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Abstract

The Jiangmen Underground Neutrino Observatory (JUNO), a 20~ktons low-background Liquid Scintillator detector (LS), was primarily designed to determine the neutrino mass ordering. JUNO requires UltraPure Water (UPW) with a ^{226}Ra concentration $<50\ Bq/m\hat{}3$ due to the direct liquid-liquid contact between Liquid Scintillator (LS) and UPW during detector filling. To meet this stringent requirement, a highly sensitive measurement system capable of detecting 3.9~μBq/m^3 of ^{226}Ra was developed, and the 100 t/h UPW production process was optimized. By integrating selective ion-exchange resin with membrane separation technologies, UPW with a ^{226}Ra concentration of $<4\ Bq/m\hat{}3$ was consistently produced, exceeding JUNO' s specifications and setting a world-leading benchmark. This paper describes the design and implementation of JUNO' s UPW system and the highly sensitive ^{226}Ra measurement system, along with a systematic evaluation of ^{226}Ra removal efficiency across purification stages and final water quality validation.

Full Text

Producing μBq/m^3 level low ^{226}Ra ultrapure water for the Jiangmen Underground Neutrino Observatory*

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The Jiangmen Underground Neutrino Observatory (JUNO), a 20 ktons low-background Liquid Scintillator detector (LS), was primarily designed to determine the neutrino mass ordering. JUNO requires UltraPure Water (UPW) with a ^{226}Ra concentration < 50 μBq/m^3 due to the direct liquid-liquid con-

tact between Liquid Scintillator (LS) and UPW during detector filling. To meet this stringent requirement, a highly sensitive measurement system capable of detecting 3.9 μBq/m^3 of ^{226}Ra was developed, and the 100 t/h UPW production process was optimized. By integrating selective ion-exchange resin with membrane separation technologies, UPW with a ^{226}Ra concentration of < 4 μBq/m^3 was consistently produced, exceeding JUNO' s specifications and setting a world-leading benchmark. This paper describes the design and implementation of JUNO' s UPW system and the highly sensitive ^{226}Ra measurement system, along with a systematic evaluation of ^{226}Ra removal efficiency across purification stages and final water quality validation.

Keywords: JUNO, Ultra Pure Water, ^{226}Ra, Revise Osmosis, Resin

I. INTRODUCTION

The Jiangmen Underground Neutrino Observatory (JUNO) [1–4] is a multipurpose experiment designed primarily to determine the neutrino mass ordering and precisely measure neutrino oscillation parameters by detecting reactor antineutrinos. With 20 ktons of low-background Liquid Scintillator (LS) and 3%@1MeV unprecedented energy resolution, JUNO is the largest LS-based underground neutrino observatory, capable of addressing numerous important topics in astroparticle physics. JUNO' s extensive physics program includes supernova neutrinos, atmospheric neutrinos, solar neutrinos, geoneutrinos, and new physics searches [1, 2]. Located in an underground laboratory with 700 m overburden, the muon flux at the JUNO site is about 4 mHz/m^2 with a mean energy of 207 GeV [5]. The primary detection channel for reactor antineutrinos in JUNO is the inverse beta decay reaction on protons. JUNO will detect only ~ 60 reactor antineutrino events per day. Therefore, strict control of radioactive background is essential [6].

Fig. 1 shows a schematic drawing of the JUNO detector, which comprises a Central Detector (CD), a Water Cherenkov Detector (WCD), and a Top Tracker (TT) detector. The CD contains 20 ktons of ultrapure LS within a spherical acrylic vessel, and is submerged in the WCD, which contains 40 ktons of Ultra Pure Water (UPW) and is equipped with 2400 20-inch MicroChannel Plate Photomultiplier Tubes (MCP-PMTs). The WCD provides sufficient water shielding to protect the CD from surrounding radioactivity and also serves as a cosmic muon veto. For background and safety considerations, the CD and WCD must be filled with UPW simultaneously initially. Subsequently, the UPW in the CD is replaced with LS at a production speed of 7 m^3/h. During the LS replacement process, UPW and LS will be in direct contact. Since this is the final stage before detector operation, strict control of radionuclides in the water is essential to prevent UPW from contaminating the LS. One of the most challenging tasks is controlling the ^{226}Ra concentration in the water to below 50 μBq/m^3 [2].

In the field of low-background water purification and ^{226}Ra detection, both the Sudbury Neutrino Observatory (SNO) [7] and Super-Kamiokande (Super-K) [8]

experiments have achieved internationally recognized advances. SNO developed a measurement technique using manganese oxide-coated beads, reaching a ^{226}Ra detection sensitivity of ~ 10 μBq/m^3. The initial ^{226}Ra concentration in SNO' s UPW was ~ 50 μBq/m^3, later reduced to 10–20 μBq/m^3 through recirculation and purification [9]. Super-K adopted SNO' s methodology and achieved a similar sensitivity of ~ 10 μBq/m^3, though with slightly higher ^{226}Ra levels in its UPW: initially 61 ± 13 μBq/m^3, falling to 32 ± 7 μBq/m^3 after recirculation [10]. In terms of production scale, Super-K' s water system capacity is 30 t/h [10], notably larger than

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Figure labels (visible):

- Top Tracker
- Earth Magnetic Field shielding coils
- Central detector:
  - Steel structure
  - Acrylic Sphere
  - 20kton LS
- PMT:
  - 17612 20" PMTs
  - 25600 3" PMTs
  - 78% Coverage
- WCD:
  - 40 kton Pure water
  - 2400 20" PMTs
- Acrylic Sphere: Φ 35.4m
- Stainless steel lattice shell: Φ 40.1m
- Water Pool: Φ 43.5m
- Pool Depth: 44m

Fig. 1. Schematic drawing of the JUNO detector showing the main components of the experiment.

SNO' s 9 t/h system [7].

This paper is structured as follows. Sec. II describes the UPW system of the WCD. Sec. III details the 3.9 μBq/m^3 highly sensitive ^{226}Ra in water measurement system. The measurement results of the ^{226}Ra concentration after each purification stage and in the final product water are presented in Sec. IV. Potential upgrades to the system for enhanced ^{226}Ra removal are discussed in

Sec. V, and a summary of the work is provided in Sec. VI.

II. UPW SYSTEM

The JUNO experiment employs a 100 t/h UPW system to provide 40 ktons of UPW for the WCD. This system produces water meeting the following specifications: a resistivity > 18.2 M $*$ cm, a ^{222}Rn concentration of $< 1 \times 10^4$ μBq/m^3, and a minimum temperature of 17 °C, ensuring high muon detection efficiency of WCD, negligible radioactive contribution to CD, and thermal stability for the CD [1]. Furthermore, for the initial filling of the acrylic vessel, this system must deliver UPW at 50 t/h with a ^{226}Ra concentration below 50 μBq/m^3 [2].

The JUNO 100 t/h UPW system utilizes tap water as feedwater to produce UPW compliant with China' s national electronic grade EW-I standard [11]. As shown in Fig. 2, the system comprises aboveground and underground sections. The aboveground treatment system consists of sequential units:

- Bag filters (with a pore size of 5 μm).
- Multi-media filters (stratified quartz sand, activated carbon, anthracite).
- Activated carbon filters (coconut shell-derived carbon).
- Softening resin columns (special ^{226}Ra removal resin from a Chinese manufacturer).
- Cartridge filters (with a pore size of 5 μm).
- Reverse Osmosis (RO) membranes.

Pretreatment begins with mechanical filtration via bag filters for bulk particulate removal, followed by multi-media filtration for suspended solids reduction. Subsequent activated carbon adsorption removes residual chlorine, organic compounds, ammonia-nitrogen species, nitrites, trace heavy metals, and microbial contaminants. Ion-exchange softening achieves Ca^{2+}/Mg^{2+} removal through cationic substitution. After intermediate storage, water passes through cartridge filters (5 μm) to protect downstream equipment. The RO array provides primary desalination via semipermeable membranes, achieving near-complete ionic rejection [12].

The multi-media filters, activated carbon units, and softening resin are regenerable. Multi-media filters and activated carbon filters undergo hydraulic backwashing to restore capacity, while softening resins are regenerated with NaCl brine to displace accumulated ions and restore exchange capacity. This ensures sustainable long-term operation.

Product water from the aboveground system is transferred to the underground through a 1,300 m stainless-steel pipeline. With an elevation differential of $\sim$ 450 m, water first passes through a pressure-reducing valve before entering the storage tank. The underground water system includes:

- Secondary RO membranes (enhanced desalination).
- ElectroDeIonization (EDI) device.
- Cartridge filters (with a pore size of 0.1 μm).

Flow chart of the JUNO 100 t/h UPW system. The process begins with tap water passing through S1, a 5 μm filter bag, S2, a raw-water tank, S3, a pump, a multi-media filter, S4, activated carbon, S5, softening resin, S6, a pre-treatment water tank, S7, two stages of 5 μm filtration, S8, a high-pressure pump, first-stage RO, S9, a first-stage RO tank, and a pump. Water is then sent via a clean PVC water pipe to the sloping tunnel and a 1300 m SST water pipe underground. The underground system includes a pressure-regulating valve, storage tank, high-pressure pump, second-stage RO, second-stage RO tank, pumps, TOC units, degassers, EDI, UV units, 0.1 μm filters, polishing resin, microbubble generator, ultrafilter, heat exchangers, and CD/WCD circulation branches.

Figure 1: Flow chart of the JUNO 100 t/h UPW system. The process begins with tap water passing through S1, a 5 μm filter bag, S2, a raw-water tank, S3, a pump, a multi-media filter, S4, activated carbon, S5, softening resin, S6, a pre-treatment water tank, S7, two stages of 5 μm filtration, S8, a high-pressure pump, first-stage RO, S9, a first-stage RO tank, and a pump. Water is then sent via a clean PVC water pipe to the sloping tunnel and a 1300 m SST water pipe underground. The underground system includes a pressure-regulating valve, storage tank, high-pressure pump, second-stage RO, second-stage RO tank, pumps, TOC units, degassers, EDI, UV units, 0.1 μm filters, polishing resin, microbubble generator, ultrafilter, heat exchangers, and CD/WCD circulation branches.

- Total Organic Carbon (TOC) removal.

Fig. 2. The flow chart of the JUNO 100 t/h UPW system.

- Ultra-Violet (UV) sterilization.
- Degassing membranes.
- Microbubble generator.
- Heat exchangers.
- Ultra-Filtration (UF).

The secondary RO membranes provide additional ion removal. EDI units combine ion-selective membranes and resin under DC fields for continuous deionization without chemical regeneration [13]. Cartridge filters capture residual particles. TOC/UV systems sterilize through UV irradiation while oxidatively decomposing organics. Degassing membranes, employing hollow fibers, vacuum pumps, and purging nitrogen, remove dissolved gases via partial pressure differentials, and are critical for ^{222}Rn removal from water [14–16]. Microbubble generators enhance the ^{222}Rn removal efficiency of degassing membranes by reloading nitrogen into water [14, 16]. Heat exchangers regulate water temper-

ature. UF membranes, with a pore size of $\leq$ 10 nm, remove trace amounts of ions, particles, colloids, and bacteria from water.

The 100 t/h UPW system supplies water for both the WCD and the initial filling of the CD. Owing to their distinct requirements, the two streams undergo separate treatments. The CD-bound water, which contacts the LS directly, receives additional UF for enhanced removal of ionic contaminants (^{238}U/^{232}Th/^{226}Ra). The WCD-bound water, however, is routed through a dedicated heat exchanger to remove heat from the submerged PMT electronics, thereby ensuring stable detector temperatures.

III. ^{226}Ra Concentration in Water Measurement

The required ^{226}Ra concentration of 50 μBq/m^3 ($\sim 2 \times 10^{-21}$ g/g) is beyond the detection capability of conventional methods like high-purity Germanium spectrometry [17] and inductively coupled plasma mass spectrometry [18]. Consequently, a custom system was developed, which determines the ^{226}Ra activity by measuring its gaseous daughter, ^{222}Rn.

A. Measurement principle

The initial step in measuring the ^{226}Ra concentration in water via ^{222}Rn emanation is ^{226}Ra pre-concentration. The method leverages the strong adsorption of ^{226}Ra onto MnO_2 [9, 19, 20], using laboratory-synthesized Manganese fiber (Mn-fiber) [21, 22].

Following ^{226}Ra extraction, the activity of ^{222}Rn emanated from the Mn-fiber during a sealed period is measured. Fig. 3 illustrates the relevant decay branch of ^{226}Ra. During sealing, the relationship between the activity of ^{226}Ra and its ^{222}Rn progeny activity can be calculated according to Eq. 1:

$$A_{\mathrm{Rn}}(t) = A_{\mathrm{Ra}} \times \frac{\lambda_{\mathrm{Rn}}}{\lambda_{\mathrm{Rn}} - \lambda_{\mathrm{Ra}}} \times (e^{-\lambda_{\mathrm{Ra}} t} - e^{-\lambda_{\mathrm{Rn}} t}) \tag{1}$$

where $A_{\mathrm{Rn}}(t)$ is the ^{222}Rn activity at time t in the unit of mBq, A_{Ra} is the initial activity of ^{226}Ra extracted by Mn-fiber in

Fig. 3. The relevant decay branches of ^{226}Ra. The times listed in the parentheses represent their half-lives. The energy for α decay is the peak energy, while for β decay is the maximum energy.

the unit of mBq, λ_{Rn} is the decay constant of ^{222}Rn, λ_{Ra} is the decay constant of ^{226}Ra, and t is the Mn-fiber sealing time in the unit of day.

Given that the half-life of ^{226}Ra is significantly longer than that of ^{222}Rn (i.e., $\lambda_{Ra} \ll \lambda_{Rn}$), Eq. 1 can be simplified to Eq. 2:

$$A_{Ra} = \frac{A_{Rn}(t)}{1 - e^{-\lambda_{Rn} t}} \tag{2}$$

B. Measurement procedures and devices

The ^{226}Ra concentration measurement comprises four steps: (1) Mn-fiber synthesis, (2) ^{226}Ra extraction from water, (3) Mn-fiber encapsulation, and (4) ^{222}Rn activity determination.

1. Mn-fiber

To meet JUNO' s requirement for μBq/m^3 level ^{226}Ra measurements, we significantly reduced the ^{226}Ra background of the key adsorbent, Mn-fiber, from $\sim$ 17 μBq/g to 10.7 ± 1.5 μBq/g. This was achieved through three major enhancements to the standard synthesis protocol [21, 22]:

(1) Nitric acid pre-cleaning of the polyurethane fibers.

(2) Moving the boiling and rinsing processes to a cleanroom.

(3) Substituting distilled water with high-purity water from China Resources C' estbon Beverage (China) Co., Ltd for rinsing—the most impactful change.

$$2\,\mathrm{KMnO_4} + 2\,\mathrm{H_2SO_4} \xrightarrow{\Delta} \mathrm{Mn_2O_7} + 2\,\mathrm{KHSO_4} + \mathrm{H_2O} \tag{3}$$

$$2\,\mathrm{Mn_2O_7} \longrightarrow 4\,\mathrm{MnO_2} + 3\,\mathrm{O_2}\uparrow \tag{4}$$

Fig. 4. A picture of the laboratory-synthesized Mn-fiber.

The Mn-fiber itself is produced by creating a firm MnO_2 coating on the polyurethane fibers via reaction of $KMnO_4$ with H_2SO_4 under heated conditions (Eq. 3, Eq. 4). A picture of the Mn-fiber is shown in Fig. 4. Gravimetric analysis indicates a $\sim$ 13% mass increase in polyurethane fibers after being made into Mn-fiber.

2. Extraction column

Fig. 5. A picture of the column with Mn-fiber.

The ^{226}Ra extraction column, illustrated in Fig. 5, is constructed from an acrylic tube ($\sim$ 20 mm inner diameter and

~185 mm long) sealed with rubber gaskets and 10 mm quick-connects. The assembled unit withstands water pressures up to $\sim$ 5 kg/cm^2. Approximately 5 g of Mn-fiber is packed in the central section, flanked by polyurethane fibers at both ends to filter particulate matter. During operation, water is directed upward through the column to maximize contact with the Mn-fiber. A residential water meter (GB/T 778 compliant [23], $\pm$2% accuracy) at the outlet measures the total volume of water passing through the Mn-fiber.

3. ^{222}Rn emanation measurement system The ^{226}Ra activity extracted by Mn-fibers was quantified by measuring its gaseous daughter ^{222}Rn using a radon emanation measurement system (Fig. 6). The system comprises a radon detector, a Mn-fiber container, a set of dehumidification systems, a mass flow controller (MFC, Model 1179A, MKS), and a vacuum pump (Model ACP40, Pfeiffer Vacuum). All connections use metal-sealed ConFlat flanges and VCR components, ensuring leak tightness $< 1 \times 10^{-9}$ Pa $*$ m^3/s. Key components are summarized below, and the full details were described in our previous work [22].

(1) Radon detector. The radon detector operates on the principle of electrostatic collection [24–30], where detection efficiency for radon progeny correlates with applied collection voltage and gas humidity. At 3% relative humidity and -700 V collection voltage, the detector achieves 90% collection efficiency for ^{222}Rn progeny ^{214}Po. This corresponds to a Calibration Factor (C_F) of 67$\pm$6.7 counts per hour per Bq/m^3 (cph/(Bq/m^3)). The system' s single-day measurement sensitivity is 0.7 mBq/m^3 for ^{222}Rn [24]. For each sample measurement, the radon detector integrates radon activity over a 24-hour data-taking period. As the measured value represents the average ^{222}Rn concentration during this interval, determination of the initial ^{222}Rn concentration requires correction for radioactive decay, which can be calculated according to Eq. 5:

$$A_{Rn} = \frac{A_{Rn-M} \times \lambda_{Rn} \times (t_2 - t_1)}{e^{-\lambda_{Rn} t_1} - e^{-\lambda_{Rn} t_2}} \tag{5}$$

where A_{Rn} is the initial ^{222}Rn activity after transferring into the detector in the unit of mBq, A_{Rn-M} is the measured ^{222}Rn activity in the unit of mBq, t_1 is the start measurement time in the unit of hour, and t_2 is the end measurement time in the unit of hour.

(2) Mn-fiber container. Two chamber types are used (Fig. 7): a standard CF35 tube ($\sim$ 150 mm long) for 5 g samples, and a custom chamber ($\sim$ 130 mm diameter and $\sim$ 300 mm length) for $\leq$ 300 g samples background measurement. All the inner surfaces were electropolished to a roughness of < 0.1 μm. After loading, chambers are purged with boil-off nitrogen to remove the residual air inside and sealed for several days to allow ^{222}Rn ingrowth. The activity ratio between ^{226}Ra and ^{222}Rn can be calculated according to Eq. 2. For instance, after a 10-day sealing interval, ^{222}Rn activity reaches 83.7% of the initial ^{226}Ra activity.

(3) Dehumidification systems. Mn-fibers that extracted ^{226}Ra retain substantial water, releasing significant water vapor during radon transfer that degrades detector efficiency through humidity interference. This system comprises a liquid nitrogen tank, a solenoid valve, a dewar, a PT100 temperature sensor, and a temperature controller. Through the thermostatic regulation of intermittent liquid nitrogen injection into the dewar, the sys-

tem maintains -60 °C inside the dewar, reducing the relative humidity to 3% at a 1 L/min gas flow rate without introducing background.

(4) MFC. The MFC is used to regulate gas flow rate during radon transfer operations, and its adjustment range is 0.5–5 L/min.

(5) Vacuum pump. Before measurements, the pump evacuates the radon detector and associated pipelines. Subsequently, boil-off nitrogen purges the emanated ^{222}Rn from the Mn-fiber container into the radon detector.

(6) Pipelines and valves. All stainless steel gas pipelines and interconnecting valves were EP-grade components.

C. Extraction efficiency calibration

The efficiency of extracting ^{226}Ra from water by Mn-fiber was calibrated using a standardized ^{226}Ra solution with a concentration of $(9.04 \pm 0.53) \times 10^3$ μBq/m^3. Our prior work [22] demonstrates consistent extraction efficiency across ^{226}Ra concentrations ($760 - 6.1 \times 10^4$ μBq/m^3) and water flow rates (1.6–8 L/min). To cover ^{226}Ra concentrations from 1 to 1×10^4 μBq/m^3 in JUNO, sample volumes are varied, which requires a dedicated calibration of the extraction efficiency for different volumes. Different from absolute quantification, we employed a relative scheme with volume-matched control experiments to simultaneously mitigate detector systematic uncertainties and background in this work.

Tab. 1 presents the calibrated ^{226}Ra extraction efficiencies across different water volumes. Throughout the test, an additional 150 μL of ^{226}Ra solution was added per 300 L of water, and the water flow rate through the Mn-fiber was maintained at $\sim$ 5 L/min.

TABLE 1. ^{226}Ra extraction efficiencies of Mn-fiber for different water volumes. The uncertainties of UPW volume are the accuracy of the water flow meter, and the uncertainties of the efficiencies are statistical only. For samples No.1 - No.4, the radon detector data-taking time is 24 h, while for samples No.5 and No.6, the data-taking time is 15 h.

No.	UPW volume (m^3)	^{226}Ra extraction efficiency (%)
1	0.3 ± 0.006	99 ± 11
2	0.5 ± 0.01	98 ± 10
3	1.0 ± 0.02	99.5 ± 7.4
4	5.0 ± 0.1	94.6 ± 3.2
5	10.0 ± 0.2	91.3 ± 2.8
6	20.0 ± 0.4	89.2 ± 1.9

Fig. 6. A picture of the radon emanation measurement system.

Fig. 7. Pictures of the Mn-fiber containers used in this work.

For water volumes below 1 m^3 passing through the Mn-fiber extraction column, ^{226}Ra extraction efficiency approached $\sim 100\%$. Beyond this volume, a progressive decline in ^{226}Ra adsorption efficiency was observed, which might be caused by a small amount of adsorbed ^{226}Ra MnO_2 shedding.

D. Sensitivity estimation The sensitivity of measuring ^{226}Ra concentration in water at 95% confidence level can be estimated according to Eq. 6:

$$L = \frac{1.645 \times \sigma_{BG} \times V_s}{24 \times C_F \times V_w \times \varepsilon \times 10^{-6}} \tag{6}$$

where L is the sensitivity in the unit of μBq/m^3, σ_{BG} is the statistical uncertainty of the system' s background event rate in the unit of Counts Per Day (CPD), $V_s = 0.042$ m^3 is the total volume of the measurement system, $C_F = 67 \pm 6.7$ cph/(Bq/m^3) is the detector calibration factor, V_w is the sample water volume in the unit of m^3, and ε is the ^{226}Ra extraction efficiency which is listed in Tab. 1. This calculation assumes a normally distributed background event rate and a radioactive equilibrium between ^{222}Rn and ^{226}Ra.

The system background was determined by measuring 5 g of unused Mn-fiber following the standard sealing and analysis procedure. Ten replicate measurements yielded a mean background of 2.7 CPD (Fig. 8), reflecting contributions from both the apparatus and the Mn-fiber.

Using the parameters mentioned above and calculated with Eq. 6, a sensitivity of 3.9 μBq/m^3 for ^{226}Ra concentration in water has been derived. This calculation assumes 20 m^3 of water passes through 5 g Mn-fiber with a ^{226}Ra extraction efficiency of 89.2%, and the data-taking time for ^{222}Rn activity measurement is 24 h.

IV. RESULTS

A. ^{226}Ra concentrations across the system Using the custom-developed device described above, the ^{226}Ra concentrations in water at different locations of the JUNO 100 t/h UPW system, which are marked as S1-S17 in Fig. 2, were measured, and the results are shown in Tab. 2. The water volume for S1-S5 is 0.5 m^3, for S6-S8 and S10

TABLE 2. Measurements of ^{226}Ra concentration (using our custom device), particulate matter count (Bettersize C400 optical particle counter), and resistivity (AZ8302 portable and +GF+ Signet 9900 in-line meters) were conducted across the 100 t/h UPW system, with uncertainties as follows: both statistical and systematic for ^{226}Ra concentration, statistical only for particulate matter, and instrument display accuracy for resistivity. Missing resistivity values are attributed to meter limitations at high resistivity ranges. For sampling locations, refer to Fig. 2.

No.	^{226}Ra concentration(μBq/m^3)	Particulate matter > 0.5 μm (Counts/L)	Resistivity(MΩ*cm)	Location
1	$(429 \pm 44) \times 10^3$	601150 ± 5482	0.019 ± 0.001	S1
2	$(186 \pm 19) \times 10^3$	298750 ± 3864	0.019 ± 0.001	S2
3	$(194 \pm 20) \times 10^3$	341850 ± 4134	0.019 ± 0.001	S3
4	$(147 \pm 15) \times 10^3$	17650 ± 939	0.019 ± 0.001	S4
5	$(426 \pm 44) \times 10^3$	22500 ± 1060	0.018 ± 0.001	S5
6	500 ± 160	46600 ± 1526	0.018 ± 0.001	S6
7	$(76.4 \pm 5.9) \times 10^3$	341850 ± 4134	0.018 ± 0.001	S7
8	$(55.3 \pm 4.5) \times 10^3$	244900 ± 3499	0.052 ± 0.001	S8
9	80 ± 27	2150 ± 328	0.190 ± 0.002	S9
10	$(15.8 \pm 1.4) \times 10^3$	10050 ± 709	0.470 ± 0.005	S10
11	85 ± 29	2750 ± 370	/	S11
12	98 ± 34	2250 ± 335	/	S12
13	56 ± 28	2150 ± 327	17.74 ± 0.01	S13
14	50 ± 25	900 ± 200	/	S14
15	6.2 ± 4.3	850 ± 206	18.19 ± 0.01	S15
16	19.3 ± 6.2	350 ± 132	/	S16
17	< 4	100 ± 70	18.20 ± 0.01	S17

Fig. 8. The distribution of the background event rate. During the background measurement, the Mn-fiber is sealed for 10 days. The uncertainties in the Y-axis are statistical only.

is 1 m^3, for S9 and S11-S14 is 5 m^3, and for S15-S17 is 20 m^3. All measurements were performed after a 10-day Mn-fiber sealing period and a 24-hour ^{222}Rn counting interval. Reported uncertainties include both statistical and systematic contributions from the extraction efficiency. Sample S17 registered only 2 counts during the measurement, below the mean detector background, and thus only an upper limit is provided.

In low-salinity solutions, ^{226}Ra exists predominantly as un-complexed Ra^{2+} [31-33], making it removable via deionization processes. According to Tab. 2, this system reduces ^{226}Ra concentration from $\sim 4 \times 10^5$ μBq/m^3 to < 4 μBq/m^3, representing a reduction of over five orders of magnitude. This $> 99.99\%$ removal efficiency was achieved primarily through the synergistic action of soft-

ening resin and two-stage RO membranes, with each exhibiting > 99% ^{226}Ra removal efficiency. The ^{226}Ra removal efficiencies of the main devices used in the UPW system are shown in Tab. 3. The slight variation in ^{226}Ra removal efficiency between the two RO stages is primarily attributable to influent ^{226}Ra concentration differences. This system employs two polishing resins in series, with tabulated efficiency calculations assuming identical ^{226}Ra removal performance.

However, according to the data shown in Tab. 2, mechanical filtration units (e.g., filter bags, cartridges, multi-media filters) also showed incidental ^{226}Ra removal via adsorption of Ra^{2+} onto particulates, enabling co-removal during filtration. Among all devices, only RO integrates both deionization and particulate removal [34].

TABLE 3. ^{226}Ra removal efficiencies of the devices used in the UPW system. When calculating the ^{226}Ra removal efficiency of the polishing resin, it is assumed that both resin stages have the same efficiency. The uncertainties of the ^{226}Ra removal efficiency are statistical only.

No.	^{226}Ra removal efficiency (%)	Device	^{226}Ra concentration before the device (μBq/m^3)
1	99.88 ± 0.04	Soften resin	$\sim 4.2 \times 10^5$
2	99.86 ± 0.05	1^{st} stage of RO	$\sim 5 \times 10^4$
3	99.46 ± 0.19	2^{nd} stage of RO	$\sim 1.6 \times 10^4$
4	42.86 ± 34.77	EDI	~ 100
5	64.78 ± 15.06	Polishing resin	~ 50

In addition, the data in Tab. 2 also indicates that the ^{226}Ra concentration in water increased after passing through each tank, which is primarily attributable to air ingress through tank ventilation valves. Fiberglass-reinforced plastic tanks require pressure-equalizing vent valves to prevent structural damage during water level fluctuations. These valves introduce ambient air (unfiltered for above-ground tanks, filtered for underground tanks) containing dust-bound ^{226}Ra progenitors that solubilize upon water contact. A significant increase in ^{226}Ra concentration after the pre-treatment water tank was traced to sediment introduced during initial commissioning, when sea salt was used for softening resin regeneration. Although sea salt was replaced by clean regeneration salt and the tank was flushed, residual sediment on the tank walls persisted as a leaching source.

B. Relationship between ^{226}Ra concentration and particulate counts and resistivity

Tab. 2 also lists the particulate counts and resistivity values across the water system. The particulate counts were measured using a Bettersize C400 optical particle counter (Dandong Baxter), the small sample volume (20 mL) contributed to significant data uncertainties. Resistivity was measured using an AZ8302 portable conductivity tester (Taiwan Hengxin) upstream of the secondary RO and a +GF+ Signet 9900 in-line meter downstream. The sampling measurements become unreliable when the resistivity exceeds 10 M $*$ cm, and the in-line measurements prevent modification of the sampling point. These constraints resulted in missing high-resistivity data at multiple locations.

The apparent correlations between ^{226}Ra concentration, particulate counts, and resistivity are merely a coincidental outcome of the purification process. The softening resin achieves $> 99\%$ ^{226}Ra removal by ion exchange (Na^+ replaces Ra^{2+}), which minimally influences resistivity and does not filter particles due to its 100–500 μm bead size. The simultaneous decrease in all parameters is due to their collective removal through successive treatment stages.

V. DISCUSSION

This system reduces ^{226}Ra concentration in water from $\sim 4 \times 10^5$ μBq/m^3 to 4 μBq/m^3. Even though the RO provides high removal efficiency of particulate matter and ions, the softening resin plays a critical complementary role. Our resin screening revealed significant variation in ^{226}Ra removal efficiency, with cationic resins demonstrating superior performance over mixed-bed (anionic/cationic) alternatives. Although the selected softening resin achieves high ^{226}Ra rejection ($> 99\%$), its pre-RO positioning is mandatory and non-interchangeable with post-RO polishing resin due to substantial organic leaching. These leachates cause measurable deterioration of water quality, primarily through resistivity reduction and TOC elevation.

In reducing the source of ^{226}Ra pollution, the following two tasks have been identified:

(1) Thoroughly clean the pre-treatment water tank. The periodic regeneration of softening resin, commonly performed with economical sea salt, was found to introduce sediment containing significant ^{226}Ra contamination. During the initial commissioning phase of the water system, conventional sea salt was used, resulting in a sharp increase in ^{226}Ra concentration – from ~ 500 μBq/m^3 to $\sim 3\times10^5$ μBq/m^3 –after water passed through the pretreatment tank. Visual inspection revealed a substantial layer of sediment at the tank bottom, which subsequent analysis confirmed originated from the sea salt. The data presented in this paper were collected after switching to clean regenerant salt and performing systematic flushing of the tank.

However, even after adopting clean salt and flushing, residual sediment remains adhered to the tank walls. This explains the persistent increase in ^{226}Ra concentration observed after the pretreatment water tank. To fully eliminate this source of contamination, a thorough cleaning of the tank interior is required. As this procedure entails water tank drainage and a temporary system shutdown, it will be scheduled for a suitable maintenance window in the future.

(2) Mitigation of contamination from storage tank breather valves. Storage tanks introduce measurable radiological contamination primarily through their air-admittance breather valves. Two mitigation strategies have been evaluated: installing particulate-retentive filters on breather assemblies or using boil-off nitrogen as a clean breathing gas. While nitrogen blanketing could thoroughly eliminate background con-

tamination, it would require a dedicated gas supply system at significant cost. Furthermore, the existing boil-off nitrogen capacity at the JUNO site is insufficient to meet the system' s operational demand. Therefore, the installation of filtration systems at each tank air inlet has been selected as the practical solution, which will be implemented during a suitable maintenance period.

VI. SUMMARY

JUNO is a multi-purpose neutrino experiment primarily designed to determine the neutrino mass ordering. To ensure detector safety and minimize background, the CD must be filled with UPW containing $< 50\,\mu$Bq/m^3 of ^{226}Ra before LS introduction.

A dedicated 100 t/h UPW production and circulation system was developed, integrating multi-stage purification —such as specialized softening resin and reverse osmosis —with a novel, highly sensitive ($3.9\,\mu$Bq/m^3) ^{226}Ra measurement system. Measurement results across the purification stages demonstrated a $> 99\%$ ^{226}Ra removal efficiency for both the softening resin and RO. Key contamination pathways, including water tank venting and regenerant salt impurities, were identified, and corresponding mitigation strategies have been proposed.

The JUNO 100 t/h water system successfully reduced ^{226}Ra concentration from $\sim 4 \times 10^5\,\mu$Bq/m^3 to $< 4\,\mu$Bq/m^3, achieving a reduction exceeding five orders of magnitude. This performance not only satisfies JUNO' s stringent technical requirements but also represents a world-leading achievement in ultra-low-^{226}Ra water purification.

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