Kr concentration in the final in the final Final Xe Recovery  
Test product (ppmV) product (ppmV) at coil assembly(%) 1 24698 <LOD 93.2 2 24126 <LOD  
97.5 3 18858 <LOD 86.0 4 28377 <LOD 105.0 5 25127 28 99.2 6 25127 <LOD 99.2

[0134] The charcoal capacity for Xenon and Krypton during adsorption was measured by following the breakthrough curve with a Mass spectrometry. The units are reported in Normal temperature and pressure (NTP) conditions of micromoles ( $\mu$ moles) per gram charcoal. The Xenon and Krypton concentration in the final product was measured by gas chromatography, with the limit of detection (LOD) for Krypton being 2 ppm. The final Xe recovery percentage was calculated by dividing the total amount of Xe recovered at the coil by the amount of Xe adsorbed on the activated charcoal column assembly for a given test.

[0135] As shown in the table above, the Xenon yield using the systems and methods described herein is relatively high. In particular, the experimental tests resulted in a yield of Xenon in excess of 90% in 4 of 6 tests, in excess of 97% in 3 of 6 tests, and in excess of 99% in 2 of 6 tests. The yield percentage greater than 100% in test 4 is believed to be the result of experimental and/or measurement error.

[0136] Three production tests were also carried out using an off gas from a Mo-99 production process in which low-enriched Uranium targets were irradiated to produce a fission gas. The production tests were carried out using a system having substantially the same configuration as the system **100** shown and described above with reference to FIG. **1**. The length of irradiation and resulting activity range of the produced Mo-99 for each production test are reported in the table below.

TABLE-US-00003 Test No. 1 2 3 Length of Irradiation (hours) 168 114 138 Activity Range (Mo-99 yield 26.86 41.97 41.07 in terabecquerel (TBq))

[0137] For each production test, the off gas generated during the Mo-99 production process was transferred and stored in a vacuum tank outside the hot cell where the Mo-99 production process was carried out. At this stage, the off-gas included primarily Helium, Xenon isotopes, and Krypton isotopes, and was the raw material used in the production tests to produce Xe-133. The off gas was analyzed using Gamma Spectroscopy at two different decay times for each production test. The results of the off gas analysis are reported in the table below.

TABLE-US-00004 Activity Decay (kBq/unit) Activity in Test Time (measuring Statistical  
kBq/bar/l No. (days) Nuclide Yield % time) Uncertainty (ref. time) 1 5.04 Xe-131m 9.96E-01  
9.12E+00 1.13E+00 3.51E+05 Xe-133 1.00E+00 7.15E+03 7.28E+02 3.99E+08 Xe-133m  
9.91E-01 1.28E+02 1.09E+01 1.81E+07 Xe-135 0.944 1.83E+00 1.54E-01 5.12E+08 2 10 Xe-  
131m 9.89E-01 5.18E+01 5.45E+00 3.58E+05 Xe-133 1.00E+00 2.97E+04 3.02E+03 4.27E+08  
Xe-133m 9.91E-01 2.11E+02 1.80E+01 1.92E+07 Xe-135 NA NA NA NA 3 5.03 Xe-131m  
9.88E-01 6.42E+01 6.74E+00 7.31E+05 Xe-133 1.00E+00 4.52E+04 4.60E+03 7.45E+08 Xe-  
133m 9.89E-01 9.01E+02 7.70E+01 3.75E+07 Xe-135 8.79E-01 5.36E+01 4.39E+00 1.25E+06 1  
32 Xe-131m 1.00E+00 1.09E+01 1.22E+00 3.29E+05 Xe-133 1.00E+00 1.29E+03 1.31E+02  
4.08E+08 Xe-133m Not Not resolved Not resolved Not resolved resolved Xe-135 Not Not resolved  
Not resolved Not resolved resolved 2 31 Xe-131m 1.00E+00 1.43E+01 1.53E+00 3.59E+05 Xe-  
133 1.00E+00 1.78E+03 1.81E+02 4.37E+08 Xe-133m 1.00E+00 2.52E-01 8.11E-02 1.87E+07  
Xe-135 Not Not resolved Not resolved Not resolved resolved 3 31 Xe-131m 1.00E+00 8.06E+00  
1.02E+00 5.13E+05 Xe-133 1.00E+00 1.13E+03 1.15E+02 6.71E+08 Xe-133m Not Not resolved  
Not resolved Not resolved resolved Xe-135 Not Not resolved Not resolved Not resolved resolved

[0138] Following a cool down period of at least 24 hours, the off gas was directed, by a vacuum pump, through a condenser, a particle filter, and a zeolite column assembly to remove fluids (e.g., water) and particles. The particle filter included a porous sintered metal media having a porosity of 2 microns or less. The zeolite column assembly included a mass of zeolite of about 16 g. The off



gas was then directed towards the vacuum pump and, pressure controlled at the discharge end of the vacuum pump, directed through a water indicator and a secondary zeolite column assembly having substantially the same configuration as the first zeolite column assembly. The lack of water vapor in the off gas was verified by visually inspecting the water indicator and confirming no change in the appearance of the water indicator.

[0139] The off gas was then directed to a Xenon collection glovebox having substantially the same configuration as the glovebox **1000** shown and described above with reference to FIGS. **2-10**. In the Xenon collection glovebox, the off gas was first directed through a CO.sub.2 removal column assembly containing a mass of Ascarite® sodium-hydroxide coated silicon dioxide of about 130 g. The off gas was then directed through a charcoal column assembly having substantially the same configuration as the charcoal column assembly **2000** shown and described above with reference to FIGS. **11-15**. The charcoal column assembly included a mass of 32 g of Norit® RB1 charcoal, which was subjected to a pre-treatment by heating the charcoal overnight at a temperature of 85° C. while subjecting the charcoal to a flow of Helium gas of 120 NmL/min. The charcoal column assembly was controlled at a reduced temperature while the off gas passed therethrough to provide selective adsorption of Xenon on the charcoal column assembly. The adsorption time and the parameters at the beginning, middle, and end of the adsorption step for each production test are reported in the below table.

TABLE-US-00005 Charcoal Off Gas Supply Off Gas Ad- Column Temp. Pressure Flow Rate  
sorption (start/middle/ (start/middle/ (start/middle/ Test Time end) end) end) No. (minutes) (° C.)  
(bar(g)) (NmL/min) 1 60 0/0/0 0.5/0.5/0.5 1500/1500/1500 2 30 0/0/0 0.5/0.5/0.5 1501/1500/1500  
3 45 0/0/0 0.5/0.6/0.6 1500/1500/1500

[0140] Following adsorption, the loaded charcoal column assembly was disconnected from the off gas supply line, and stored for a maximum decay period of 7 days. Following the decay period, the charcoal column assembly was heated to a temperature of about 101° C. within the Xenon collection glovebox, and connected to a Helium carrier gas supply system to desorb Xenon adsorbed onto the charcoal assembly. The charcoal column assembly was also connected to a cooled coil assembly, also within the Xenon collection glovebox. The coil assembly had substantially the same configuration as the coil assembly **3000** shown and described above with reference to FIGS. **19-23**. The coil assembly was submerged in a liquid N.sub.2 bath within a Dewar flask and allowed to cool for a suitable pre-cooling period (e.g., 1 hour) before the flow of Helium gas was started. After suitable pre-heating and pre-cooling periods for the charcoal column assembly and the coil assembly, respectively, the Helium carrier gas was directed, in series, through the heated charcoal column assembly and through the cooled coil assembly such that Xenon was desorbed from the charcoal column assembly and condensed in the cooled coil assembly. The carrier gas flow was carried out for no more than 80 minutes in each test. The Helium gas supply pressure and flow rate, and the temperature of the charcoal column assembly at the beginning, middle, and end of the desorption step for each test are reported in the table below.

TABLE-US-00006 He Supply Pressure He Gas Flow Rate Test (start/middle/end) Charcoal  
Column Temp. (start/middle/end) No. (bar(g)) (start/middle/end) (° C.) (NmL/min) 1 0.1/0.1/0.1  
101/101/101 163/165/165 2 0.1/0.1/0.1 101/101/101 180/165/165 3 0.1/0.1/0.1 101/101/101  
180/165/165

[0141] Following the desorption step, the coil assembly was evacuated to remove Helium carrier gas from the coil assembly while the coil assembly was submerged in the liquid N.sub.2 bath. After evacuation, the coil assembly was sealed and allowed to reach ambient temperature, and the activity of Xenon gas collected in the coil assembly was measured using an ionization chamber. The Xenon activity levels from each test are reported in the table below.

TABLE-US-00007 Test No. Radioactivity Level (Ci) 1 93.35 2 46.5 3 90.12

[0142] Samples were then collected from each coil assembly, and analyzed to measure the quality and radionuclide purity of the Xenon gas collected in the coil assembly. The appearance of each

sample was visually inspected to confirm the samples were clear and colorless. The identity of the Xenon gas of each sample was confirmed using Gamma Spectrometry to identify major peaks at 31 KeV (X-ray) and 81 KeV. The radionuclidic purity of each sample (based on the percentage of the sample made up of radioxenons (Xe-133, Xe-133m, and Xe-131m)) was also measured using Gamma Spectrometry. Results from each production test are reported below.

TABLE-US-00008

Test No.	1	2	3	Appearance	Clear	and Clear	and Clear	and colorless	colorless
Radionuclide Identification	Peaks at 31 KeV and 81 KeV	Peaks at 31 KeV and 81 KeV	Peaks at 31 KeV and 81 KeV	Total Radioactivity at activity 4.35	1.79	3.24	reference time (TBq)		
Radionuclidic Purity at activity	>99.9%	>99.9%	>99.9%	reference time (as radioxenons)	Xe-133m	0.22%	0.22%	0.22%	Xe-131m
	0.22%	0.22%	0.22%	Xe-131m	0.19%	0.19%	0.19%	Kr-85	<0.008%
	<0.007%	I-131	<0.001%	<0.003%	<0.005%				

[0143] As shown in the table above, each production test resulted in high purity Xenon-133 having a purity of radioxenons (i.e., Xe-133, Xe-133m, and Xe-131m) of at least 99.9%. In some embodiments, the system and methods of the present disclosure may be used to produce Xe-133 gas having a minimum purity of 99.9% of radioxenons, with Xe-133m less than or equal to 0.6%, Xe-131m less than or equal to 1.0%, and all other radioactive impurities (e.g., Kr-85 and I-131) less than 0.1%, with Kr-85 less than or equal to 0.03%, I-131 less than or equal to 0.01%, and all other impurities less than or equal to 0.06%.

[0144] When introducing elements of the present invention or the embodiment(s) thereof, the articles “a”, “an”, “the” and “said” are intended to mean that there are one or more of the elements. The terms “comprising”, “including” and “having” are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0145] As various changes could be made in the above constructions and methods without departing from the scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

## Claims

1. A coil assembly for separation of Xenon-133 from an off gas stream, the coil assembly comprising: a coil flange having a first side and a second side, the coil flange defining a flange inlet and a flange outlet; a coil positioned on the first side of the coil flange, the coil including an inlet portion, an outlet portion, and a helical portion having a double-helix configuration, the helical portion having a top positioned a first distance from the first side of the coil flange, wherein the inlet portion extends through the flange inlet, the outlet portion extends through the flange outlet, and the helical portion is fluidly connected to the inlet portion and the outlet portion; and a fluid control assembly attached to the second side of the coil flange, the fluid control assembly including an inlet assembly and an outlet assembly, wherein the inlet portion is fluidly connected to the inlet assembly and the outlet portion is fluidly connected to the outlet assembly.
2. The coil assembly of claim 1 further comprising a volume of Xenon-133 stored within the coil.
3. The coil assembly of claim 1, wherein the helical portion comprises a first helical portion and a second helical portion, wherein the first helical portion and the second helical portion are each wound around a central axis such that the first helical portion and the second helical portion form the double-helix configuration.
4. The coil assembly of claim 1, wherein the inlet portion and the outlet portion each have a length equal to the first distance.
5. The coil assembly of claim 1, wherein the coil includes a tube formed into the inlet portion, the outlet portion, and the helical portion.
6. A transportation vessel for transportation of Xenon-133, the transportation vessel comprising: a coil assembly comprising: a coil flange having a first side and a second side, the coil flange

defining a flange inlet and a flange outlet; a coil positioned on the first side of the coil flange, the coil including an inlet portion, an outlet portion, and a helical portion having a double-helix configuration, the helical portion having a top positioned a first distance from the first side of the coil flange, wherein the inlet portion extends through the flange inlet, the outlet portion extends through the flange outlet, and the helical portion is fluidly connected to the inlet portion and the outlet portion; and a fluid control assembly attached to the second side of the coil flange, the fluid control assembly including an inlet assembly and an outlet assembly, wherein the inlet portion is fluidly connected to the inlet assembly and the outlet portion is fluidly connected to the outlet assembly; a first nuclear radiation shield removably attached to the first side of the coil flange, the first shield defining a first shield cavity, wherein the coil assembly is positioned within the first shield cavity; and a second nuclear radiation shield removably attached to the second side of the coil flange, the second shield defining a second shield cavity, wherein the fluid control assembly is positioned within the second shield cavity; wherein the first and second shields completely enclose the coil assembly.

**7.** The transportation vessel of claim 6 further comprising a volume of Xenon-133 stored within the coil.

**8.** The transportation vessel of claim 6, wherein the helical portion comprises a first helical portion and a second helical portion, wherein the first helical portion and the second helical portion are each wound around a central axis such that the first helical portion and the second helical portion form the double-helix configuration.

**9.** The transportation vessel of claim 6, wherein the inlet portion and the outlet portion each have a length equal to the first distance.

**10.** The transportation vessel of claim 6, wherein the coil includes a tube formed into the inlet portion, the outlet portion, and the helical portion.

**11.** A system for producing Xenon-133 from an off gas produced during a Molybdenum-99 production process, the system comprising: at least one nuclear radiation shielded enclosure; a storage tank for containing the off gas from the Molybdenum-99 production process, the off gas including Xenon-133 and Krypton-85; and a coil assembly positioned within the at least one nuclear radiation shielded enclosure, the coil assembly comprising: a coil including an inlet portion, an outlet portion, and a helical portion having a double-helix configuration, wherein the helical portion is fluidly connected to the inlet portion and the outlet portion; and a fluid control assembly including an inlet assembly and an outlet assembly, wherein the inlet portion is fluidly connected to the inlet assembly and the outlet portion is fluidly connected to the outlet assembly.

**12.** The system of claim 11 further comprising a vacuum flask positioned within the at least one nuclear radiation shielded enclosure, the vacuum flask containing a volume of cooling fluid, wherein the coil assembly is at least partially submerged in the cooling fluid.

**13.** The system of claim 11, wherein the coil assembly further comprises a coil flange having a first side and a second side, the coil flange defining a flange inlet and a flange outlet, wherein the coil is positioned on the first side of the coil flange, wherein the helical portion has a top positioned a distance from the first side of the coil flange, and wherein the inlet portion of the coil extends through the flange inlet, and the outlet portion of the coil extends through the flange outlet.

**14.** The system of claim 13, wherein the fluid control assembly is attached to the second side of the coil flange.

**15.** The system of claim 11, wherein the coil assembly has a volume of between 10 mL and 100 mL.

**16.** The system of claim 11 further comprising a charcoal column assembly within the at least one nuclear radiation shielded enclosure and selectively connectable to the storage tank to receive the off gas therefrom.

**17.** The system of claim 16, wherein the coil assembly is selectively connectable to the charcoal column assembly to receive a heated gas flow containing Xenon-133 from the charcoal column

assembly.

**18.** The system of claim 17 further comprising a heating and cooling system in thermal communication with the charcoal column assembly and operable to: cool the charcoal column assembly during a selective adsorption step; and heat the charcoal column assembly during a desorption step.

**19.** The system of claim 18 further comprising at least one vacuum pump connected in fluid communication with the storage tank and the charcoal column assembly, the at least one vacuum pump operable to pump the off gas from the storage tank and through the charcoal column assembly.

**20.** The system of claim 18 further comprising at least one evacuated container selectively connectable to an outlet of the coil assembly following the desorption step to evacuate the coil assembly.

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