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Status and progress of the JUNO liquid scintillator

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The Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose experiment designed to elucidate fundamental neutrino properties, study neutrinos with astrophysical or terrestrial origins, and search for rare processes beyond the Standard Model of particle physics. Its central detector is a 20 kton liquid scintillator (LS) located 650 m underground in Guangdong, China. To achieve its physics goals, the JUNO LS must have high transparency and very high radio-purity. To purify the LS, five plants were designed: alumina filtration, distillation, mixing, water extraction, and gas stripping. In addition, two corollary plants were designed to supply ultra-pure water and high pure nitrogen for the LS purification system. The installation of all seven plants has been thoroughly completed, and both self-commissioning and joint commissioning of the plants have been carried out. The commissioned samples are currently undergoing testing.

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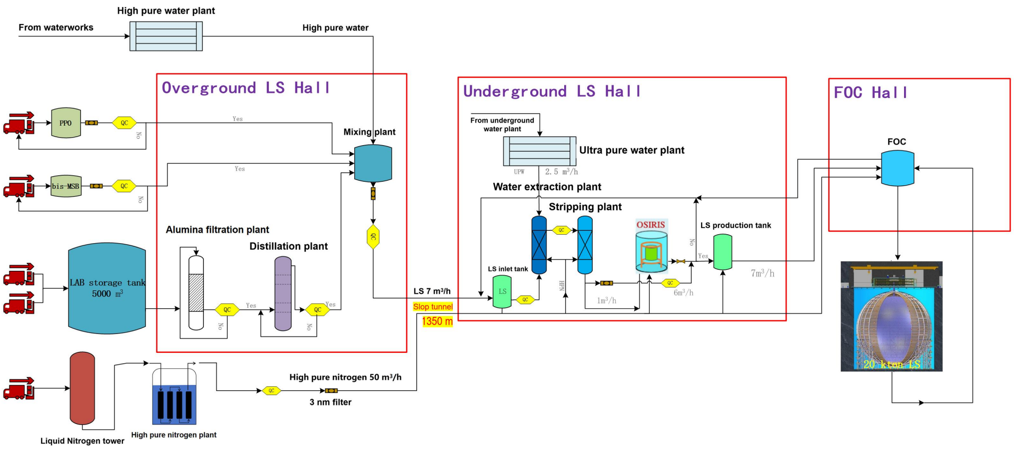

Figure 1: The flow chart of JUNO liquid scintillator system

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a large-scale multi-purpose underground experiment, under construction near Jiangmen city, China. Data taking is expected to start in 2025. The primary purpose of JUNO is to determine the neutrino mass hierarchy and precisely measure the three neutrino oscillation parameters by measuring the energy spectrum of the reactor neutrino [1] [2].

JUNO is located in a 650 m underground neutrino laboratory. JUNO consists of a central detector, a top muon tracker and a water Cherenkov detector. The central detector of JUNO is an acrylic sphere with a diameter of 35.4 m placed in cylindrical water pool of 43.5 m in diameter. A total number of 17612 20-inch photomultiplier tubes (PMTs) and 25600 3-inch PMTs sit outside of the central detector.

JUNO will use 20 kton LS as sensitive medium in the central detector. The JUNO LS is a specific organic compound of Linear Alkyl Benzene (LAB) as solvent, 2,5-Diphenyloxazole (PPO, 2.5 g/L) as primary solute, and 1,4-Bis (2-methylstyryl) benzene (bis-MSB, 3 mg/L) as wavelength shifter [3]. Due to the huge size of the central detector, it is necessary to improve the transparency of the LS as much as possible. To achieve an unprecedented 3% (at 1 MeV) energy resolution at JUNO, the attenuation length (A.L.) is required to be better than 20 m at 430 nm. JUNO LS also requires an extremely high radio-purity: ^{238}U, ^{232}Th in LS $<1\times10^{-15}$ g/g, ^{40}K in LS $<1\times10^{-18}$ g/g for reactor neutrino physics [4].

The JUNO LS purification system consists of five main processes (Figure 1): alumina filtration removes optical impurities to raise the attenuation length, distillation removes high boiling point impurities from LAB, mainly metal and oxides. The Mixing system uses acid extraction to remove the radioactivity in PPO and bis-MSB and then mixes the LS raw materials. Water extraction removes dissolved radioactive metal ions. Gas stripping uses gaseous nitrogen stream or superheated steam to remove dissolved gases, mainly ^{85}Kr, ^{39}Ar, ^{222}Rn and oxygen, from LS phase.

Figure 2: The PPO storage, bis-MSB production and Th/U measurement

Figure 3: The ISO-tank, the stainless steel tank and the interior of tank

2. LS material transportation and storage

The JUNO LS recipe is Linear Alkyl Benzene (LAB)+2.5 g/L PPO +3 mg/L bisMSB. The 20 kton high-quality LAB will be produced with a special process, and will undergo quality checks at the Nanjing LAB factory. The main LAB selection criterion is attenuation length @430$nm \geq 24m$. 200 tons LAB had been transported and filled to big tank on JUNO site in March 2021 for LS commissioning. A purchase contract for 10k tons of LAB has been signed.

For 60 tons PPO need by the JUNO LS, the A.L. requirement of LAB+PPO solution is $> 20m$. ^{232}Th/^{238}U in PPO $\leq 0.43 \times 10^{-12}$g/g. The 50 tons PPO have been accepted and safely stored at the JUNO site. The optical properties of PPO have been qualified. The mass weighted mean value of ^{232}Th(or ^{238}U) concentration of 50 tons PPO is much better than the value specified in the purchase contract. Another 10 tons of PPO will be delivered to the JUNO site before Jun. 2024. The 72 kg bis-MSB is working on the production. ^{232}Th(^{238}U) content in bis-MSB should be lower than 8.3×10^{-12} g/g, the total ^{232}Th(^{238}U) introduced to LS by bis-MSB is lower than that of PPO by one order. The ^{232}Th and ^{238}U concentrations in one of the pilot bis-MSB sample is about 6×10^{-12} g/g for ^{232}Th and about 3×10^{-12} g/g for ^{238}U, this result is better than our requirement (Figure 2).

A 200 new ISO-tanks will be used to transport LAB from factory to the JUNO site. Each ISO-tank has a volume of 25-26 m^3 and can carry about 20 tons of LAB. Figure 3 shows the picture of the ISO-tank. Five batches transportation is organized in six months, which is matched with the six months LS filling plan. About 4000 tons of LAB will send to JUNO site in each batch. The ISO tank was cleaned in company, then sealed with 1 bar nitrogen. A 5000 m^3 tank was constructed at the JUNO site as buffer tank. The 304L stainless steel was used with 0.4 µm roughness of inner surface. It was sealed with 1500 Pa nitrogen. Figure 3 shows the appearance and interior of the 5000 m^3 stainless steel tank.

Figure 4: The alumina filtration plant

3. LS Purification Plant

For achieving the JUNO physics goals, the JUNO LS must have high transparency and ultra-low radiation background. For purifying the LS, five plants were designed and constructed: alumina filtration plant, distillation plant, mixing plant, water extraction plant, and gas stripping plant. In addition, two corollary plants were designed and constructed to supply ultra-pure water and high pure nitrogen for the liquid scintillator purification system. Now, all seven plants have been installed and tested, and have completed two joint commissioning involving all plants.

3.1 Alumina filtration plant

To increase the attenuation length of LS, alumina absorption columns are used to purify the optical impurities in Linear Alkyl Benzene (LAB). An alumina filtration plant (AFP) with eight filtration columns (0.6 m diameter and 2.8 m height) were constructed to remove the optical impurities (Figure 4). The alumina filtration plant can increase the LAB A.L. from about 20 m to more than 24 m without increasing radioactive background at 10^{-15} g/g level. This result was proved by the pilot plant experiment in DYB neutrino station [5]. The AFP has participated in the joint commissioning, the result show that it can work at 7 m^3/h, the optical and radioactive quality of purified LAB meet the JUNO LS requirement.

3.2 Distillation plant

The distillation process is effective in separating and eliminating some heavy and high-boiling radioactive contaminants, such as ^{232}Th, ^{238}U and ^{40}K, from the LAB, while also enhancing its optical parameters, particularly the attenuation length and absorption spectrum. This procedure

Figure 5: Distillation plant

involves boiling the LAB in a seven-meter-tall distillation column (Figure 5). The heavier, less volatile impurities settle and concentrate in the bottom section of the column and are regularly removed twice per hour, while the lightest and purified vapours are extracted at column head, where they are liquified and then stored in a product tank. Up to 50% of the nominal flow rate (7 m^3/h) of the distilled LAB can be redirected back into the column for increased purification efficiency. Equipped with 6 sieve trays featuring liquid build-up, the column establishes a deep contact with the upward stream of LAB vapours, creating multiple gas-liquid stages of equilibrium. The nominal operating conditions of 220 °C in partial vacuum (about 60-70 mbar) have been chosen to ensure a lower boiling temperature of the LAB, in order to prevent thermal degradation [6]. The distillation plant has participated in the joint commissioning, the result show that it can work at 7 m^3/h flux rate smoothly, samples of commissioning are still under measurement.

3.3 Mixing plant

The Mixing Plant, serves two primary functions. Firstly, it combines LAB, PPO, and bis-MSB to form the liquid scintillator. Secondly, it radioactively purifies PPO, achieving a reduction by two orders of magnitude. In the feeding process, PPO and bis-MSB are introduced into the dissolving tank under a pure nitrogen atmosphere, utilizing a glove box. Following dissolution, a more concentrated master solution is formed, subsequently purified through pickling and water washing. The pickling process uses 5% dilute nitric acid at 40 ℃, succeeded by two water washes.

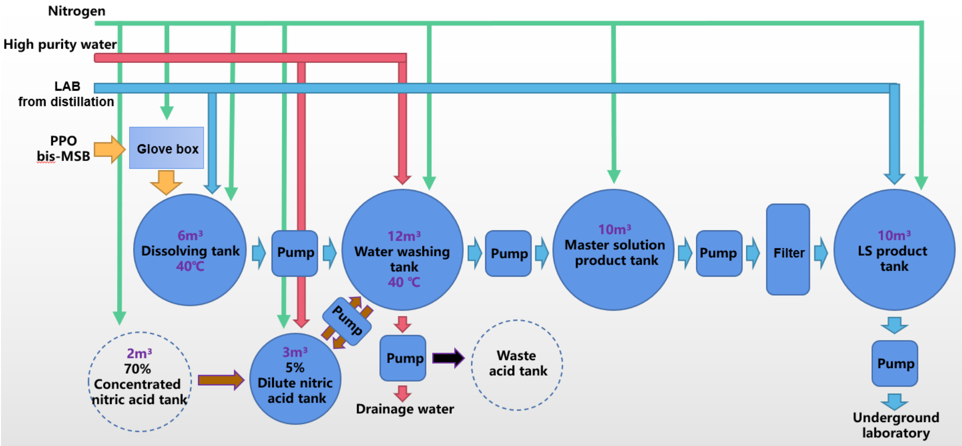

Figure 6: Mixing plant flow chart

Figure 7: The JUNO mixing plant

Post-pickling, the master solution undergoes two-stage filtration using 200 nm and 50 nm filters to eliminate particulate impurities. The filtered master solution is then mixed with LAB to become the liquid scintillator, pumped to the underground laboratory via an inclined pipeline at 7 m^3/h. Figure 6 shows the flow chart of mixing plant, Figure 7 shows the mixing plant. Joint commissioning results show that the pickling process reduced U/Th radioactivity in the LS master solution by an order of magnitude, and filtration reduced particulate matter by three orders of magnitude.

3.4 Water extraction plant

Water extraction use high-purity water to purify the liquid scintillator and remove radioactive metal ions from LS. The aim is to reduce Uranium and Thorium levels in LS from 10^{-16} g/g to 10^{-17} g/g. The extraction tower has a diameter of 1 meter and a height of 13 meters. The inner wall of the tower is divided into 30 chambers by 31 partitions. Inside the tower, there is a 12-meter-long shaft connected to 30 turbines, each located in the center of a chamber. A motor drives the shaft to rotate at a speed of 30 to 50 rpm, which in turn stirs the water and liquid scintillator using the

Figure 8: Water extraction plant

turbines. The extraction tower adopts a counter-current extraction working mode, with a liquid scintillator flow rate of 7 m^3/h, a water flow rate of 2.3 m^3/h, and an LS-water ratio of 3:1. Water is in continuous phase and LS in dispersed phase, which is broken into small droplets due to the stirring of the turbine inside the tower and fully contacts with water for mass transfer. The metal ions in the liquid scintillation dissolve into the water [7].

The installation of the water extraction plant has been completed on May 2023 (Figure 8). The full functional test of the water extraction plant has been completed. Now, the water extraction plant has participated in two rounds of joint commissioning with the LS. It worked smoothly during the joint commissioning.

3.5 Stripping Plant

Gas stripping is a separation technique which aims to eliminate gaseous contaminants naturally dissolved inside the LS (Liquid Scintillator), primarily targeting ^{222}Rn, ^{39}Ar, ^{85}Kr, along with O^2. The purification of the scintillator occurs by flushing a stream of high-purity nitrogen and/or purified water vapor in a counter-current flow mode inside a 9-meter-tall stripping column (Figure 9). The stripping mixture can be adjusted using either just one gas or both of them in variable percentages, ensuring flexible combinations. The liquid is introduced into the column from the top and falls down by gravity, while the gas is fed from the bottom. The column is provided with an internal unstructured packing composed of metal Pall rings, to increase the time and surface of contact between the liquid and gas phases. The nominal operating parameters of the plant have been studied to be approximately 300 mbar and 90 °C, in order to lower the viscosity of the scintillator and ensure better performances [6]. The nominal flow rate for the purified LS is set at 7 m^3/h.The stripping plant has participated in the joint commissioning, the result show that it can work at 7 m^3/h smoothly, samples of commissioning are still under measurement.

3.6 High purity nitrogen plant

High purity nitrogen (HPN) is used in several JUNO sub-systems. For LS purification, HPN is used as purging gas in stainless steel tank and pipeline and as the stripping gas for LS stripping

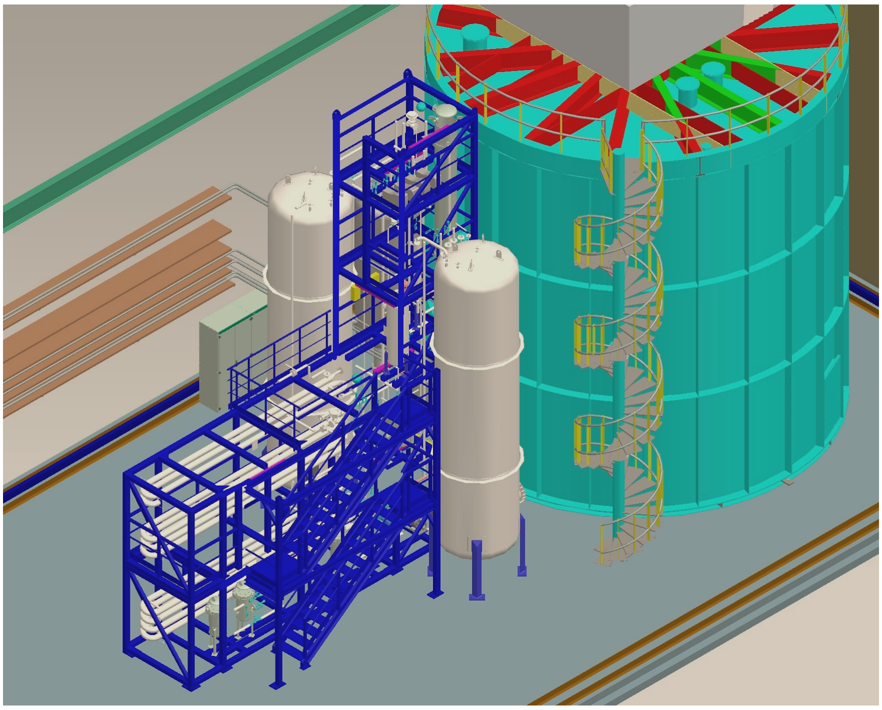

Figure 9: Stripping plant

plant to remove the radioactive gas dissolved in LS. According to JUNO's requirements, the radon concentration in HPN should be less than 10 µBq/m ^{3}. To meet this requirement, a high-purity nitrogen plant with 100 Nm3/h maximum rate was designed and constructed. High purification efficiency was ensured by using an high pure activated carbon column with high column height-to-diameter ratio.

The HPN plant is shown in Figure 10. The raw nitrogen of the HPN plant is liquid nitrogen. After the liquid nitrogen is filtered to remove trace particles, it is directly sent to the activated carbon column for low temperature adsorption purification. The purified liquid nitrogen is then vaporized into high purity nitrogen through heat exchange by a water bath heater. The pressure in the adsorption column is kept at 8 bar controlled by the back pressure valve. The flow rate of the plant is controlled by the proportional control valve operating at 50 Nm^3/h while working at single column. After passing through 3 nm filter, the HPN is transported through pipelines to underground LS hall. Follow this process, after ten days of continuous operation at 50 Nm^3/h flux rate, the plant can to reduce the radon concentration in nitrogen from 37.4 ± 1.8 µBq/m^3 to less than 1.33 µBq/m ^{3}.

3.7 Ultra pure water plant

Water extraction needs ultra pure water (UPW) to remove the radioactive elements from LS, a ultra pure water plant was designed and constructed (Figure 11). The low radioactivity requirement of the UPW for water extraction plant are U(Th) concentration in water < 1×10^{-16} g/g, Rn concentration in water < 1 mBq/m^3.Therefore, the UPW plant is not only based on the top technologies of UPW in semiconductor industry, but also added some special, such as micro bubble

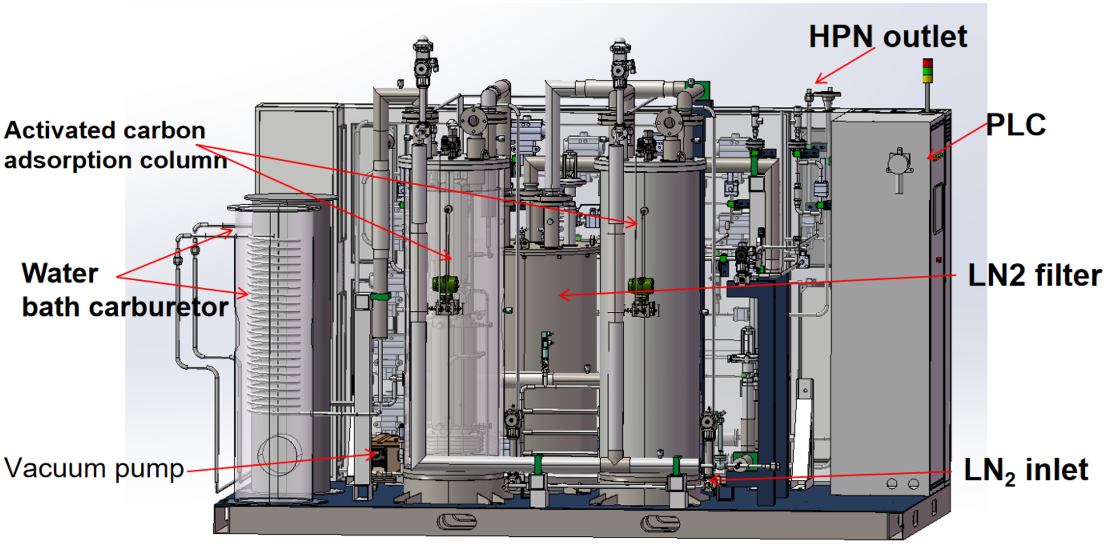

Figure 10: Stripping plant

Figure 11: Ultra pure water plant

device and modified ion filter. The UPW plant has been finished self-commissioning in May 2023. Now it is running for Water Extraction plant commissioning. Most of indexes (online measurement) are qualified now, and particles count is 50% lower than design. Anions/metals, U(Th,Rn) will be measured in May 2024.

4. Summary

The JUNO LS recipe has been decided and the materials of LS have been produced or are in porduction. The JUNO LS plants were constructed according to strict material and cleaning requirements. All JUNO LS plants have been installed on the JUNO site. The Alumina filtration plant, distillation plant, mixing plant, water extraction plant, stripping plant, high pure nitrogen plant and ultra pure water plant have been joint commissioned twice. The preliminary test results of the joint commissioning LAB/LS samples meet the expectations. The LS filling time of JUNO will be the end of this year.

5. Acknowledgments

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