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$×104*m*3)*and*200*daysforLS*(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

INTRODUCTION

The Jiangmen Underground Neutrino Observatory (JUNO) is strategically positioned approximately 53 km from the Taishan and Yangjiang Nuclear Power Plants [1]. The primary physics objective of JUNO is to determine the neutrino mass ordering (NMO) through measuring the oscillated energy spectrum of reactor neutrinos emitted by the reactors at at 53 km away and to achieve sub-percent precision on oscil2lation parameters such as $ $12 , ∆m21 , and |∆m32 |. Additionally, JUNO will study solar neutrinos, atmospheric neutrinos, supernova neutrinos, cosmic diffuse neutrinos, proton decay, etc, thus advancing research in these areas [2].

To achieve these physics objectives, the JUNO Central Detector (CD) uses 20 kton of Liquid Scintillator (LS) as its target mass, requiring an energy resolution of 3% at 1 MeV and ultra-low radioactive background levels. The LS is contained within a 35.4-meter-diameter acrylic sphere (120 mm thick), which is supported by a 41.1-meter-diameter stainless steel structure, connected via 590 supporting bars. The entire CD is submerged in the high purity water of the Water Cherenkov detector and covered by a plastic scintillator array on the top, which together serve as a muon veto system. All components in contact with the LS are fabricated from low radioactivity, LS-compatible materials, subjected to rigorous cleaning procedures to minimize background, and engineered 26 with high air-tightness to prevent radon intrusion. For com27 prehensive details on JUNO’ s design and its updated physics

goals, please refer to the JUNO Conceptual Design Report and recent publications [3].

LS have played a central role in neutrino physics for decades, from the discovery of the neutrino in the 1950s [4], 32 to the precise measurement of the neutrino mass squared 33 splitting Δm21 at KamLAND [5], the measurement of so34 lar neutrinos at Borexino [6], the observation of \$ \$13 -driven 35 neutrino oscillation at Daya Bay [7].

This sustained suc36 cess is attributed to the scalability, homogeneity, ease of pu37 rification, and cost-effectiveness of liquid scintillators. Fur38 thermore, they offer high light yield and detection efficiency, 39 which provide excellent sensitivity. To satisfy the stringent 40 demands of JUNO, given its massive detector size, the LS 41 must achieve an attenuation length greater than 20 meters 42 while maintaining exceptional radiopurity. The key radioac43 tive contaminants and their maximum allowed concentrations 44 are summarized in Table 1 ; for instance, concentrations of U and 232 Th must be below 10−15 g/g for reactor neu46 trino studies, and even lower for solar neutrino analyses. The 47 stringent limits on these radio-contaminants are dictated by 48 JUNO’ s physics goals:

U and 232 Th decay chains produce 49 backgrounds that can be misidentified as the inverse beta de40 50 cay signal; K emits a 1.46 MeV γ-ray contributing to the 51 continuum background; Rn, as a gaseous isotope, is a di14 52 rect measure of system leak tightness; and C, 7 Be, 39 Ar, 53 and Kr are key backgrounds for low-energy solar neutrino 54 studies[8].

The optimal LS composition employs linear alkyl benzene (LAB) as the solvent, loaded with 3 g/L of 57 diphenyloxazole (PPO) as the fluor and 2.5 mg/L of bis(2-methylstyryl)benzene (bis-MSB) as the wavelength ∗ Supported by NO.2023YFA1606100, National Key R&D Program of shifter emits nm, and bis-MSB shifts the China. † Corresponding author, hengyk@ihep.ac.cn 60 wavelength to 420 nm, matching the PMT peak efficiency ‡ Corresponding author, lingjj5@mail.sysu.edu.cn 61 while reducing LS self-absorption, thus achieving both high § Corresponding author, wuz@ihep.ac.cn 62 light yield and long attenuation length (>20 m) essential for

the energy resolution required for neutrino mass ordering de- 121 the FOC system incorporates stringent radiopurity controls, termination. This differs from Borexino’ s PC+PPO formula- 122 high-precision instrumentation, and a robust automated con65 tion (without bis-MSB)[10], reflecting their different physics 123 trol system. 66 priorities.

This paper provides a comprehensive overview of the FOC system’ s design, operational procedures, and performance.

The LAB solvent was supplied by the Alkylbenzene Plant 68 of Sinopec Jinling Petrochemical Co., Ltd.[11], while the 126 Section II details the system' s design philosophy, radiopu69 PPO and bis-MSB were supplied by Haiso Technology Co., 127 rity requirements, and architectural components. Section III 70 Ltd[12].

The initial purity of these materials was verified 128 describes the strategies and implementation for water filling, 71 prior to purification: the concentrations of U and 232 Th 129 LS filling, and overflow management. Section IV summa−15 72 were measured to be at the 10 g/g level in LAB, at the 130 rizes the system' s results, achievements and outlines future 131 perspectives. 73 0.1 ppt level in PPO, and at the ppt level in bis-MSB.

The JUNO LS production and purification system was 75 meticulously designed and constructed to fulfill these specifi132 II. FOC SYSTEM: DESIGN AND REQUIREMENTS 76 cations, capable of providing purified LS at a rate of 7 m /h 77 for the CD LS filling.

Building on the pioneering experiA. Functional Overview and System Requirements 78 ence of Borexino in achieving extreme radiopurity through 133 79 distillation, water extraction, and gas stripping, JUNO scales 80 these techniques to an order-of-magnitude higher production 134 The primary functions of the FOC system encompass four 81 rate.

The system encompasses multiple integrated plants: 135 critical processes for the JUNO detector: (1) the initial fill3 82 a 5000 m storage tank for raw LAB and transportation 136 ing of the CD and WP with pure water; (2) the subsequent 83 pipeline system for raw LAB, connecting the surface and 137 exchanging water with LS in the CD; (3) managing LS over84 underground laboratories; an Alumina Filtration Plant [13] 138 flow to accommodate thermal expansion and contraction dur85 for optical purification; a Distillation Plant [14] for remov- 139 ing long-term operation; and (4) facilitating online LS circu86 ing heavy metals such as uranium and thorium; and a Mix- 140 lation for re-purification if necessary. As the final stage in 87 ing Plant [15] for compounding PPO and bis-MSB with LAB 141 detector commissioning, the FOC system must execute these 88 into the master solution, which involves significant purifica- 142 processes while rigorously preserving the structural integrity 89 tion of PPO before dilution into the final LS. After mixing, 143 of the CD and the optical/radiopurity properties of the LS. 90 the LS is transferred to the underground hall via an inclined 144 This mandates a comprehensive set of system requirements: 91 shaft pipeline. Subsequent purification stages in the under- 145 Ultra-low Background Contribution: The FOC system' s 92 ground hall include a Water Extraction Plant [16] for remov- 146 contribution to the overall radioactive background in the LS 93 ing water-soluble elements (e.g., K, Pb, Ra) , after which 147 must be minimal. A paramount constraint is the concentra94 the LS and water are separated by gravity settling.

Fol- 148 tion of 210 Pb, which must not exceed 10−24 g/g in the LS. 95 lowed by a Stripping Plant [14] for extracting gaseous el- 149 The FOC system is allocated no more than 10% of this total 96 ements (e.g., Rn, Ar, Kr), which also reduces the residual 150 budget. This requirement drives the need for ultra-high pu97 water content in the LS to approximately 20 ppm—well be-151 rity materials and exceptional leak tightness throughout the 98 low the saturation limit of water in LAB (about 50 ppm at 152 system. 99 20 C)—effectively preventing droplet formation that could 153 Liquid Level and Flow Control: Based on the primary 100 degrade optical transparency. The system is also equipped 154 function, the system must provide highly precise and reli101 with the Online Scintillator Internal Radioactivity Investiga- 155 able control of liquid levels and flow rates. This necessitates 102 tion System (OSIRIS) [17] for real-time radioactivity assay, 156 high-accuracy sensors and robust control logic to maintain 103 and supported by auxiliary High-Purity Water and Nitrogen 157 level differences and flow setpoints within strict safety mar104 Plants to supply essential utilities for the purification pro- 158 gins during all phases of operation. 105 cesses.

Automation and Operational Safety: Full automation of A specialized Filling, Overflow, and Circulation (FOC) 160 the filling processes is required to ensure reproducibility and 107 system has been designed and implemented to accomplish the 161 minimize human error. This includes the implementation of 108 precise filling and long-term stable operation of the ultra-pure 162 a comprehensive multi-mode alarm system and safety inter109 LS. This system is responsible for several critical processes: 163 locks (e.g., for level and pressure) to guarantee operational 110 the initial water filling, which involves the synchronous fill- 164 safety and equipment protection.

Material Purity and Leak Tightness: All components in 111 ing of the CD and the surrounding Water Pool (WP) to dis- 165 112 place air—minimizing subsequent LS exposure—and to pro- 166 contact with the LS or water, including stainless steel tanks, 113 vide a final rinse of the CD' s inner surface; the subsequent 167 pipes, and valves, must meet stringent purity and sealing stan238 U concentration must be below 0.7 ppb, with 114 LS filling operation, which systematically replaces the wa- 168 dards. The 115 ter with LS to fill the CD—enabling the detector' s primary 169 an inner surface roughness ≤ 0.4 µm (typically 0.2–0.3 µm) Leak tightness is criti116 data-taking function; the management of LS overflow to ac- 170 achieved through electropolishing. 117 commodate volume changes induced by temperature fluctu- 171 cal for preventing radon ingress; individual components must mbar · L · s−1 , while assem118 ations during long-term operation; and finally, providing the 172 achieve a leak rate less than 10 119 capability for online circulation and re-purification of the LS. 173 bled systems and critical connections (e.g., chimney flanges) mbar · L · s−1 through120 To meet the exceptional demands of the JUNO experiment, 174 must maintain a leak rate less than 10

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 out the 20-year operational lifespan. This stringent require- 216 ment is critical for preventing radon ingress from the under3 177 ground air (100 Bq/m), as even microscopic leaks would Stringent cleanliness protocols are mandated for all FOC 178 compromise the LS radiopurity. 218 components that contact the LS or water. All internal surfaces 219 undergo a meticulous multi-stage cleaning procedure to elim220 inate organic, inorganic, and particulate contaminants. The 221 process sequentially includes: degreasing with high-purity 222 detergents to remove oils, greases, and other organic residues; B. System Architecture and Components 223 acid pickling with a dilute nitric acid solution to eliminate 224 scale, oxides, and metallic contaminants from the activated The architecture of the FOC system comprises several key 225 surface; and passivation using concentrated nitric acid to 226 form a stable, inert chromium oxide layer on stainless steel 181 subsystems, engineered to handle the large liquid volumes 227 surfaces, thereby enhancing corrosion resistance and reduc182 while adhering to the requirements outlined in Section II A. 228 ing future radon emanation. These operations are followed 183 Its core infrastructure includes: 229 by a thorough rinsing with ultra-pure water (UPW) and dry184 Storage and Overflow Tanks: One primary LS storage 230 ing under a high-purity nitrogen flush to prevent recontamina185 tank and two LS overflow tanks, each with a volume of 50 231 tion. After drying, components are properly sealed and stored 186 m , serve as buffers during filling and circulation. They are 232 under controlled conditions to maintain cleanliness. During 187 crucial for compensating volume fluctuations caused by tem233 installation, exposure to ambient air is minimized to prevent 188 perature changes, given the LS' s thermal volume coefficient 234 recontamination. The acceptance criteria for the final rinse −4 ◦ −1 189 of 8.8 × 10 235 water are rigorously defined, requiring compliance with the Piping, Chimney, Pumping and Valving Network: A 236 particle count specifications shown in Table 2 and achieving 191 comprehensive network of pipelines, the top and bottom 237 radiochemical contamination levels for U and 232 Th below 192 chimneys, and valves facilitates the transfer of water and LS. 238 10 g/g. These measures are essential to prevent the intro193 All valves and fittings are required to have a helium leak rate 239 duction of particulate or radioactive contaminants that could 194 < 10 mbar ·L ·s−1 to prevent radon ingress from un- 240 jeopardize the detector' s background levels. 195 derground air. Dedicated pump sets are employed for trans196 ferring water and LS. This includes electromagnetic pumps 197 for LS and self-priming pumps for water, all configured with Particle Size Surface density Volume density 198 standby units for redundancy. All flanges are designed with (counts/0.1 m2) (counts/L) 199 double O-ring seals and the space between two O-rings is 200 filled with protection nitrogen. All the connection points are 201 sealed with gastight nitrogen boxes or aluminum foils as an 202 additional layer of protection.

Control System: An automated control system, based on 204 PLC and the EPICS framework, orchestrates all operations. It 205 integrates high-precision sensors, actuators, safety interlocks, 206 and data management to ensure precise and stable control. A 207 detailed description is provided in Section II D.

Automatic Control System

Ultra-Pure Nitrogen System: A dedicated radon-free ni- 242 The FOC automatic control system [19] is a core technitrogen system, comprising storage tanks, mass flow meters, 243 cal component, ensuring the safe filling and 20-year stable 210 and bubble bottles, provides a protective blanket over the 244 operation of the 20-kton LS in the CD. Based on the ISA-88 211 FOC tanks, calibration house, and top chimney. This prevents 245 standard [20], it adopts a four-layer architecture (Sensor, Con212 the LS from exposure to oxygen, moisture, and atmospheric 246 troller, Actuator, and Alarm & Data Management Layers), in213 radon. 247 tegrating high-precision hardware and advanced control logic

The overall layout of the FOC system is depicted in Figure 248 [Figure 248: see original paper] to meet JUNO' s physics requirements.

Sensor Layer: All sensors (Endress+Hauser [21]) 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 283 strategies, including Proportional-Integral-Derivative (PID) implemented for key parameters: the CD level is monitored 284 control for continuous parameters like flow rate, sequential 252 by 2 differential pressure level gauges (0.20% FS), 1 laser 285 control for complex operational procedures, and comprehenCommissioning tests confirmed the 253 gauge (0.10% FS), and 2 chimney differential pressure level 286 sive safety interlocks. 254 sensors; the WP level uses 5 static pressure gauges; tank lev- 287 flow or liquid level control accuracy of 0.5%, fully meeting 255 els employ dual sensors (differential pressure + radar, 0.10-288 JUNO' s stringent specifications. The architecture of the au256 0.20% FS). Shielded twisted-pair cables, LC filtering, iso- 289 tomatic control system is illustrated in Figure 2 [Figure 2: see original paper]. 257 lators, and hybrid software filtering are utilized to suppress 258 electromagnetic interference.

Controller Layer: A S7-300 PLC with microsecond-level 290 E. Comparison with Previous Large-Scale LS Experiments 260 response forms the core of this layer.

Control software is 261 developed on TIA Portal [22] for Human-Machine Interface The FOC system' s design reflects the unique challenges 262 (HMI) based visualization and integrated with EPICS [23] for 292 posed by JUNO' s scale and detector configuration, which dif263 cross-system data exchange and real-time status monitoring. 293 fer fundamentally from previous large-scale LS experiments.

Actuator Layer: This layer includes valves (SED[24], 294 Compared to KamLAND (1 kt) and Borexino (0.3 kt), 265 leak rate < 10 mbar ·L ·s−1 , regulating valve accuracy 295 which used thin nylon balloons immersed in buffer liquids, 266 $±$1%, on/off valve response < 1 s) and pumps (8 units: 296 JUNO employs a different containment approach. Its 20 kt 267 CDR[25] electromagnetic for LS, Yamei[26] self-priming for 297 LS is contained in a 35.4-m diameter thin-shell acrylic sphere 268 water, all with standby units). Real-time status monitoring 298 that is directly exposed to external water pressure. This con269 and protection interlocks (e.g., level, pressure) are imple299 figuration introduces a critical requirement: precise real-time 270 mented. 300 control of the pressure differential across the acrylic vessel Alarm and Data Management Layer: This layer is re- 301 during filling, strictly adhering to the safety windows derived 272 sponsible for system-wide supervision, event logging, and 302 from detailed Finite Element Analysis. Furthermore, the to273 ensuring operational safety.

A multi-mode alarm system 303 tal filling process, including both water and LS, lasted over 274 integrates on-site audiovisual alerts for immediate operator 304 eight months, demanding a high degree of automation and 275 awareness, real-time highlighting on the HMI, remote noti- 305 long-term operational stability. 276 fications for off-site monitoring, and independent hardware 306 Compared to Daya Bay, which employed a three-nested277 emergency stop buttons for critical safety interventions. All 307 vessel design with Gd-doped LS in the innermost acrylic ves278 operational data—including sensor readings, valve states, and 308 sel, normal LS in the second acrylic vessel, and mineral oil 279 alarm histories—are stored locally with high reliability and 309 in the outermost stainless steel vessel—all filled in a dedi280 simultaneously synchronized to the Detector Control System 310 cated hall before transport to the underground experimental 281 (DCS) for distributed access and long-term archiving. 311 site—JUNO requires in-situ exchanging of 20 kt of water The integrated control system employs a combination of 312 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 343 with LS. To reduce engineering risks, the filling scheme of for coordination with upstream LS production over many 344 replacing water with LS is adopted. 315 months.

The radiopurity requirements for U/Th are also 345 The pure water production system, with a capacity of 316 pushed by three orders of magnitude (from 10 g/g to 346 100 m3 /h, was developed to meet stringent requirements for g/g). Additionally, while Daya Bay' s detectors were 347 detector filling and operation. The final product water must 318 filled once and sealed, JUNO' s FOC must accommodate ther- 348 satisfy radiopurity criteria including 222 Rn < 10 mBq m−3 , 319 mal expansion and enable online circulation throughout its 349 226 Ra < 50 µBq m−3 , and 235 U/232 Th concentrations be−15 320 20-year lifetime. 350 low 10 g g−1 , along with physicochemical specifications Thus, while JUNO inherits valuable experience from its 351 of 20 ◦ C temperature, dissolved oxygen < 10 ppb, and re322 predecessors, the FOC system represents a significant tech- 352 sistivity > 18 MΩ ·cm.

The purification employs a two323 nological advance necessitated by the unprecedented scale, 353 stage process. Aboveground pretreatment includes bag fil324 geometry, and operational lifetime of the JUNO detector. 354 tration, multi-media filtration, activated carbon adsorption, 355 radium-removal softening resin columns, and primary Re356 verse Osmosis (RO). The water is then transported via a 325 III.

LIQUID MANAGEMENT DESIGN AND OPERATION 357 1300 m stainless-steel pipeline to the underground facility for 358 further polishing through secondary RO, Electrodeionization This section provides a comprehensive overview of the 359 (EDI), 0.1 µm cartridge filtration, UV sterilization, and ad327 control strategies, operational execution, and performance 360 vanced radon removal using a five-stage degassing membrane 328 outcomes for the key liquid handling processes managed by 361 system augmented by microbubble technology. This configu329 the FOC system: water filling, LS filling, and LS overflow 362 ration achieves a radon removal efficiency exceeding 99.9 %, 330 management. For each process, we first describe the underly- 363 reducing concentrations to (0.61 ± 0.50) mBq m in recir331 ing control logic and design considerations, followed by a de- 364 culation mode. For CD filling, an additional Ultrafiltration 332 tailed account of the operational implementation, challenges 365 (UF) step is implemented, with approximately 5 m h wa333 encountered, and the final achieved results. This integrated 366 ter loss during this process. The system operates in both fill334 presentation highlights the seamless transition from theoret- 367 ing and recirculation modes to support initial commissioning 335 ical control principles to practical execution, demonstrating 368 and long-term detector operation [27]. 336 the system' s robustness and adaptability in meeting JUNO' s Prior to water filling, the Acrylic Spheroidal Vessel (ASV) 337 stringent requirements. 370 undergoes comprehensive cleaning to meet ultra-high purity 371 standards. This process includes reducing airborne dust via 372 water mist spraying, mitigating radon through natural decay, A. Water Filling 373 and stripping protective films/cleaning the acrylic inner sur374 face with high-pressure rotary nozzles. Those films were ap339

1. Control Strategy and Logic

375 plied during the ASV installation to prevent airborne radon 376 from penetrating the acrylic material, while also providing an To minimize LS exposure to air, the air inside the CD must 377 additional protective layer for the acrylic. Concurrently, the 341 first be replaced with water or ultrapure nitrogen, followed 378 commissioning pipeline tests and debugs the water filling au342 by replacing the water or ultrapure nitrogen inside the CD 379 tomatic control system to ensure reliability.

during water filling [28]

The main challenge in synchronizing the CD and WP wa- 434 381 ter filling was managing their differing cross-sectional areas, 382 which vary with height.

The paramount objective was to 436 383 maintain the liquid level difference (ΔH, defined as HCD − 384 HWP) strictly within the safe limits predetermined by finite 385 element analysis (FEA) [28]. Controlling ΔH is essential to 386 protect the structural integrity of the acrylic sphere; exceed440 387 ing these limits would induce stresses beyond design speci441 388 fications, where the maximum axial tensile forces on support 389 bars must not exceed 90 kN and the maximum axial compres443 390 sive forces must not exceed 150 kN. As visualized in Figure 3 [Figure 3: see original paper], 391 a larger allowable range on the left (negative ΔH), which in445 392 dicates that the spherical acrylic vessel can withstand a higher 393 external pressure from the WP than internal pressure. Conse447 394 quently, a slightly higher WP level was permitted during the 395 water filling process. The implemented control strategy was 396 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, re455 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 457 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- 458 tures (such as PMTs, electronics boxes, and the support grid), combined with the total available water flow rate 459 The water filling operation was meticulously executed in 460 one pre-stage and three filling stages (Figure 4 [Figure 4: see original paper]), each tai(90 m3 /h). 461 lored to the specific geometric and mechanical challenges • PID Control for Flow Distribution: Two sets of pneu- 462 presented by different regions of the detector: matically actuated regulating valves, one for the CD 463 Pre-stage - ASV Cleaning: This initial stage was successbranch and another for the WP branch, were controlled 464 fully completed, with all measured parameters exceeding the by PID algorithms. These valves automatically ad- 465 stringent predefined specifications. A pure water mist genjusted their opening to distribute the inlet flow, striv- 466 erator was employed to suppress airborne dust, significantly ing to achieve synchronized rising of the liquid levels 467 improving the internal air cleanliness from Class 100,000 to in both vessels. 468 Class 100. Throughout the cleaning process, the distribution

and flow rate of the rinse water were precisely managed by the 507 the remaining WP volume. The "on-off"mode was reinFOC system. Particulate contamination levels and absorption 508 stated for the North Pole region. A significant and advan471 spectra of the rinse water fully complied with the technical 509 tageous phenomenon was observed for the top chimney: with of water already inside the CD, when CD 472 standards. Crucially, the cleaning procedure resulted in the 510 over 23,000 m 473 near-complete removal of protective films, and the rinse wa- 511 filling was paused and WP filling continued, the increasing 474 ter achieved exceptional ultralow radiochemical contamina- 512 hydraulic pressure from the rising WP level caused a slight 513 elastic contraction of the CD sphere.

This contraction, in 475 tion levels. 514 turn, caused the water level in the top chimney to rise syn515 chronously with the WP level, even without active CD filling.

CD Filling 516 During actual operations, only minimal supplemental filling 517 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 477 the WP volume below and at the South Pole while intermit70 478 tently synchronizing the filling of the CD' s South Polar re60 479 gion itself, the CD filling pipelines, and the bottom chimney. 480 Given the extremely small volumes of the CD components in 481 this area (200 m for the South Polar region) compared 482 to the WP, achieving synchronized level rise was exception20 483 ally challenging. Consequently, a conservative "on-off" mode 484 was employed. The WP was filled continuously at a high rate 485 of 75 m /h. After every 20-30 cm rise in the WP level, 486 the filling process was briefly paused to allow for minimal3 Filling changes 487 flow (1-2 m /h) topping-up of the CD-related components 488 until their levels matched the new WP height. This method 489 ensured successful and safe filling of this critical region.

Stage 2 - Interpolar Region: Covering the vast volume 491 between the poles, this stage benefited from slower and more 518 The entire process of filling approximately 6.4 × 104 tons 492 predictable changes in the cross-sectional areas of both the 519 of ultra-pure water was completed successfully within 45 493 CD and WP. The CD filling pipeline could now sustain a sta- 520 days, commencing on December 18th, 2024, and concluding 494 ble controlled flow of 8 m /h. The primary control logic 521 on February 1st, 2025. Throughout the operation, the flow 495 involving PID-controlled valve adjustment and guidance flow 522 rate was precisely controlled, with the actual flow maintained 496 rate calculation was deployed here.

A total filling rate of 523 within $±$1% of the theoretical target flow. The evolution of 497 80 m /h was maintained.

To accommodate necessary 524 the water levels and filling flow rates throughout this period 498 daily maintenance of the pure water production system (e.g., 525 is depicted in Figure 5 [Figure 5: see original paper]. Visual documentation of the filling 499 filter bag replacements) and to enable accurate verification of 526 process is provided in Figure 6 [Figure 6: see original paper]. At the very end of the detec500 the level difference through periodic pauses, two scheduled 527 tor water filling, on the far right side of the Figure 5, a minor 501 daily reductions or interruptions in the total filling flow were 528 calibration issue with the WP level gauge towards led to a 502 incorporated, ensuring both operational efficiency and detec- 529 deviation in the final WP level control. However, critically, 503 tor safety. 530 the liquid level difference (ΔH) throughout the entire filling Stage 3 - North Pole & Top Chimney: Similar to Stage 531 period consistently remained within the safe design require505 2, this final stage handled the North Polar region of the CD 532 ments stipulated by the mechanical analysis (Figure 3). 506 (volume 200 m) and the top chimney separately from 533 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 from the significant density difference between LS (ρ 0.856 g/cm at 21 $\circ$ C) and water. As the lighter LS progressively exchanged the pure water in the CD, the increasing buoyant force exerted on the submerged acrylic vessel raised the risk of mechanical failure. To mitigate this risk and manage the pressure differential across the acrylic vessel, the liquid level inside the CD was deliberately and incrementally raised during the filling process. This level adjustment aimed to shift the pressure equilibrium point close to the vessel' s equator, with the goal of minimizing the resultant pressure differential across the acrylic vessel. The primary objective of this strategy was to reduce the maximum stress on the spherical structure throughout the exchange.

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

The control logic for the LS filling was designed to manage 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 long-term operation, the top and bottom distributors enable independent control of inlet temperature and flow for active thermal regulation to counteract heat ingress from the surrounding rock and PMT electronics. The target temperature for the water pool is 21 ± 1 C, which has been achieved following 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 CD interior was purged with ultrapure nitrogen that had a 600 Rn contamination level below 10 µBq/m3 , the critical LS 601 546 filling operation commenced. This process involved the con- 602 547 tinuous injection of purified LS into the CD from the top 603 548 chimney while simultaneously draining the water from the 604 549 bottom pipeline. The LS was supplied at a nominal rate of 605 550 7 m /h by the dedicated JUNO LS production and purifi- 606 551 cation system [9], which encompasses nine subsystems in- 607 552 cluding storage, alumina filtration, distillation, mixing, wa- 608 553 ter extraction, gas stripping, online radioactivity monitoring 609 554 (OSIRIS), along with ultrapure water and high-purity nitro- 610

- 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 663 the newly produced scintillator met the experiment' s stringent 664 requirements using the OSIRIS system. the operation.

Commencement of Continuous Filling (Feb.25, 2025): • Stringent Safety Interlock: The utmost priority was 666 Following the positive initial assessment, the purification the structural integrity of the ASV. The control system 667 plants were configured for round-the-clock operation, and the continuously monitored the calculated pressure differ- 668 continuous phase of LS filling began. A deliberately cautious ential across the acrylic vessel. If this differential ap- 669 approach was adopted initially: the filling rate was set to a proached a predefined maximum allowable threshold 670 low range of 1-2 m3 /h for the first few hours. This allowed (derived from FEA), a paramount safety interlock was 671 for a final verification of the stability and safety of the entire triggered. This interlock activated an "on-off" LS fill- 672 integrated supply chain—from production to injection—and ing mode, which immediately halted either LS injec- 673 the CD' s response to the ongoing LS filling. tion or water drainage (whichever action would most 674 Running-in Phase (Feb.25 - Mar.10, 2025): After the ini622 effectively reduce the pressure differential) until the 675 tial verification, the flow rate was promptly ramped up to its condition returned to a safe range. 676 nominal value of 7 m /h. This period, lasting approximately 677 two weeks, is identified as the running-in phase for the filling • Coordination with LS Production: The FOC sys- 678 system supporting the LS filling. During this phase, contin625 tem' s extraction of LS from the product tank needed to 679 uous

24/7 operation could not yet be fully sustained due to be synchronized with the production plant’ s output rate 680 teething issues and planned initial adjustments, resulting in of 7 m3 /h. In the absence of a dedicated flow meter 681 an operational availability of approximately 50%. on this transfer line, synchronization was achieved by 682 Stable Operation Phase (Mar.11 - Aug.22, 2025): From periodically fine-tuning the transfer pump’ s frequency 683 March 11th onward, the system entered a period of highly sta630 based on the measured liquid levels in both the LS 684 ble operation for the LS filling. Near-continuous 24/7 filling product tank and the FOC storage tank, ensuring a dy- 685 was achieved with significantly improved reliability, boast632 namic balance between production and consumption 686 ing an operational availability of 90%. Throughout this entire for the LS filling. 687 period, the control system demonstrated exceptional perfor688 mance: the liquid level inside the CD was meticulously main634 • Backup of Water Drainage Capability: A backup de- 689 tained within a variation of $±$2 cm of the predetermined tar635 sign consideration was the evolving hydraulic head for 690 get level trajectory, and the LS filling flow rate was precisely water drainage. As LS replaced the denser water and 691 controlled within an accuracy of $±$0.5% of the setpoint. This the LS/water interface descended, the static pressure 692 high-precision flow control is essential to maintain a quies638 difference between the CD and the WP gradually in- 693 cent LS surface, ensure the liquid level difference balance, creased. This meant the self-priming drainage pumps 694 and maintain a stable balance with the upstream LS produc640 effectively had to lift water from an increasingly greater 695 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 tem642 0.5 m to a design maximum of approximately 4 m. To 697 perature of the injected LS was primarily regulated by the up643 safeguard against potential pump performance degra698 stream Stripping Plant[14], which can control the LS produc644 dation or instability under this varying load, a vacuum ◦ 699 tion temperature via heat exchange with a precision of 0.1 C. assisted backup system was engineered. Although this 700 Four temperature sensors at the injection line and storage system was never activated during actual operation, as 701 tanks outlet within the FOC system provided real-time moni647 the primary drainage system maintained stable perfor702 toring of the LS temperature. The ambient temperature of the mance throughout the entire LS filling process, its de703 underground laboratory was also actively controlled to mini649 sign and integration provided a critical safety margin to 704 mize thermal gradients. Based on the real-time LS tempera650 ensure the continuous outflow rate of 7 m3 /h under all 705 ture readings from the FOC system, the injection temperature anticipated conditions. 706 was coordinately adjusted with the Stripping Plant to main707 tain stable filling conditions.

Following the completion of LS filling, temperature moni652

2. Operational Implementation and Results

709 toring using the Automatic Calibration Unit (ACU) showed 710 that the LS within the CD exhibited a uniform tempera653 The LS filling operation was executed in a carefully se- 711 ture distribution, with measured values ranging from approx ∘ 654 quenced manner, prioritizing both system verification and ra- 712 imately 21.05 C at the top to 21.02 C at the bottom, well 713 within the operational requirement of (21 ± 1) C. 655 diopurity assessment:

Initial Batch and Purity Check (Feb.8-10, 2025): The 714 Throughout the LS filling process, comprehensive radiop657 operation commenced with the successful injection of an ini- 715 urity monitoring was implemented to ensure ultra-low back3 658 tial batch of 100 m of LS. This batch was then held within 716 ground levels, consistent with the requirements for JUNO' s Real-time 222 Rn activity monitoring was 659 the CD for several days to acquire data. This waiting period 717 physics goals. 660 allowed for the decay of any Rn that was not in secular 718 achieved by tagging 214 Bi-214 Po cascade decays in the CD 661 equilibrium with its parent nuclide and provided the first cru- 719 data stream, complemented by periodic batch testing of 3662 cial opportunity to assess whether the intrinsic radiopurity of 720 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 723 of 5 mBq/m [29]. This excellent performance was attributed 724 to the stringent leakage control measures, continuous nitro725 gen purging of the filling system and CD chimney, and the 726 high-efficiency radon removal in the LS purification chain.

Furthermore, independent radiopurity monitoring was con728 ducted using Inductively Coupled Plasma Mass Spectrom729 etry (ICP-MS), a highly sensitive technique capable of deDate 730 tecting trace levels of U and 232 Th [30]. In this method, 731 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 732 tillator via acid digestion, concentrated, and then introduced filling process 733 into the ICP-MS system for quantitative analysis. With strin734 gent cleanliness control throughout sample preparation—735 including the use of ultra-pure reagents and meticulously LS Filling Flow 736 cleaned labware—the method achieves recovery efficiencies Water Drainage Flow 737 close to 100% and a detection limit at the sub-ppq level. The 738 ICP-MS results confirmed that the concentrations of U and Th in the LS were maintained below the 10−16 g/g level 740 throughout the filling process. This provides direct evidence 741 that the FOC system did not introduce contamination from 742 these critical long-lived radioisotopes.

Following the completion of LS filling, an integrated ra3 744 diopurity analysis of the LS within the CD fiducial volume 745 was performed. The results confirmed that the concentrations 746 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 2025-05-12 748 imately 5 × 10 cpd/kton [29] [31], fully meeting the strin749 gent requirements for both neutrino mass ordering and solar 750 neutrino studies. This demonstrates that the FOC system ef751 fectively prevented the introduction of external contaminants 752 throughout the filling process, thereby preserving the ultra753 high radiopurity of the LS. 779 level, the detector exhibited stable and safe mechanical con754 The monumental task of LS filling 2.3 × 104 m3 of water 780 ditions, as validated by the continuous monitoring of the sup755 with LS was successfully concluded on August 22nd, 2025, 781 port rod forces throughout the entire exchange period. The 756 after a total duration of 200 days. Following the main LS 782 measured forces on the rods showed general agreement with 757 filling, an additional 80 m of LS was deliberately drained 783 the FEA predictions within acceptable margins. The moni758 from the bottom of the detector. This volume, which con- 784 toring data confirmed that the maximum compressive force 759 stituted the initial batch filled into the CD, was purged due 785 on the rods was around −160 kN, and the maximum tensile 760 to its higher contamination risk from prolonged contact with 786 force was around 99 kN. A few individual rods exhibited 761 residual water and particulates introduced during the initial 787 readings moderately higher than the FEA predictions, not ex762 pipeline flushing. This operation functioned as a one-time, 788 ceeding 10% of the maximum design values. The prelimi763 unidirectional flushing cycle aimed at removing the poten- 789 nary assessment attributes this deviation to potential factors 764 tially compromised scintillator from the detector’ s lowest 790 such as the connection and installation details between the 765 point, thereby ensuring the final optimal purity within the CD. 791 rods and the acrylic vessel. This aspect will continue to be 766 It is noteworthy that this process can be regarded as a spe- 792 monitored closely. Overall, the mechanical data indicate a 767 cific form of circulation, albeit without routing the drained 793 very low risk of structural damage to the acrylic vessel or its 768 LS back through the external purification system. The con- 794 support structure due to overstress under the current loading 769 trol logic and operational procedures for this operation were 795 conditions. 770 fundamentally similar to those implemented for the online LS 796 Inevitably, during the extended stable operation period 771 circulation described in Section III C. 797 of the LS filling, several intermittent filling stops occurred.

The downward migration of the water/LS interface and the 798 These were primarily attributed to two factors: temporary 773 corresponding increase in the total LS volume inside the CD 799 shortages of the raw LAB material from the supplier, and nec774 throughout the LS filling process are clearly depicted in Fig- 800 essary adjustments and maintenance of the equipment. These 775 ure 7. The flow rate stability during the stable phase is illus- 801 intervals were utilized productively to conduct an intensive 776 trated in Figure 8 [Figure 8: see original paper]. 802 detector calibration campaign, which yielded valuable data The LS filling process concluded with the liquid level in 803 for enhancing the understanding of the detector's response 778 the CD stabilized at approximately 47 meters. At this liquid 804 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 com857 menced on August 26th, 2025. The overflow system immedi807 During the long-term operation of the JUNO detector, the 858 ately became active to manage diurnal and other minor tem808 FOC system' s role transitions from filling to managing the 859 perature variations. 809 thermal dynamics of the large LS volume. The thermal vol860 The initial operation of the designated dedicated overflow 810 ume expansion coefficient of LS (8.8 × 10 / C) means 861 pipeline encountered a technical challenge: an airlock phe811 that temperature fluctuations may cause significant volume 862 nomenon prevented the establishment of a reliable hydraulic 812 changes—approximately 20 m per 1 ◦ C change for the CD 863 communication between the overflow tanks and the top chim813 volume—which must be accommodated to maintain stable 864 ney of the CD. To promptly resolve this and ensure detector 814 pressure conditions inside the sealed CD. The overflow sys865 stability, the original LS filling pipeline was repurposed as a 815 tem is specifically designed to handle these LS volume varia866 backup overflow pathway. This solution proved effective; the 816 tions. The strategy for managing this employs a combination 867 overflow process through this backup line operated smoothly, 817 of passive and active mechanisms: 868 achieving overflow rates exceeding 2 m /h, which adequately 869 met the initial operational requirements for handling thermal 870 expansion. • Passive Thermal Regulation via Overflow Tanks: 871 However, to ensure mechanical safety, the final LS filling The primary buffer for routine temperature fluctuations 872 level was intentionally stabilized at approximately 47 meters, is provided by two dedicated overflow tanks. These 873 as validated by force monitoring data as mentioned in Sec821 tanks are connected to the CD' s top chimney. For mi- 874 tion III B 2. This operational liquid level is below the original nor temperature variations, the resulting LS volume 875 design value. Consequently, the liquid level in the intercon823 change is passively absorbed or replenished by these 876 nected FOC overflow tanks was also correspondingly lower. tanks through gravity-driven flow without any active 877 This reduction decreased the tanks' effective cross-sectional intervention. 878 area for buffering level variations, reducing the system' s pas879 sive overflow capacity to approximately 80% of its nominal 880 design value. • Active Volume Adjustment via Storage Tank: For 881 To maintain detector stability under this adapted configu827 larger temperature shifts, the system switches to active 882 ration, two key measures were implemented: mode. A separate storage tank is employed for this pur- 883 The operational liquid level variation was constrained to pose. When the temperature drops significantly, valves 884 within $±$5 cm to minimize level-induced pressure variations and pumps are activated to transfer LS from the stor- 885 on the acrylic vessel, a key requirement for mechanical safety. age tank into the CD circuit to compensate for the con- 886 This liquid level tolerance is well within the high-precision traction. Conversely, when the temperature rises sig- 887 control capabilities of the automated system, which can main833 nificantly, the expanded LS volume automatically over- 888 tain level stability at this or even finer scales, thereby provid834 flows into the overflow tanks. If needed, LS is actively 889 ing a robust safeguard for the detector' s structural integrity. transferred from the overflow tanks to the storage tank 890 An active liquid level adjustment function was integrated to prevent overfilling. 891 into the automatic control system to compensate for the re892 duced passive capacity. This system dynamically regulates 893 the liquid level in the overflow tanks through small-volume • Online Purification Circulation: To further reduce 894 transfers to and from the storage tank, maintaining precise impurities over the detector' s lifetime, the LS can 895 balance with the CD' s requirements. The control loop has be continuously purified through an online circulation 896 been thoroughly validated and remains operational, ensuring loop. LS is extracted from the bottom of the CD, passed 897 long-term detector stability. through external purification systems (e.g., water ex- 898 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 899 tanks and the CD exhibit excellent synchronization. Cur843 of the CD. Computational Fluid Dynamics (CFD) sim- 900 rently, during the initial phase shortly after the completion ulations were employed to optimize this process [3]. 901 of LS filling, the entire detector is undergoing a gradual cool845 The simulations revealed that the efficiency of purify- 902 down. This results in a combined effect of thermal contrac846 ing the entire CD volume depends on the temperature 903 tion in both the LS and the acrylic vessel itself, accompanied difference between the injected and in-situ LS. By ap- 904 by elastic deformation of the spherical structure due to the propriately controlling the temperature of the purified 905 changing liquid head. These factors collectively contribute to LS relative to the CD LS, convection currents can be 906 a progressive decrease in the liquid level. Under these condi850 suppressed to improve circulation efficiency. Based on 907 tions, the active replenishment function is activated, transfer851 these studies and the hydraulic characteristics, the op- 908 ring LS into the CD to raise its liquid level slightly. This timal flow rate for this purification circulation was de- 909 proactive compensation is crucial for maintaining the me910 chanical stability of the detector structure during this tran853 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 relia953 bility. The stringent radiopurity controls—including the use 954 of ultra-high purity materials, meticulous cleanliness proto—6 955 cols, and exceptional leak tightness (helium leak rate < 10 956 mbar-L · s for assembled systems)—were instrumental in 957 preserving the LS purity throughout the filling process. This 958 foundational role is demonstrated by two key achievements: 959 the maintenance of Rn concentration below 1 mBq/m3 in fresh during filling, and the establishment of the condiDate 961 tions necessary for the outstanding ultimate radiopurity levels U and Th concentrations below 10 g/g and an initial 210 Po operation 964 rate of approximately 5 × 10 cpd/kton. These collective re965 sults underpin the detector' s potential for achieving its pre966 mier physics goals. 911 sitional phase.

During long-term operation, the LS temperature inside the 913 CD is is primarily influenced by the Water Pool temperature JUNO' s physics goals demand ultra-low backgrounds 914 through heat exchange across the acrylic vessel. g/g) and 3% energy resolution at After approximately six months of detector operation, the 968 (U/ Th < 10 969 1 MeV. These requirements impose constraints rarely encoun916 LS temperature has been monitored multiple times and exradiopurity for LS and 917 hibits a little dynamic variations.

The measured tempera- 970 tered in industry: semiconductor-grade 971 water, leak tightness below 10 mbar · L/s over two decades, 918 ture within the CD has ranged from approximately 20.2 C 972 and surface roughness ≤ 0.4 µm for all wetted materials. The 919 to 20.6 C, with a temperature non-uniformity of less than 973 FOC system achieves these through precise background con920 0.5 C. This minor stratification results from natural density974 trol, stringent material selection, and cleanliness protocols. 921 driven convection and is influenced by residual temperature 975 The control system operates from 100 m /h during water fill922 non-uniformity in the Water Pool. The overall temperature 976 ing down to 7 m /h for LS filling, maintaining $±$0.5% flow 923 range is well within the operational requirement, and the tem977 stability and $±$2 cm level control over six months LS filling 924 perature uniformity meets the detector' s operational require978 period—protecting the acrylic sphere and coordinating with 925 ments. 979 upstream production. The fully automated PLC/EPICS sys980 tem integrates redundant sensors, alarms, and interlocks for 981 long-term reliability, with overflow management and online IV. SUMMARY 982 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 983 Looking forward, the established FOC infrastructure and 929 role in JUNO. Through meticulous design and robust auto984 operational expertise provide a solid foundation for future 930 mated control, the system safely and precisely managed the 985 JUNO upgrades. Specifically, the system is designed to sup931 large-scale liquid handling operations, ensuring the structural 986 port potential next-phase physics programs, by enabling con932 integrity of the CD and preserving the exquisite optical and 987 tinuous online LS circulation to achieve even higher purity 933 radiopurity properties of the LS. Its accomplishments can be 988 levels. Also it can replace LS for the research of neutrinoless 934 summarized in three key aspects: 989 double-beta decay. JUNO advances large-scale LS detector First, the FOC system has accomplished the filling of the 990 technology through its scale (20 kt), energy resolution (3% at 936 world' s largest liquid scintillator detector, taking 45 days for 991 1 MeV), radiopurity control, automated fluid handling, and 937 the initial water filling of approximately 6.4 × 10 tons and 992 mechanical innovations—providing a foundation for future 938 200 days for the subsequent LS filling of 2.3 × 10 m , with 993 generation experiments. 939 90% operational availability during stable operation, while 940 also ensuring the functionality of overflow management and 941 future circulation.

In summary, the FOC system has proven to be a reliable, Second, the integration of an automated control system 995 adaptable, and indispensable component for JUNO. Its suc943 based on PLC and EPICS software provided the founda-996 cessful implementation underscores the importance of inte944 tion for this success, enabling real-time monitoring, precise 997 grated design, automated control, and continuous monitoring 945 control, and robust safety interlocking throughout all opera- 998 in large-scale neutrino detector operations, providing a solid 946 tions. The system has achieved fully automated liquid con- 999 foundation for JUNO' s scientific exploration over its planned 947 trol, meeting stringent requirements for high-precision liquid 1000 20-year lifetime and beyond. The design principles, control 948 level control within $±$2 cm and flow rate regulation within 1001 strategies, and lessons learned from this project offer valuable 949 $±$0.5% of setpoints. 1002 insights for other large-scale, high-purity liquid-based detec950 Third, the design and operation of the FOC system have 1003 tors in particle physics and related fields.

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