Liquid Handling of the JUNO Experiment

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Abstract

The Filling, Overflow, and Circulation (FOC) system is a critical subsystem of the Jiangmen Underground Neutrino Observatory (JUNO), responsible for the safe handling of the Liquid Scintillator (LS) and water throughout the detector's commissioning and operational lifetime. This paper details the design and operation of the FOC system, which accomplished the filling of the world's largest LS detector—taking 45 days for water (6.4$×104m3)and200daysforLS(2.3×$104 m3). Throughout water filling, the liquid level difference between the Central Detector and Water Pool was rigorously maintained within safety limits. During LS filling, level control achieved $±$2 cm precision with flow regulation within $±$0.5% of setpoints. An automated control system based on Programmable Logic Controllers and the Experimental Physics and Industrial Control System framework ensured reliable operation. The system preserved LS radiopurity, maintaining 222Rn below 1 mBq/m3 during filling and achieving 238U/232Th concentrations below 10-16 g/g. The successful commissioning and operation of the FOC system have established it as an indispensable foundation for the stable long-term operation of the JUNO detector.

Full Text

Preamble

Liquid Handling of the JUNO Experiment∗ Jiajun Li,1 Yuekun Heng,2, † Jiajie Ling,1, ‡ Zhi Wu,2, § Xiao Tang,2 Cong Guo,2 Jinchang Liu,2 Xiaolan Luo,2 Xiao Cai,2 Chengfeng Yang,1 Xiaoyan Ma,2 Xiaohui Qian,2 Tao Huang,1 Bi Wu,1 Pengfei Yang,1 Shiqi Zhang,1 Baobiao Yue,1 Shuaijie Li,1 Lei Yang,3 Mei Ye,2 and Shenghui Liu2

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The Filling, Overflow, and Circulation (FOC) system is a critical subsystem of the Jiangmen Underground Neutrino Observatory (JUNO), responsible for the safe handling of the Liquid Scintillator (LS) and water throughout the detector' s commissioning and operational lifetime. This paper details the design and operation of the FOC system, which accomplished the filling of the world' s largest LS detector—taking 45 days for water (6.4 × 104 m3) and 200 days for LS (2.3 × 104 m3). Throughout water filling, the liquid level difference between the Central Detector and Water Pool was rigorously maintained within safety limits. During LS filling, level control achieved $±$2 cm precision with flow regulation within $±$0.5% of setpoints. An automated control system based on Programmable Logic Controllers and the Experimental Physics and Industrial Control System framework ensured reliable operation. The system preserved LS radiopurity, maintaining 222 Rn below 1 mBq/m3 during filling and achieving 238 U/232 Th concentrations below 10−16 g/g. The successful commissioning and operation of the FOC system have established it as an indispensable foundation for the stable long-term operation of the JUNO detector.

Keywords

JUNO, Central Detector, Liquid Scintillator, Filling System, Automation

cleaning procedures to minimize background, and engineered with high airtightness to prevent radon intrusion. For com30 prehensive details on JUNO' s design, technical implementa2 The Jiangmen Underground Neutrino Observatory (JUNO) 31 tions, and updated physics goals, please refer to the JUNO 3 is strategically positioned approximately 53 km from the 32 Conceptual Design Report and recent publications [5–7]. 4 Taishan and Yangjiang Nuclear Power Plants [1]. The pri5 mary physics objective of JUNO is to determine the neutrino LS have played a central role in neutrino physics for 6 mass ordering (NMO) through measuring the oscillated en34 decades, from the discovery of the neutrino in the 1950s [8], 7 ergy spectrum of reactor neutrinos emitted by the reactors at 35 to the precise measurement of the neutrino mass squared 8 at 53 km away and to achieve sub-percent precision on oscil36 splitting Δm21 at KamLAND [9], the measurement of solar 9 lation parameters such as $ $12 , Δm21 , and |Δm32 |. Addition37 neutrinos at Borexino [10], the observation of $ $13 -driven neu10 ally, JUNO will study solar neutrinos, atmospheric neutrinos, 38 trino oscillation at Daya Bay [11]. This sustained success is 11 supernova neutrinos, cosmic diffuse neutrinos, proton decay, 39 attributed to the scalability, homogeneity, ease of purification, 12 etc, thus advancing research in these areas [2]. 40 and cost-effectiveness of liquid scintillators.

Furthermore, To achieve these physics objectives, the JUNO Central De- 41 they offer high light yield and detection efficiency, which pro14 tector (CD) uses 20 kton of Liquid Scintillator (LS) as its tar42 vide excellent sensitivity. To satisfy the stringent demands of 15 get mass, requiring an energy resolution of 3% at 1 MeV and 43 JUNO, given its massive detector size, the LS must achieve 16 ultra-low radioactive background levels. The LS is contained 44 an attenuation length greater than 20 meters while maintain17 within a 35.4-meter-diameter acrylic sphere (120 mm thick), 45 ing exceptional radiopurity[12].The key radioactive contam18 which is supported by a 41.1-meter-diameter stainless steel 46 inants and their maximum allowed concentrations are sum238 19 structure, connected via 590 supporting bars. The entire CD 47 marized in Table 1 ; for instance, concentrations of U and 20 is submerged in the high purity water of the Water Cherenkov Th must be below 10 g/g for reactor neutrino studies, 21 detector and covered by a plastic scintillator array on the top, 49 and even lower for solar neutrino analyses.

The stringent 22 which together serve as a muon veto system.

The CD is 50 limits on these radio-contaminants are dictated by JUNO’ s 23 equipped with 17,612 20-inch photomultiplier tubes (PMTs) 51 physics goals:

U and 232 Th decay chains produce back24 and 25,600 3-inch PMTs, providing high photodetection cov52 grounds that can be misidentified as the inverse beta decay 25 erage for precise energy and position reconstruction[3, 4]. All 53 signal; K emits a 1.46 MeV γ-ray contributing to the con222 26 components in contact with the LS are fabricated from low54 tinuum background; Rn, as a gaseous isotope, is a di14 27 radioactivity, LS-compatible materials, subjected to rigorous 55 rect measure of system leak tightness; and C, 7 Be, 39 Ar, 56 and Kr are key backgrounds for low-energy solar neutrino 57 studies[13].

INTRODUCTION

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The optimal LS composition employs linear alkyl benzene (LAB) as the solvent, loaded with 3 g/L of 60 diphenyloxazole (PPO) as the fluor and 2.5 mg/L of 61 bis(2-methylstyryl)benzene (bis-MSB) as the wavelength 62 shifter [14]. PPO emits at 360 nm, and bis-MSB shifts the

wavelength to 420 nm, matching the PMT peak efficiency 121 ations during long-term operation; and finally, providing the while reducing LS self-absorption, thus achieving both high 122 capability for online circulation and re-purification of the LS. 65 light yield and long attenuation length (>20

m) essential for 123 To meet the exceptional demands of the JUNO experiment, 66 the energy resolution required for neutrino mass ordering de- 124

> the FOC system incorporates stringent radiopurity controls, 67 termination. This differs from Borexino's PC+PPO formula- 125 high-precision instrumentation, and a robust automated con68 tion (without bis-MSB)[15], reflecting their different physics 126 trol system. 69 priorities.

This paper provides a comprehensive overview of the FOC The LAB solvent was supplied by the Alkylbenzene Plant 128 system' s design, operational procedures, and performance. 71 of Sinopec Jinling Petrochemical Co., Ltd.[16], while the 129 Section II details the system' s design philosophy, radiopu72 PPO and bis-MSB were supplied by Haiso Technology Co., 130 rity requirements, and architectural components. Section III 73 Ltd[17].

The initial purity of these materials was verified 131 describes the strategies and implementation for water filling, 74 prior to purification: the concentrations of U and 232 Th 132 LS filling, and overflow management. Section IV summa−15 75 were measured to be at the 10 g/g level in LAB, at the 133 rizes the system' s results, achievements and outlines future 134 perspectives. 76 0.1 ppt level in PPO, and at the ppt level in bis-MSB.

The JUNO LS production and purification system was meticulously designed and constructed to fulfill these specifi135

II. FOC SYSTEM: DESIGN AND REQUIREMENTS 79 cations, capable of providing purified LS at a rate of 7 m /h 80 for the CD LS filling.

Building on the pioneering experiA. Functional Overview and System Requirements 81 ence of Borexino in achieving extreme radiopurity through 136 82 distillation, water extraction, and gas stripping, JUNO scales 83 these techniques to an order-of-magnitude higher production 137 The primary functions of the FOC system encompass four 84 rate.

The system encompasses multiple integrated plants: 138 critical processes for the JUNO detector: (1) the initial fill3 85 a 5000 m storage tank for raw LAB and transportation 139 ing of the CD and WP with pure water; (2) the subsequent 86 pipeline system for raw LAB, connecting the surface and 140 exchanging water with LS in the CD; (3) managing LS over87 underground laboratories; an Alumina Filtration Plant [18] 141 flow to accommodate thermal expansion and contraction dur88 for optical purification; a Distillation Plant [19] for remov- 142 ing long-term operation; and (4) facilitating online LS circu89 ing heavy metals such as uranium and thorium; and a Mix- 143 lation for re-purification if necessary. As the final stage in 90 ing Plant [20] for compounding PPO and bis-MSB with LAB 144 detector commissioning, the FOC system must execute these 91 into the master solution, which involves significant purifica- 145 processes while rigorously preserving the structural integrity 92 tion of PPO before dilution into the final LS. After mixing, 146 of the CD and the optical/radiopurity properties of the LS. 93 the LS is transferred to the underground hall via an inclined 147 This mandates a comprehensive set of system requirements: 94 shaft pipeline. Subsequent purification stages in the under- 148 Ultra-low Background Contribution: The FOC system' s 95 ground hall include a Water Extraction Plant [21] for remov- 149 contribution to the overall radioactive background in the LS 96 ing water-soluble elements (e.g., K, Pb, Ra) , after which 150 must be minimal. A paramount constraint is the concentra97 the LS and water are separated by gravity settling.

Fol- 151 tion of 210 Pb, which must not exceed 10−24 g/g in the LS. 98 lowed by a Stripping Plant [19] for extracting gaseous el- 152 The FOC system is allocated no more than 10% of this total 99 ements (e.g., Rn, Ar, Kr), which also reduces the residual 153 budget. This requirement drives the need for ultra-high pu100 water content in the LS to approximately 20 ppm—well be- 154 rity materials and exceptional leak tightness throughout the 101 low the saturation limit of water in LAB (about 50 ppm at 155 system. 102 20 C)—effectively preventing droplet formation that could 156 Liquid Level and Flow Control: Based on the primary 103 degrade optical transparency. The system is also equipped 157 function, the system must provide highly precise and reli104 with the Online Scintillator Internal Radioactivity Investiga- 158 able control of liquid levels and flow rates. This necessitates 105 tion System (OSIRIS) [22] for real-time radioactivity assay, 159 high-accuracy sensors and robust control logic to maintain 106 and supported by auxiliary High-Purity Water and Nitrogen 160 level differences and flow setpoints within strict safety mar107 Plants to supply essential utilities for the purification pro- 161 gins during all phases of operation. 108 cesses.

Automation and Operational Safety: Full automation of A specialized Filling, Overflow, and Circulation (FOC) 163 the filling processes is required to ensure reproducibility and 110 system has been designed and implemented to accomplish the 164 minimize human error. This includes the implementation of 111 precise filling and long-term stable operation of the ultra-pure 165 a comprehensive multi-mode alarm system and safety inter112 LS. This system is responsible for several critical processes: 166 locks (e.g., for level and pressure) to guarantee operational 113 the initial water filling, which involves the synchronous fill- 167 safety and equipment protection.

Material Purity and Leak Tightness: All components in 114 ing of the CD and the surrounding Water Pool (WP) to dis- 168 115 place air—minimizing subsequent LS exposure—and to pro- 169 contact with the LS or water, including stainless steel tanks, 116 vide a final rinse of the CD' s inner surface; the subsequent 170 pipes, and valves, must meet stringent purity and sealing stan238 U concentration must be below 0.7 ppb, with 117 LS filling operation, which systematically replaces the wa- 171 dards. The 118 ter with LS to fill the CD—enabling the detector' s primary 172 an inner surface roughness $\leq$ 0.4 µm (typically 0.2–0.3 µm) Leak tightness is criti119 data-taking function; the management of LS overflow to ac- 173 achieved through electropolishing. 120 commodate volume changes induced by temperature fluctu- 174 cal for preventing radon ingress; individual components must

Radioisotope Contamination source JUNO minimum requirements Air, emanation from material < 5 mBq/m3 Dust suspended in liquid < 10−15 g/g Dust suspended in liquid < 10−15 g/g Dust suspended in liquid, PPO < 10−16 g/g < 50 µBq/m3 < 50 µBq/m3

C. Cleanliness and Quality Assurance achieve a leak rate less than 10−8 mbar • L • s−1 , while assem- 219 176 bled systems and critical connections (e.g., chimney flanges) 177 must maintain a leak rate less than 10 mbar • L • s−1 through- 220 Stringent cleanliness protocols are mandated for all FOC 178 out the 20-year operational lifespan. This stringent require221 components that contact the LS or water. All internal surfaces 179 ment is critical for preventing radon ingress from the under222 undergo a meticulous multi-stage cleaning procedure to elim3 180 ground air (100 Bq/m), as even microscopic leaks would 223 inate organic, inorganic, and particulate contaminants. The 181 compromise the LS radiopurity. 224 process sequentially includes: degreasing with high-purity 225 detergents to remove oils, greases, and other organic residues; 226 acid pickling with a dilute nitric acid solution to eliminate 227 scale, oxides, and metallic contaminants from the activated

B. System Architecture and Components 228 surface; and passivation using concentrated nitric acid to 229 form a stable, inert chromium oxide layer on stainless steel The architecture of the FOC system comprises several key 230 surfaces, thereby enhancing corrosion resistance and reduc184 subsystems, engineered to handle the large liquid volumes 231 ing future radon emanation. These operations are followed 185 while adhering to the requirements outlined in Section II

A. 232 by a thorough rinsing with ultra-pure water (UPW) and dry186 Its core infrastructure includes: 233 ing under a high-purity nitrogen flush to prevent recontamina187 Storage and Overflow Tanks: One primary LS storage 234 tion. After drying, components are properly sealed and stored 188 tank and two LS overflow tanks, each with a volume of 50 235 under controlled conditions to maintain cleanliness. During 189 m , serve as buffers during filling and circulation. They are 236 installation, exposure to ambient air is minimized to prevent 190 crucial for compensating volume fluctuations caused by tem237 recontamination. The acceptance criteria for the final rinse 191 perature changes, given the LS' s thermal volume coefficient 238 water are rigorously defined, requiring compliance with the −4 ◦ −1 192 of 8.8 × 10 239 particle count specifications shown in Table 2 and achieving Piping, Chimney, Pumping and Valving Network: A 240 radiochemical contamination levels for 238 U and 232 Th below 194 comprehensive network of pipelines, the top and bottom g/g. These measures are essential to prevent the intro195 chimneys, and valves facilitates the transfer of water and LS. 242 duction of particulate or radioactive contaminants that could 196 All valves and fittings are required to have a helium leak rate 243 jeopardize the detector' s background levels. 197 < 10 mbar • L • s−1 to prevent radon ingress from un198 derground air. Dedicated pump sets are employed for transTable

2. JUNO Requirements for the cleanliness of rinsed water [23] 199 ferring water and LS. This includes electromagnetic pumps 200 for LS and self-

priming pumps for water, all configured with Particle Size Surface density Volume density 201 standby units for redundancy. All flanges are designed with (counts/0.1 m2) (counts/L) 202 double O-ring seals and the space between two O-rings is 203 filled with protection nitrogen. All the connection points are 204 sealed with gastight nitrogen boxes or aluminum foils as an 205 additional layer of protection.

Control System: An automated control system, based on 207 PLC and the EPICS framework, orchestrates all operations. It 208 integrates high-precision sensors, actuators, safety interlocks,

D. Automatic Control System 209 and data management to ensure precise and stable control. A 244 210 detailed description is provided in Section II D.

Ultra-Pure Nitrogen System: A dedicated radon-free ni- 245 The FOC automatic control system [24] is a core techni212 trogen system, comprising storage tanks, mass flow meters, 246 cal component, ensuring the safe filling and 20-year stable 213 and bubble bottles, provides a protective blanket over the 247 operation of the 20-kton LS in the CD. Based on the ISA-88 214 FOC tanks, calibration house, and top chimney. This prevents 248 standard [25], it adopts a four-layer architecture (Sensor, Con215 the LS from exposure to oxygen, moisture, and atmospheric 249 troller, Actuator, and Alarm & Data Management Layers), in216 radon. 250 tegrating high-precision hardware and advanced control logic The overall layout of the FOC system is depicted in Figure 251 [Figure 251: see original paper] to meet JUNO' s physics requirements.

Sensor Layer: All sensors (Endress+Hauser [26]) feature

FOC Nitrogen system From High-purity Nitrogen Plant Nitrogen Buffer

Nitrogen Buffer

Nitrogen Supply Pipeline

LS exchanging CD LS filling from top

From High-purity Nitrogen Plant

Overflow Tank A

OSIRIS

Inlet

Overflow Tank B

Product Storage Tank

Water Water

LS Filling Pipeline

Catchpit

Level guage

CDR pump

Pressure transmitter

Regulating valve

Temperature sensor

Vacuum breaker valve

Flowmeter

Calibration House

Filter Elements

Central Central Detector Detector

Water/LS Drainage Pipeline

N2 buffer

N2 supply

Pure Water Production

Pure Water for CD

Ultrafiltration Units

Pure Water for WP

Backwater

Test pipeline

CD/WP water filling from bottom

CD water/LS drainage from bottom

PWfilling filling Water

an accuracy better than 0.2% of full scale (FS). Redundancy is 286 strategies, including Proportional-Integral-Derivative (PID) implemented for key parameters: the CD level is monitored 287 control for continuous parameters like flow rate, sequential 255 by 2 differential pressure level gauges (0.20% FS), 1 laser 288 control for complex operational procedures, and comprehenCommissioning tests confirmed the 256 gauge (0.10% FS), and 2 chimney differential pressure level 289 sive safety interlocks. 257 sensors; the WP level uses 5 static pressure gauges; tank lev- 290 flow or liquid level control accuracy of 0.5%, fully meeting 258 els employ dual sensors (differential pressure + radar, 0.10–291 JUNO' s stringent specifications. The architecture of the au259 0.20% FS). Shielded twisted-pair cables, LC filtering, iso- 292 tomatic control system is illustrated in Figure 2 [Figure 2: see original paper]. 260 lators, and hybrid software filtering are utilized to suppress 261 electromagnetic interference.

Controller Layer: A S7-300 PLC with microsecond-level 293

E. Comparison with Previous Large-Scale LS Experiments 263 response forms the core of this layer.

Control software is 264 developed on TIA Portal [27] for Human-Machine Interface The FOC system’ s design reflects the unique challenges 265 (HMI) based visualization and integrated with EPICS [28] for 295 posed by JUNO’ s scale and detector configuration, which dif266 cross-system data exchange and real-time status monitoring. 296 fer fundamentally from previous large-scale LS experiments.

Actuator Layer: This layer includes valves (SED[29], 297 Compared to KamLAND (1 kt) and Borexino (0.3 kt), 268 leak rate < 10 mbar ·L ·s−1 , regulating valve accuracy 298 which used thin nylon balloons immersed in buffer liquids, 269 $±$1%, on/off valve response < 1

s) and pumps (8 units: 299 JUNO employs a different containment approach. Its 20 kt 270 CDR[30] electromagnetic for LS, Yamei[31] self-priming for 300 LS is contained in a 35.4-m diameter thin-shell acrylic sphere 271 water, all with standby units). Real-time status monitoring 301 that is directly exposed to external water pressure. This con272 and protection interlocks (e.g., level, pressure) are imple302 figuration introduces a critical requirement: precise real-time 273 mented. 303 control of the pressure differential across the acrylic vessel Alarm and Data Management Layer: This layer is re- 304 during filling, strictly adhering to the safety windows derived 275 sponsible for system-wide supervision, event logging, and 305 from detailed Finite Element Analysis. Furthermore, the to276 ensuring operational safety.

A multi-mode alarm system 306 tal filling process, including both water and LS, lasted over 277 integrates on-site audiovisual alerts for immediate operator 307 eight months, demanding a high degree of automation and 278 awareness, real-time highlighting on the HMI, remote noti- 308 long-term operational stability. 279 fications for off-site monitoring, and independent hardware 309 Compared to Daya Bay, which employed a three-nested280 emergency stop buttons for critical safety interventions. All 310 vessel design with Gd-doped LS in the innermost acrylic ves281 operational data—including sensor readings, valve states, and 311 sel, normal LS in the second acrylic vessel, and mineral oil 282 alarm histories—are stored locally with high reliability and 312 in the outermost stainless steel vessel—all filled in a dedi283 simultaneously synchronized to the Detector Control System 313 cated hall before transport to the underground experimental 284 (DCS) for distributed access and long-term archiving. 314 site—JUNO requires in-situ exchanging of 20 kt of water The integrated control system employs a combination of 315 with lighter LS while maintaining mechanical safety. This

Alarm and data management layer (ground)

Monitor PC (ground duty room)

Optical fiber

AI signal

Level gauge

Flowmeter Sensor layer Ethernet

HTML monitor

Switch Heartbeat packet

AO DO signal Valve

DI signal

PLC Module (cabinet)

Touch screen (TIA HMI)

Wiring

Industrial PC (EPICS HMI Data management)

Controller layer

Actuator layer

Flashing highlight Sound and light alarm

Flashing highlight Alarm data recording

Alarm and data management layer (underground)

task is complicated by the spherical geometry and the need 346 with LS. To reduce engineering risks, the filling scheme of for coordination with upstream LS production over many 347 replacing water with LS is adopted. 318 months.

The radiopurity requirements for U/Th are also 348 The pure water production system, with a capacity of 319 pushed by three orders of magnitude (from 10 g/g to 349 100 m3 /h, was developed to meet stringent requirements for g/g). Additionally, while Daya Bay' s detectors were 350 detector filling and operation. The final product water must 321 filled once and sealed, JUNO' s FOC must accommodate ther- 351 satisfy radiopurity criteria including 222 Rn < 10 mBq m−3 , 322 mal expansion and enable online circulation throughout its 352 226 Ra < 50 µBq m−3 , and 235 U/232 Th concentrations be−15 323 20-year lifetime. 353 low 10 g g−1 , along with physicochemical specifications Thus, while JUNO inherits valuable experience from its 354 of 20 ∘ C temperature, dissolved oxygen < 10 ppb, and re325 predecessors, the FOC system represents a significant tech- 355 sistivity > 18 MΩ ·cm.

The purification employs a two326 nological advance necessitated by the unprecedented scale, 356 stage process. Aboveground pretreatment includes bag fil327 geometry, and operational lifetime of the JUNO detector. 357 tration, multi-media filtration, activated carbon adsorption, 358 radium-removal softening resin columns, and primary Re359 verse Osmosis (RO). The water is then transported via a 328 III.

LIQUID MANAGEMENT DESIGN AND OPERATION 360 1300 m stainless-steel pipeline to the underground facility for 361 further polishing through secondary RO, Electrodeionization This section provides a comprehensive overview of the 362 (EDI), 0.1 µm cartridge filtration, UV sterilization, and ad330 control strategies, operational execution, and performance 363 vanced radon removal using a five-stage degassing membrane 331 outcomes for the key liquid handling processes managed by 364 system augmented by microbubble technology. This configu332 the FOC system: water filling, LS filling, and LS overflow 365 ration achieves a radon removal efficiency exceeding 99.9 %, 333 management. For each process, we first describe the underly- 366 reducing concentrations to (0.61 ±

0.

50) mBq m in recir334 ing control logic and design considerations, followed by a de- 367 culation mode. For CD filling, an additional Ultrafiltration 335 tailed account of the operational implementation, challenges 368 (UF) step is implemented, with approximately 5 m h wa336 encountered, and the final achieved results. This integrated 369 ter loss during this process. The system operates in both fill337 presentation highlights the seamless transition from theoret- 370 ing and recirculation modes to support initial commissioning 338 ical control principles to practical execution, demonstrating 371 and long-term detector operation [32]. 339 the system' s robustness and adaptability in meeting JUNO' s Prior to water filling, the Acrylic Spheroidal Vessel (ASV) 340 stringent requirements. 373 undergoes comprehensive cleaning to meet ultra-high purity 374 standards. This process includes reducing airborne dust via 375 water mist spraying, mitigating radon through natural decay,

A. Water Filling 376 and stripping protective films/cleaning the acrylic inner sur377 face with high-pressure rotary nozzles. Those films were ap342

1. Control Strategy and Logic 378 plied during the ASV installation to prevent airborne radon 379 from penetrating the acrylic material, while also providing an To minimize LS exposure to air, the air inside the CD must 380 additional protective layer for the acrylic. Concurrently, the 344 first be replaced with water or ultrapure nitrogen, followed 381 commissioning pipeline tests and debugs the water filling au345 by replacing the water or ultrapure nitrogen inside the CD 382 tomatic control system to ensure reliability.

during water filling [33]

The main challenge in synchronizing the CD and WP wa- 437 384 ter filling was managing their differing cross-sectional areas, 385 which vary with height.

The paramount objective was to 439 386 maintain the liquid level difference (ΔH, defined as HCD − 387 HWP) strictly within the safe limits predetermined by finite 388 element analysis (FEA) [33]. Controlling ΔH is essential to 389 protect the structural integrity of the acrylic sphere; exceed443 390 ing these limits would induce stresses beyond design speci444 391 fications, where the maximum axial tensile forces on support 392 bars must not exceed 90 kN and the maximum axial compres446 393 sive forces must not exceed 150 kN. As visualized in Figure 3 [Figure 3: see original paper], 394 a larger allowable range on the left (negative ΔH), which in448 395 dicates that the spherical acrylic vessel can withstand a higher 396 external pressure from the WP than internal pressure. Conse450 397 quently, a slightly higher WP level was permitted during the 398 water filling process. The implemented control strategy was 399 multifaceted and relied on several key pillars:

- WP Level as Primary Reference: The real-time WP level, being highly accurate and stable, served as the primary control parameter. Accurate assessment of the CD level, susceptible to dynamic flow interference, re458 quired periodic intentional pauses in filling.

- Multi-Tiered Compensation Logic: If the measured level difference (ΔH) indicated that one vessel was lagging, the guidance flow rate for that branch was increased in predefined incremental steps (1%, 3%, or 5%) to expedite its filling and correct the imbalance. • Stringent Safety Interlock: As a paramount protective measure, if ΔH exceeded a threshold set at onequarter of the absolute design limit (providing a significant safety margin), a strict "on-off" control mode was automatically activated. In this mode, filling to the vessel with the higher level was completely halted, and flow was directed exclusively to the other vessel until the level difference was reduced to a safe value. • Special Handling at Critical Structural Regions:

Recognizing the non-linear volume changes and heightened mechanical sensitivity near the detector' s South Pole, North Pole, equatorial region, and chimney interfaces, the control logic incorporated tailored measures for these zones. This included significantly reduced flow rates or the exclusive use of the cautious "on-off" filling mode to absolutely ensure mechanical safety and prevent excessive stress on the acrylic vessel. • Mitigation of Liquid Column Separation: The significant 44 meter static head loss in the vertical filling pipelines created a risk of column separation. This phenomenon can be visualized as the water column undergoing a free fall within the pipe, which can tear the continuous liquid apart, creating discrete segments and pulling a vacuum between them. Physically, this occurs when the local pressure drops below the vapor pressure of the liquid, leading to the formation of vapor cavities.

The subsequent collapse of these cavities can generate destructive water hammer. To mitigate this, vacuum break valves were installed on both the CD and WP filling lines. For the CD line, where the introduction of air was strictly prohibited to maintain radiopurity, a 1500 L nitrogen buffer tank was implemented instead.

This tank supplied high-purity nitrogen at a controlled rate of approximately 15 m3 h−1 to compensate for the pressure drop and prevent a vacuum, thereby ensuring safe and stable flow.

- Guidance Flow Rate Calculation: The required flow 460 rates into the CD and WP branches were continuously calculated based on the precisely known geometries of

2. Operational Implementation and Results the CD sphere, the WP cylinder, and all internal struc- 461 tures (such as PMTs, electronics boxes, and the support grid), combined with the total available water flow rate 462 The water filling operation was meticulously executed in 463 one pre-stage and three filling stages (Figure 4 [Figure 4: see original paper]), each tai(90 m3 /h). 464 lored to the specific geometric and mechanical challenges • PID Control for Flow Distribution: Two sets of pneu- 465 presented by different regions of the detector: matically actuated regulating valves, one for the CD 466 Pre-stage - ASV Cleaning: This initial stage was successbranch and another for the WP branch, were controlled 467 fully completed, with all measured parameters exceeding the by PID algorithms. These valves automatically ad- 468 stringent predefined specifications. A pure water mist genjusted their opening to distribute the inlet flow, striv- 469 erator was employed to suppress airborne dust, significantly ing to achieve synchronized rising of the liquid levels 470 improving the internal air cleanliness from Class 100,000 to in both vessels. 471 Class
3. Throughout the cleaning process, the distribution

and flow rate of the rinse water were precisely managed by the 510 the remaining WP volume. The "on-off" mode was reinFOC system. Particulate contamination levels and absorption 511 stated for the North Pole region. A significant and advan474 spectra of the rinse water fully complied with the technical 512 tageous phenomenon was observed for the top chimney: with of water already inside the CD, when CD 475 standards. Crucially, the cleaning procedure resulted in the 513 over 23,000 m 476 near-complete removal of protective films, and the rinse wa- 514 filling was paused and WP filling continued, the increasing 477 ter achieved exceptional ultralow radiochemical contamina- 515 hydraulic pressure from the rising WP level caused a slight 516 elastic contraction of the CD sphere.

This contraction, in 478 tion levels. 517 turn, caused the water level in the top chimney to rise syn518 chronously with the WP level, even without active CD filling.

CD Filling 519 During actual operations, only minimal supplemental filling 520 was required for final level adjustment.

WP Filling Water Pool (WP)

Stage 3

Liquid Level [m]

WP Liquid Level CD Liquid Level

Stage 2

Stage 1

(a) Water level changes

Filling Flux [m3/h]

Central Detector

WP Filling Flux

Stage 1 - South Pole Region: This stage involved filling CD Filling Flux 480 the WP volume below and at the South Pole while intermit70 481 tently synchronizing the filling of the CD' s South Polar re60 482 gion itself, the CD filling pipelines, and the bottom chimney. 483 Given the extremely small volumes of the CD components in 484 this area (200 m for the South Polar region) compared 485 to the WP, achieving synchronized level rise was exception20 486 ally challenging. Consequently, a conservative "on-off" mode 487 was employed. The WP was filled continuously at a high rate 488 of 75 m /h. After every 20-30 cm rise in the WP level, 489 the filling process was briefly paused to allow for minimal3 Filling changes 490 flow (1-2 m /h) topping-up of the CD-related components 491 until their levels matched the new WP height. This method 492 ensured successful and safe filling of this critical region.

Stage 2 - Interpolar Region: Covering the vast volume 494 between the poles, this stage benefited from slower and more 521 The entire process of filling approximately 6.4 × 104 tons 495 predictable changes in the cross-sectional areas of both the 522 of ultra-pure water was completed successfully within 45 496 CD and WP. The CD filling pipeline could now sustain a sta- 523 days, commencing on December 18th, 2024, and concluding 497 ble controlled flow of 8 m /h. The primary control logic 524 on February 1st,

2025. Throughout the operation, the flow 498 involving PID-controlled valve adjustment and guidance flow 525 rate was precisely controlled, with the actual flow maintained 499 rate calculation was deployed here.

A total filling rate of 526 within $±$1% of the theoretical target flow. The evolution of 500 80 m /h was maintained.

To accommodate necessary 527 the water levels and filling flow rates throughout this period 501 daily maintenance of the pure water production system (e.g., 528 is depicted in Figure 5 [Figure 5: see original paper]. Visual documentation of the filling 502 filter bag replacements) and to enable accurate verification of 529 process is provided in Figure 6 [Figure 6: see original paper]. At the very end of the detec503 the level difference through periodic pauses, two scheduled 530 tor water filling, on the far right side of the Figure 5, a minor 504 daily reductions or interruptions in the total filling flow were 531 calibration issue with the WP level gauge towards led to a 505 incorporated, ensuring both operational efficiency and detec- 532 deviation in the final WP level control. However, critically, 506 tor safety. 533 the liquid level difference (ΔH) throughout the entire filling Stage 3 - North Pole & Top Chimney: Similar to Stage 534 period consistently remained within the safe design require508 2, this final stage handled the North Polar region of the CD 535 ments stipulated by the mechanical analysis (Figure 3). 509 (volume 200 m) and the top chimney separately from 536 During filling, water was injected through the bottom in-

gen supply systems for comprehensive purification and quality assurance.

The primary challenge, central to the control strategy, arose 561 from the significant density difference between LS (ρ 562 0.856 g/cm at 21 $\circ$

C) and water. As the lighter LS pro563 gressively exchanged the pure water in the CD, the increasing 564 buoyant force exerted on the submerged acrylic vessel raised 565 the risk of mechanical failure. To mitigate this risk and man566 age the pressure differential across the acrylic vessel, the liq567 uid level inside the CD was deliberately and incrementally 568 raised during the filling process. This level adjustment aimed 569 to shift the pressure equilibrium point close to the vessel' s 570 equator, with the goal of minimizing the resultant pressure 571 differential across the acrylic vessel. The primary objective of 572 this strategy was to reduce the maximum stress on the spher573 ical structure throughout the exchange.

Consequently, the 574 control strategy was designed to maintain the pressure equi575 librium point near the ASV' s equator by gradually increasing 576 the CD liquid level during the filling process. Ultimately, the 577 design required the final LS level to be maintained several 578 meters above the external WP water level to ensure a safe and 579 stable pressure differential throughout the detector' s opera580 tional lifetime.

The control logic for the LS filling was designed to manage 582 this dynamic process automatically and safely:

(a) Start of Water filling (detector bottom)

(b) Completion of Water filling (detector top)

let while pool temperature was continuously monitored. For 590 538 long-term operation, the top and bottom distributors enable 539 independent control of inlet temperature and flow for active 540 thermal regulation to counteract heat ingress from the sur541 rounding rock and PMT electronics. The target temperature 542 for the water pool is 21 ± 1 C, which has been achieved fol595 543 lowing the completion of filling.

- Real-time Level Guidance and LS/Water Interface Tracking: The control system relied on multiple redundant sensor inputs. Two sets of differential pressure level gauges installed on the CD chimney provided the primary measurement of the LS surface level. The position of the LS-water interface inside the CD was tracked in real-time based on the total volume of LS injected and water drained, and was continuously validated against measurements from four additional CD level gauges and independent float level gauge readings.

- Flow Control and Balancing: The primary control objective was to maintain the LS surface level within $±$20 cm of its expected value at any given stage. The water drainage flow rate was typically fixed at the nominal production rate of 7 m3 /h. The LS injection flow rate was then finely adjusted around this baseline value using regulating valves and auxiliary pump frequency control, based on the real-time discrepancy between the actual and target LS levels.

Following the successful completion of water filling, the 547 CD interior was purged with ultrapure nitrogen that had a 603 Rn contamination level below 10 µBq/m3 , the critical LS 604 549 filling operation commenced. This process involved the con- 605 550 tinuous injection of purified LS into the CD from the top 606 551 chimney while simultaneously draining the water from the 607 552 bottom pipeline. The LS was supplied at a nominal rate of 608 553 7 m /h by the dedicated JUNO LS production and purifi- 609 554 cation system [14], which encompasses nine subsystems in- 610 555 cluding storage, alumina filtration, distillation, mixing, wa- 611 556 ter extraction, gas stripping, online radioactivity monitoring 612 557 (OSIRIS), along with ultrapure water and high-purity nitro- 613

- Periodic Recalibration and Phase Management: Recognizing potential deviations from ideal conditions (e.g., slight mismatches in inflow/outflow, density variations), the LS filling process was programmed for periodic pauses. During these pauses, the current state of the LS filling (the current ' phase') was thoroughly reassessed based on the most accurate level measurements. The guidance flow rates for the subsequent segment were then adjusted accordingly, often involving compensatory increases or decreases in the LS injection rate to bring the levels back in line with the pres-

LS Filling

Control Strategy and Logic

sure differential limits defined for that specific stage of 666 the newly produced scintillator met the experiment' s stringent 667 requirements using the OSIRIS system. the operation.

Commencement of Continuous Filling (Feb.25, 2025): • Stringent Safety Interlock: The utmost priority was 669 Following the positive initial assessment, the purification the structural integrity of the ASV. The control system 670 plants were configured for round-the-clock operation, and the continuously monitored the calculated pressure differ- 671 continuous phase of LS filling began. A deliberately cautious ential across the acrylic vessel. If this differential ap- 672 approach was adopted initially: the filling rate was set to a proached a predefined maximum allowable threshold 673 low range of 1-2 m3 /h for the first few hours. This allowed (derived from FEA), a paramount safety interlock was 674 for a final verification of the stability and safety of the entire triggered. This interlock activated an "on-off" LS fill- 675 integrated supply chain—from production to injection—and ing mode, which immediately halted either LS injec- 676 the CD' s response to the ongoing LS filling. tion or water drainage (whichever action would most 677 Running-in Phase (Feb.25 - Mar.10, 2025): After the ini625 effectively reduce the pressure differential) until the 678 tial verification, the flow rate was promptly ramped up to its condition returned to a safe range. 679 nominal value of 7 m /h. This period, lasting approximately 680 two weeks, is identified as the running-in phase for the filling • Coordination with LS Production: The FOC sys- 681 system supporting the LS filling. During this phase, contin628 tem' s extraction of LS from the product tank needed to 682 uous 24/7 operation could not yet be fully sustained due to be synchronized with the production plant' s output rate 683 teething issues and planned initial adjustments, resulting in of 7 m3 /h. In the absence of a dedicated flow meter 684 an operational availability of approximately 50%. on this transfer line, synchronization was achieved by 685 Stable Operation Phase (Mar.11 - Aug.22, 2025): From periodically fine-tuning the transfer pump' s frequency 686 March 11th onward, the system entered a period of highly sta633 based on the measured liquid levels in both the LS 687 ble operation for the LS filling. Near-continuous 24/7 filling product tank and the FOC storage tank, ensuring a dy- 688 was achieved with significantly improved reliability, boast635 namic balance between production and consumption 689 ing an operational availability of 90%. Throughout this entire for the LS filling. 690 period, the control system demonstrated exceptional perfor691 mance: the liquid level inside the CD was meticulously main637 • Backup of Water Drainage Capability: A backup de- 692 tained within a variation of $±$2 cm of the predetermined tar638 sign consideration was the evolving hydraulic head for 693 get level trajectory, and the LS filling flow rate was precisely water drainage. As LS replaced the denser water and 694 controlled within an accuracy of $±$0.5% of the setpoint. This the LS/water interface descended, the static pressure 695 high-precision flow control is essential to maintain a quies641 difference between the CD and the WP gradually in- 696 cent LS surface, ensure the liquid level difference balance, creased. This meant the self-priming drainage pumps 697 and maintain a stable balance with the upstream LS produc643 effectively had to lift water from an increasingly greater 698 tion rate to avoid supply-demand imbalance. depth, equivalent to a suction head rising from an initial For temperature control during the filling process, the tem645 0.5 m to a design maximum of approximately 4

m. To 700 perature of the injected LS was primarily regulated by the up646 safeguard against potential pump performance degra701 stream Stripping Plant[19], which can control the LS produc647 dation or instability under this varying load, a vacuum ◦ 702 tion temperature via heat exchange with a precision of 0.1

C. assisted backup system was engineered. Although this 703 Four temperature sensors at the injection line and storage system was never activated during actual operation, as 704 tanks outlet within the FOC system provided real-time moni650 the primary drainage system maintained stable perfor705 toring of the LS temperature. The ambient temperature of the mance throughout the entire LS filling process, its de706 underground laboratory was also actively controlled to mini652 sign and integration provided a critical safety margin to 707 mize thermal gradients. Based on the real-time LS tempera653 ensure the continuous outflow rate of 7 m3 /h under all 708 ture readings from the FOC system, the injection temperature anticipated conditions. 709 was coordinately adjusted with the Stripping Plant to main710 tain stable filling conditions.

Following the completion of LS filling, temperature mon655

2. Operational Implementation and Results 712 itoring using the calibration system[34, 35] indicated that 713 the LS within the CD exhibited a uniform temperature dis656 The LS filling operation was executed in a carefully se- 714 tribution, with measured values ranging from approximately 657 quenced manner, prioritizing both system verification and ra- 715 21.05 C at the top to 21.02 C at the bottom, well within the 716 operational requirement of (21 ±

1)

C. 658 diopurity assessment:

Initial Batch and Purity Check (Feb.8-10, 2025): The 717 Throughout the LS filling process, comprehensive radiop660 operation commenced with the successful injection of an ini- 718 urity monitoring was implemented to ensure ultra-low back3 661 tial batch of 100 m of LS. This batch was then held within 719 ground levels, consistent with the requirements for JUNO’ s Real-time 222 Rn activity monitoring was 662 the CD for several days to acquire data. This waiting period 720 physics goals. 663 allowed for the decay of any Rn that was not in secular 721 achieved by tagging 214 Bi-214 Po cascade decays in the CD 664 equilibrium with its parent nuclide and provided the first cru- 722 data stream, complemented by periodic batch testing of 3665 cial opportunity to assess whether the intrinsic radiopurity of 723 5 tons LS samples using the OSIRIS system. The average

Height of LS/water Interface

Total LS Volume in CD

Exchanging Flow Rate [m /h]

Total LS Volume in CD [m 3]

Height of LS/water Interface [m]

Rn contamination in the filled LS was measured to be less than 1 mBq/m3 , which is well below the design requirement 726 of 5 mBq/m [36]. This excellent performance was attributed 727 to the stringent leakage control measures, continuous nitro728 gen purging of the filling system and CD chimney, and the 729 high-efficiency radon removal in the LS purification chain.

Furthermore, independent radiopurity monitoring was con731 ducted using Inductively Coupled Plasma Mass Spectrom732 etry (ICP-MS), a highly sensitive technique capable of deDate 733 tecting trace levels of U and 232 Th [37]. In this method, 734 uranium and thorium are first extracted from the liquid scinFig. 7 [Figure 7: see original paper]. LS/Water interface and LS volume changes during the LS 735 tillator via acid digestion, concentrated, and then introduced filling process 736 into the ICP-MS system for quantitative analysis. With strin737 gent cleanliness control throughout sample preparation—738 including the use of ultra-pure reagents and meticulously LS Filling Flow 739 cleaned labware—the method achieves recovery efficiencies Water Drainage Flow 740 close to 100% and a detection limit at the sub-ppq level. The 741 ICP-MS results confirmed that the concentrations of U and Th in the LS were maintained below the 10−16 g/g level 743 throughout the filling process. This provides direct evidence 744 that the FOC system did not introduce contamination from 745 these critical long-lived radioisotopes.

Following the completion of LS filling, an integrated ra3 747 diopurity analysis of the LS within the CD fiducial volume 748 was performed. The results confirmed that the concentrations 749 of U and 232 Th were successfully maintained below the g/g level, along with an initial 210 Po rate of approx2025-02-11 2025-03-13 2025-04-12 2025-05-12 751 imately 5 × 10 cpd/kton [36] [38], fully meeting the strin752 gent requirements for both neutrino mass ordering and solar 753 neutrino studies. This demonstrates that the FOC system ef754 fectively prevented the introduction of external contaminants 755 throughout the filling process, thereby preserving the ultra756 high radiopurity of the LS. 782 level, the detector exhibited stable and safe mechanical con757 The monumental task of LS filling 2.3 × 104 m3 of water 783 ditions, as validated by the continuous monitoring of the sup758 with LS was successfully concluded on August 22nd, 2025, 784 port rod forces throughout the entire exchange period. The 759 after a total duration of 200 days. Following the main LS 785 measured forces on the rods showed general agreement with 760 filling, an additional 80 m of LS was deliberately drained 786 the FEA predictions within acceptable margins. The moni761 from the bottom of the detector. This volume, which con- 787 toring data confirmed that the maximum compressive force 762 stituted the initial batch filled into the CD, was purged due 788 on the rods was around −160 kN, and the maximum tensile 763 to its higher contamination risk from prolonged contact with 789 force was around 99 kN. A few individual rods exhibited 764 residual water and particulates introduced during the initial 790 readings moderately higher than the FEA predictions, not ex765 pipeline flushing. This operation functioned as a one-time, 791 ceeding 10% of the maximum design values. The prelimi766 unidirectional flushing cycle aimed at removing the poten- 792 nary assessment attributes this deviation to potential factors 767 tially compromised scintillator from the detector' s lowest 793 such as the connection and installation details between the 768 point, thereby ensuring the final optimal purity within the CD. 794 rods and the acrylic vessel. This aspect will continue to be 769 It is noteworthy that this process can be regarded as a spe- 795 monitored closely. Overall, the mechanical data indicate a 770 cific form of circulation, albeit without routing the drained 796 very low risk of structural damage to the acrylic vessel or its 771 LS back through the external purification system. The con- 797 support structure due to overstress under the current loading 772 trol logic and operational procedures for this operation were 798 conditions. 773 fundamentally similar to those implemented for the online LS 799 Inevitably, during the extended stable operation period 774 circulation described in Section III

C. 800 of the LS filling, several intermittent filling stops occurred.

The downward migration of the water/LS interface and the 801 These were primarily attributed to two factors: temporary 776 corresponding increase in the total LS volume inside the CD 802 shortages of the raw LAB material from the supplier, and nec777 throughout the LS filling process are clearly depicted in Fig- 803 essary adjustments and maintenance of the equipment. These 778 ure

7. The flow rate stability during the stable phase is illus- 804 intervals were utilized productively to conduct an intensive 779 trated in Figure 8 [Figure 8: see original paper]. 805 detector calibration campaign, which yielded valuable data The LS filling process concluded with the liquid level in 806 for enhancing the understanding of the detector’ s response 781 the CD stabilized at approximately 47 meters. At this liquid 807 and refining subsequent data analysis parameters.

LS Overflow and Circulation

Operational Implementation and Results

Following the completion of the LS filling on August 22nd, 2025, formal data acquisition for the JUNO experiment com860 menced on August 26th,

2025. The overflow system immedi810 During the long-term operation of the JUNO detector, the 861 ately became active to manage diurnal and other minor tem811 FOC system’ s role transitions from filling to managing the 862 perature variations. 812 thermal dynamics of the large LS volume. The thermal vol863 The initial operation of the designated dedicated overflow 813 ume expansion coefficient of LS (8.8 × 10 /

C) means 864 pipeline encountered a technical challenge: an airlock phe814 that temperature fluctuations may cause significant volume 865 nomenon prevented the establishment of a reliable hydraulic 815 changes—approximately 20 m per 1 ◦ C change for the CD 866 communication between the overflow tanks and the top chim816 volume—which must be accommodated to maintain stable 867 ney of the CD. To promptly resolve this and ensure detector 817 pressure conditions inside the sealed CD. The overflow sys868 stability, the original LS filling pipeline was repurposed as a 818 tem is specifically designed to handle these LS volume varia869 backup overflow pathway. This solution proved effective; the 819 tions. The strategy for managing this employs a combination 870 overflow process through this backup line operated smoothly, 820 of passive and active mechanisms: 871 achieving overflow rates exceeding 2 m /h, which adequately 872 met the initial operational requirements for handling thermal 873 expansion. • Passive Thermal Regulation via Overflow Tanks: 874 However, to ensure mechanical safety, the final LS filling The primary buffer for routine temperature fluctuations 875 level was intentionally stabilized at approximately 47 meters, is provided by two dedicated overflow tanks. These 876 as validated by force monitoring data as mentioned in Sec824 tanks are connected to the CD' s top chimney. For mi- 877 tion III B

2. This operational liquid level is below the original nor temperature variations, the resulting LS volume 878 design value. Consequently, the liquid level in the intercon826 change is passively absorbed or replenished by these 879 nected FOC overflow tanks was also correspondingly lower. tanks through gravity-driven flow without any active 880 This reduction decreased the tanks' effective cross-sectional intervention. 881 area for buffering level variations, reducing the system' s pas882 sive overflow capacity to approximately 80% of its nominal 883 design value. • Active Volume Adjustment via Storage Tank: For 884 To maintain detector stability under this adapted configu830 larger temperature shifts, the system switches to active 885 ration, two key measures were implemented: mode. A separate storage tank is employed for this pur- 886 The operational liquid level variation was constrained to pose. When the temperature drops significantly, valves 887 within $±$5 cm to minimize level-induced pressure variations and pumps are activated to transfer LS from the stor- 888 on the acrylic vessel, a key requirement for mechanical safety. age tank into the CD circuit to compensate for the con- 889 This liquid level tolerance is well within the high-precision traction. Conversely, when the temperature rises sig- 890 control capabilities of the automated system, which can main836 nificantly, the expanded LS volume automatically over- 891 tain level stability at this or even finer scales, thereby provid837 flows into the overflow tanks. If needed, LS is actively 892 ing a robust safeguard for the detector' s structural integrity. transferred from the overflow tanks to the storage tank 893 An active liquid level adjustment function was integrated to prevent overfilling. 894 into the automatic control system to compensate for the re895 duced passive capacity. This system dynamically regulates 896 the liquid level in the overflow tanks through small-volume • Online Purification Circulation: To further reduce 897 transfers to and from the storage tank, maintaining precise impurities over the detector' s lifetime, the LS can 898 balance with the CD' s requirements. The control loop has be continuously purified through an online circulation 899 been thoroughly validated and remains operational, ensuring loop. LS is extracted from the bottom of the CD, passed 900 long-term detector stability. through external purification systems (e.g., water ex- 901 As

observed in Figure 9 [Figure 9: see original paper], the liquid levels in the overflow traction, gas stripping), and then reinjected into the top 902 tanks and the CD exhibit excellent synchronization. Cur846 of the CD. Computational Fluid Dynamics (CFD) sim- 903 rently, during the initial phase shortly after the completion ulations were employed to optimize this process [5]. 904 of LS filling, the entire detector is undergoing a gradual cool848 The simulations revealed that the efficiency of purify- 905 down. This results in a combined effect of thermal contrac849 ing the entire CD volume depends on the temperature 906 tion in both the LS and the acrylic vessel itself, accompanied difference between the injected and in-situ LS. By ap- 907 by elastic deformation of the spherical structure due to the propriately controlling the temperature of the purified 908 changing liquid head. These factors collectively contribute to LS relative to the CD LS, convection currents can be 909 a progressive decrease in the liquid level. Under these condi853 suppressed to improve circulation efficiency. Based on 910 tions, the active replenishment function is activated, transfer854 these studies and the hydraulic characteristics, the op- 911 ring LS into the CD to raise its liquid level slightly. This timal flow rate for this purification circulation was de- 912 proactive compensation is crucial for maintaining the me913 chanical stability of the detector structure during this tran856 termined to be 7 m3 /h.

Control Strategy and Logic

CD Liquid Level Overflow Tank Liquid Level

Overflow Tank Liquid Level [m]

CD Liquid Level [m]

satisfied the demanding criteria of ultra-low background, minimal leakage, and long-term structural safety and relia956 bility. The stringent radiopurity controls—including the use 957 of ultra-high purity materials, meticulous cleanliness proto—6 958 cols, and exceptional leak tightness (helium leak rate < 10 959 mbar-L · s for assembled systems)—were instrumental in 960 preserving the LS purity throughout the filling process. This 961 foundational role is demonstrated by two key achievements: 962 the maintenance of Rn concentration below 1 mBq/m3 in fresh during filling, and the establishment of the condiDate 964 tions necessary for the outstanding ultimate radiopurity levels U and Th concentrations below 10 g/g and an initial 210 Po operation 967 rate of approximately 5 × 10 cpd/kton. These collective re968 sults underpin the detector' s potential for achieving its pre969 mier physics goals. 914 sitional phase.

During long-term operation, the LS temperature inside the 916 CD is is primarily influenced by the Water Pool temperature JUNO' s physics goals demand ultra-low backgrounds 917 through heat exchange across the acrylic vessel. g/g) and 3% energy resolution at After approximately six months of detector operation, the 971 (U/ Th < 10 972 1 MeV. These requirements impose constraints rarely encoun919 LS temperature has been monitored multiple times and exradiopurity for LS and 920 hibits a little dynamic variations.

The measured tempera- 973 tered in industry: semiconductor-grade 974 water, leak tightness below 10 mbar · L/s over two decades, 921 ture within the CD has ranged from approximately 20.2 C 975 and surface roughness ≤ 0.4 μm for all wetted materials. The 922 to 20.6 C, with a temperature non-uniformity of less than 976 FOC system achieves these through precise background con923 0.5

C. This minor stratification results from natural density977 trol, stringent material selection, and cleanliness protocols. 924 driven convection and is influenced by residual temperature 978 The control system operates from 100 m /h during water fill925 non-uniformity in the Water Pool. The overall temperature 979 ing down to 7 m /h for LS filling, maintaining $±$0.5% flow 926 range is well within the operational requirement, and the tem980 stability and $±$2 cm level control over six months LS filling 927 perature uniformity meets the detector' s operational require981 period—protecting the acrylic sphere and coordinating with 928 ments. 982 upstream production. The fully automated PLC/EPICS sys983 tem integrates redundant sensors, alarms, and interlocks for 984 long-term reliability, with overflow management and online

IV. SUMMARY 985 circulation for 20-year detector life support.

10/04 10/05 10/06 10/07 10/08 10/09 10/10 10/11 10/12 10/13 10/14 10/15 10/16 10/17

The Filling, Overflow, and Circulation system has been successfully commissioned and has demonstrated its critical 986 Looking forward, the established FOC infrastructure and 932 role in JUNO. Through meticulous design and robust auto987 operational expertise provide a solid foundation for future 933 mated control, the system safely and precisely managed the 988 JUNO upgrades. Specifically, the system is designed to sup934 large-scale liquid handling operations, ensuring the structural 989 port potential next-phase physics programs, by enabling con935 integrity of the CD and preserving the exquisite optical and 990 tinuous online LS circulation to achieve even higher purity 936 radiopurity properties of the LS. Its accomplishments can be 991 levels. Also it can replace LS for the research of neutrinoless 937 summarized in three key aspects: 992 double-beta decay. JUNO advances large-scale LS detector First, the FOC system has accomplished the filling of the 993 technology through its scale (20 kt), energy resolution (3% at 939 world' s largest liquid scintillator detector, taking 45 days for 994 1 MeV), radiopurity control, automated fluid handling, and 940 the initial water filling of approximately 6.4 × 10 tons and 995 mechanical innovations—providing a foundation for future 941 200 days for the subsequent LS filling of 2.3 × 10 m , with 996 generation experiments. 942 90% operational availability during stable operation, while 943 also ensuring the functionality of overflow management and 944 future circulation.

In summary, the FOC system has proven to be a reliable, Second, the integration of an automated control system 998 adaptable, and indispensable component for JUNO. Its suc946 based on PLC and EPICS software provided the founda-999 cessful implementation underscores the importance of inte947 tion for this success, enabling real-time monitoring, precise 1000 grated design, automated control, and continuous monitoring 948 control, and robust safety interlocking throughout all opera- 1001 in large-scale neutrino detector operations, providing a solid 949 tions. The system has achieved fully automated liquid con- 1002 foundation for JUNO' s scientific exploration over its planned 950 trol, meeting stringent requirements for high-precision liquid 1003 20-year lifetime and beyond. The design principles, control 951 level control within $±$2 cm and flow rate regulation within 1004 strategies, and lessons learned from this project offer valuable 952 $±$0.5% of setpoints. 1005 insights for other large-scale, high-purity liquid-based detec953 Third, the design and operation of the FOC system have 1006 tors in particle physics and related fields.

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Note: Figure translations are in progress. See original paper for figures.