A compact ultra-clean system for deploying radioactive sources inside the KamLAND detector

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Abstract

We describe a compact, ultra-clean device used to deploy radioactive sources along the vertical axis of the KamLAND liquid-scintillator neutrino detector for purposes of calibration. The device worked by paying out and reeling in precise lengths of a hanging, small-gauge wire rope (cable); an assortment of interchangeable radioactive sources could be attached to a weight at the end of the cable. All components exposed to the radiopure liquid scintillator were made of chemically compatible UHV-cleaned materials, primarily stainless steel, in order to avoid contaminating or degrading the scintillator. To prevent radon intrusion, the apparatus was enclosed in a hermetically sealed housing inside a glove box, and both volumes were regularly flushed with purified nitrogen gas. An infrared camera attached to the side of the housing permitted real-time visual monitoring of the cable's motion, and the system was controlled via a graphical user interface.

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(solid, gas and liquid scintillators)
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Figure 1: The KamLAND detector.

1. Introduction

The Kamioka Liquid-scintillator Anti-Neutrino Detector (KamLAND) is a physics experiment located 1 km underground in a mine near Kamioka-cho, Gifu, Japan. KamLAND (Fig. 1) contains 1 kton of ultra-pure liquid scintillator (LS) which serves as both the target and detecting medium for neutrino interactions. A detailed description of the detector is given in [1].

KamLAND was commissioned in 2001 and used primarily to study the flux and energy spectrum of electron anti-neutrinos emitted by surrounding nuclear reactors. The experiment provided convincing evidence that anti-neutrinos are massive particles that undergo flavor oscillations during propagation and it yielded precision determinations of the neutrino oscillation parameters [2–5]. In addition, KamLAND was the first experiment to report

evidence of geoneutrinos, which are anti-neutrinos produced by radioactivity in the Earth’s interior [6]. A subsequent measurement by KamLAND indicated that decay of radiogenic isotopes accounts for roughly half of the heat flux emanating from the Earth’s interior; this was the first geoneutrino result to constrain geothermal models [7].

From May 2007–February 2009 the KamLAND Collaboration conducted an intensive campaign to further purify the detector’s LS, with the goal of enabling detection of solar neutrinos from ${}^7\text{Be}$ decay in order to test aspects of the Standard Solar Model [8–10]. Purification was necessary because monoenergetic ${}^7\text{Be}$ solar neutrinos are detected via elastic scattering by electrons, a method that requires much lower backgrounds than the delayed-coincidence technique used to detect higher-energy reactor anti-neutrinos. In order to render a ${}^7\text{Be}$ solar neutrino measurement possible, the already low concentrations in the LS of certain unwanted, long-lived isotopes—primarily ${}^{40}\text{K}$, ${}^{85}\text{Kr}$, and ${}^{210}\text{Pb}$ —had to be reduced by several orders of magnitude.

Detector calibrations—in which radioactive sources of known energy are deployed to precise positions inside the LS in order to determine the timing of the surrounding photomultiplier tubes, the uncertainty in reconstructed event positions, and the detector’s energy response—were identified as a potential threat to the radiopurity improvements expected from LS purification. There was strong evidence that the existing calibration systems had introduced contamination (primarily ${}^{222}\text{Rn}$, a highly mobile noble gas which generates the problematic long-lived daughter ${}^{210}\text{Pb}$) in amounts that would be unacceptable under the new experimental circumstances [11]. Given that routine calibrations would be essential to the collection of high-quality data, the collaboration decided to implement a new, ultra-clean source deployment system for use following the LS purification campaign. The new calibration system, nicknamed “MiniCal” due to its compact size, is the subject of this paper.

2. System design

2.1. Requirements and constraints

The primary challenge in designing and building MiniCal lay in meeting oft-competing requirements regarding its size, cleanliness, and capabilities.

1. **Compact size** — Every calibration system used in KamLAND has been installed inside a glove box atop the detector’s chimney (Fig. 1).

Figure 2: Drawings of the MiniCal calibration device alone (right) and installed inside the glove box atop the KamLAND detector (left). MiniCal is highlighted in blue in the latter for visibility. Space inside the glove box was limited due to the continued presence of hardware from the previous, full-detector-volume calibration system.

Access to the chimney and detector was possible via an 8-inch flanged opening in the floor of the glove box. During normal data taking, detector access was blocked by two hermetically sealing gate valves located in series along the chimney's column, and the glove box was typically overpressured with nitrogen gas to prevent intrusion of contaminants, primarily radon.

Prior to MiniCal, hardware from a previous, full-detector-volume calibration system [11] occupied a large fraction of the space in the glove box. We wanted to leave that system intact to preserve the possibility of making future off-axis deployments, so MiniCal was designed to fit in the small space available beneath it (Fig. 2). It should be mentioned that the full-volume calibration system could not be deployed while MiniCal was installed because the latter blocked access to the detector.

The largest components of MiniCal also needed to be small enough to fit inside the glove box’s 1-cubic-foot transfer box so that the new system could be moved into the glove box piecemeal and assembled inside. And despite its small size, MiniCal needed to be amenable to servicing via the glove box’s thick Viton gloves.

2. Materials and cleanliness — The KamLAND LS is a highly active, radiopure solvent composed primarily of dodecane and pseudocumene [1]. All MiniCal components to be submerged in the LS had to be ultra-clean and possess low intrinsic radioactivity (so as to avoid contaminating the detector), and they had to be made of materials that would not be damaged by the LS or degrade its optical purity. The MiniCal hardware in the glove box needed to be capable of withstanding prolonged exposure to LS vapors without suffering negative effects or emitting contaminants.

The two preceding calibration systems had used large-gauge wire rope and wide-ribbon woven-nylon cables, respectively, and the large surface areas of these materials tended to collect radon and radon daughters during idle periods and then transport them into the detector during deployments. To reduce this problem—and also to meet the stringent spatial constraints—it was necessary that MiniCal utilize a small-gauge cable of some kind. We also elected to enclose the apparatus within its own hermetically sealed housing to provide a secondary barrier against radon intrusion.

3. Accuracy and precision — The KamLAND vertex reconstruction algorithm is tuned to minimize the difference between the nominal position of a deployed source and the mean of its corresponding event distribution, for a number of different source positions. Consequently, a systematic error in the positioning of sources—even if small compared to the detector resolution of $\sim 12 \text{ cm}/\sqrt{E(\text{MeV})}$ —can introduce a vertex reconstruction bias that significantly increases the systematic uncertainty in the fiducial volume estimate and thus negatively impacts the final physics result [11]. Prior to MiniCal, the systematic error due to vertex reconstruction bias along the detector’s central vertical axis (z-axis) was $\sim 2 \text{ cm}$. We aimed to strongly limit the new deployment system’s contribution to this error by making it capable of placing a

96 source within ± 2 mm of any point along the z-axis, a length spanning
97 19 m from the glove box to the bottom of the LS balloon.

98 *2.2. Materials selection and radioassay*

99 The KamLAND LS is a mixture of 20% pseudocumene, 80% dodecane,
100 and 1.36 g/l of the fluor PPO. Pseudocumene is a highly active organic
101 solvent which can damage the structural integrity of many materials, so care
102 had to be taken when choosing components for the calibration system.

103 The MiniCal components to be submerged in the LS or exposed to its
104 vapors were made almost exclusively from materials that had been identified
105 in past tests by the KamLAND collaboration [11] and others [12] as being
106 chemically compatible with the LS—namely, 304 and 316 stainless steel, gold,
107 titanium, nylon, Teflon, Viton, and quartz. Only 416 stainless steel, whose
108 magnetic properties were needed for one small component which would be
109 submerged (see Sec. 2.5), required new examination. LS soak and light atten-
110 tuation tests on 416 samples indicated the component would not negatively
111 affect the LS, or vice versa. All other MiniCal components to be submerged
112 in the LS were made of 304 or 316 stainless steel.

113 To guard against introducing radioactive contaminants into the Kam-
114 LAND detector, strict protocols were followed in cleaning and certifying the
115 parts of the calibration system that would enter the detector volume or be ex-
116 posed to LS vapors. All such parts were UHV cleaned according to a standard
117 protocol employed at Lawrence Berkeley National Laboratory (LBNL) [13]
118 and the system was preassembled and packaged in a class 10,000 clean room
119 at LBNL before shipment to the experimental site. Items that were to be
120 submerged in the LS, or that would come into direct contact with components
121 to be submerged in the LS, underwent an additional cleaning and certifica-
122 tion procedure [11] consisting of a series of heated ultrasonic cleanings in a
123 weak solution of aqueous trace-metal-grade nitric acid and deionized water
124 (0.2 mol/l). A 100-ml sample of the nitric solution was collected at the end
125 of the final cleaning and counted using a surface Ge detector operated by
126 the LBNL Low Background Facility [14]. No evidence of U, Th, or K con-
127 tamination above the detector’s sensitivity limits was observed; the upper
128 limits after a ~ 30 -day count were $U < 4$ mBq/kg, $Th < 2$ mBq/kg, and
129 $K < 130$ mBq/kg, where kg refers to leachate mass.

2.3. Hardware

The basic concept for the MiniCal system is simple: it used a stepper motor to turn a spool of cable and thereby lower and raise a radioactive source along the z-axis of the KamLAND detector (Figure 3). The motion of the cable was measured by an encoded pulley located above the z-axis, enabling precise positioning of the source.

We elected to use a thin-gauge cable because compared to the alternatives (e.g., a chain or sprocketed cable) it offered the best combination of simplicity and cleanliness. The primary drawback was that great care had to be taken to prevent cable slippage on the encoded pulley, as that would have ruined positioning accuracy. The cable was made by Strand Products, Inc., from 1/32-inch-diameter, 7×19-stranded, 120-pound tensile wire rope that had been proof-loaded to 60% of its breaking strength to eliminate constructional stretch¹⁶. This particular cable was selected for several reasons: it is composed entirely of T304 stainless steel, which is LS-compatible; it has a small diameter, which served to minimize both the amount of space it occupied when spooled and the amount of surface area that could collect contaminants; and its 7×19 strand lay renders the cable very supple and allowed it to maintain good contact with the encoded z-axis pulley, which was machined from titanium to minimize its rotational inertia. Each end of the cable terminated in a swaged bushing: one end was anchored to the spool, while the other end was attached to a free-hanging 0.55 kg weight which kept the cable under tension to ensure good contact with the encoded pulley. A captured, spring-loaded pin in the underside of the weight was used for easy attachment of different radioactive sources. The attachment mechanism was designed to be backwards-compatible with existing sources used with the previous calibration systems, requiring only that each source be fitted with an adaptor bolt.

The cable was wound on a custom spool modeled after a Penn GTO 220 level-wind fishing reel. This device contained a cable guide mechanically coupled to the spool's rotation to wind cable evenly and compactly along the length of the spool. A small guide pulley located between the spool and the z-axis pulley prevented the side-to-side motion of the spooling cable from affecting its smooth passage over the z-axis pulley. The spool was turned

¹⁶Our own dynamometer tests demonstrated that the breaking strength of the cable assemblies was approximately 100 pounds (45 kg).

Figure 3: Cutaway drawing of the interior of the MiniCal housing. The cable is drawn in green and the components it touches are shaded red. The driveshaft and level-wind mechanism are shaded blue.

164 by an Anaheim Automation 23MDSI integrated stepper motor performing
 165 1600 steps/revolution.

166 It had been observed that the previous KamLAND calibration system
 167 had introduced small amounts of radon into the LS, likely due to small leaks
 168 in the glove box that allowed ingress of ambient outside air. In order to
 169 provide an added barrier against radon intrusion, the MiniCal hardware was
 170 enclosed within a hermetically sealed housing (Figure 4) which was bolted
 171 to the 8-inch-diameter conflat flange welded to the floor of the KamLAND
 172 glove box (Figure 2). The housing was constructed by welding together
 173 jointed, $\frac{1}{8}$ -inch-thick stainless steel panels; afterwards it was electropolished
 174 to remove oxidation and passivate the surface. The interior was accessed
 175 through a 5.5×7.4 in² rectangular opening which faced the glove box's gloves
 176 and was usually covered by a removable door. A Viton O-ring seated in the
 177 face of the door formed a seal against the housing when the the door's hand-
 178 operated dial was cranked to press the two surfaces together. The housing sat
 179 atop a 1.8-inch-tall stand tube (3-inch OD, 2.75-inch ID) in order to provide
 180 clearance for inserting bolts into the 8-inch flange at its base.

Figure 4: The MiniCal housing in a test bench setup.

181 The z-axis pulley was mounted to the housing’s ceiling on a movable stage
 182 which could be translated in two dimensions to center the hanging cable over
 183 the detector’s vertical axis. The centering procedure was performed at the
 184 time of installation with assistance from a cross-hair-engraved cover plate
 185 inserted in the stand-tube opening inside the MiniCal housing.

186 The floor of the housing was angled slightly so that LS brought up by the
 187 cable during deployments collected in its front. The accumulated LS—which
 188 was prevented from returning to the detector by a small collar around the
 189 stand-tube opening in the housing’s floor—was periodically drained through
 190 a manually operated Swagelok Whitey P-series stainless steel purge valve
 191 (with PTFE ball) mounted on the lower corner of the housing. This valve
 192 and an identical one located above it also functioned as vents during nitrogen
 193 gas purges of the MiniCal housing volume (see Sec. 3.1). The spring-loaded
 194 valves were bracketed by steel retaining arms to prevent them from being
 195 unscrewed to the point of disassembly.

196 In order to prevent the stepper motor from introducing contaminants
 197 or coming into contact with corrosive LS vapors, it was enclosed inside a
 198 leak-tight stainless steel canister attached to the side of the housing. The

199 motor’s 1/4-inch driveshaft connected to the cable spool via an MDC Vacuum
200 direct-drive rotary mechanical feedthrough.

201 An infrared camera provided real-time visual monitoring of the cable
202 when the housing was sealed shut during deployment operations. Like the
203 motor, the camera—an Allied Vision Technologies Guppy F-038B black-and-
204 white, near-infrared, asynchronous Firewire digital camera with a Kowa
205 Model LM25JC 2/3-inch machine vision lens—was enclosed in a sealed canis-
206 ter. The camera viewed the interior of the housing through a quartz window,
207 with two Advanced Illumination SL4301 880-nm IR LED 5-volt spot lights
208 attached to the underside of the camera providing illumination. Infrared
209 imaging equipment was chosen because the operating spectrum lies above
210 the ~ 600 nm optical cutoff of the detector’s PMTs.

211 All MiniCal flanges were made of stainless steel and joined using titanium
212 bolts to avoid galling. The bolts were tethered to prevent being dropped or
213 lost during assembly and disassembly. The flanges did not rely on knife
214 edges to form gas-tight seals; instead, they had been modified to employ
215 seated Viton O-rings, based on a design developed at LBNL. This technique
216 offers several advantages over conventional flange gasket seals, which are
217 single-use and can be awkward to manipulate manually. A rotatable 8-inch
218 flange was used for the base of the MiniCal housing to permit convenient
219 alignment of the housing during installation. The camera canister contained
220 the assembly’s lone quick flange, which was useful for providing prompt access
221 to the camera during its initial tuning.

222 *2.4. Motion control software*

223 The MiniCal system was controlled and monitored using custom Java
224 software running on a dedicated computer in an electronics room adjacent
225 to the experiment. The software consisted of two independently functioning
226 parts: a control side which communicated with the hardware, and a graphical
227 user interface, or GUI (Figure 5), which communicated with the control
228 side. The two layers used the Java Remote Method Invocation protocol to
229 communicate with each other in real time via changes to the values of a set
230 of shared parameters. All system actions and parameter changes were logged
231 to a PostgreSQL database.

232 The computer, a small-form-factor CappuccinoPC SlimPRO 620S, ran
233 the open-source Fedora 9 Linux operating system. Three 9-pin serial ports
234 were used to communicate with the stepper motor and encoders, and a
235 Firewire port was used to communicate with the camera. The camera’s

Figure 5: MiniCal graphical user interface (GUI).

236 output was viewed using the software program Coriander. One of the serial
 237 ports was used to communicate with both the stepper motor and a Crouzet
 238 XT20 Millenium II+ programmable logic controller (PLC) which enabled
 239 software-controlled switching of power to the hardware. The PLC was used
 240 primarily to power the hardware on and off at system startup and shutdown,
 241 and to toggle power to the driveshaft safety brake and the IR lights during
 242 system operation.

243 The stepper motor's rotation was measured by a US Digital E5D optical
 244 encoder which was read out by a US Digital AD4-B-D quadrature encoder
 245 counter. The motor's revolutions could not be used to precisely determine
 246 cable payout, however, because the spool's effective radius changed with the
 247 amount of spooled cable. Instead, cable payout (and hence the source's
 248 position) was determined using the 3.6-cm-diameter titanium z-axis pulley,
 249 whose rotations were measured by a Renishaw RM22I non-contact rotary

250 encoder with a resolution of 800 counts/revolution. The z-axis pulley was
251 attached to a gold-plated rare-earth magnetic actuator which rotated inside
252 the fixed stainless steel RM22I encoder housing; the encoder transmitted
253 standard incremental quadrature output which was counted by another US
254 Digital AD4-B-D unit. The pulley encoder electronics were enclosed inside
255 a small hermetically sealed stainless steel box inside the MiniCal housing.

256 Because cable payout was controlled by the motor but measured by the
257 z-axis pulley, the system generally had to iterate several motions before the
258 deployed source reached the desired destination. When the user instructed
259 the system to move the source to a new destination, the software computed
260 a conservatively low estimate for the number of motor steps required and
261 programmed this number into the motor. After the stepper motor executed
262 the programmed index, the software compared the source's current position
263 against the destination and reprogrammed the motor as necessary. This
264 process was repeated until the source converged to within 0.1 mm of its
265 destination. The maximum translational speed of the cable during motion
266 was restricted to ~ 3.5 cm/s. The software took into account the fact that
267 the amount of cable stretch varied slightly according to the weight of the
268 attached source and the length of cable paid out¹⁷. Most of the sources
269 generated a maximum additional stretch of only 0.15 cm, though for one
270 unusually heavy source the value was 0.6 cm.

271 The computer and power supplies were physically separated from the
272 hardware by roughly 130 feet of distance and several barriers, chiefly the
273 glove box and the MiniCal housing. To span the gap, the system utilized two
274 intervening custom-built electronics boxes, one at each end, which contained
275 devices for transmitting and processing data and power. The stepper motor
276 and the two encoders communicated in RS485 protocol, which is well-suited
277 for long-distance transmission; the motor and encoder signals were converted
278 to RS232 protocol by a special adaptor and encoder counters, respectively,
279 to communicate with the computer's serial ports. The camera's communica-
280 tions were transmitted using a Newnex FireNEX-CAT5 S400 extender pair,
281 which converted the short-range IEEE 1394a (Firewire) protocol into a form
282 suitable for long-distance transmission over standard cat5e ethernet cable at
283 400 Mbps. CeramTec sub-D and micro-D weldable hermetic feedthroughs

¹⁷We characterized the cable's stretching behavior by measuring lengths of a similar cable when hung with loads of 0 kg, 0.5 kg, and 1.0 kg.

284 were used to pass the electrical signals and power through the walls of the
285 glove box and the MiniCal housing. Radiopurity considerations prohibit the
286 use of solder in components exposed to the glove box environment, so all
287 in-glove box electrical wiring was made from Teflon-coated wires and PEEK
288 connectors using gold-plated crimped connections.

289 2.5. Safeguards

290 The MiniCal system possessed several built-in safety features, both in
291 hardware and software, to prevent accidents or damage to either the detector
292 or to the system itself.

- 293 • An Anaheim Automation NEMA23 electromagnetic friction brake was
294 attached to the driveshaft between the stepper motor and the spool.
295 When electrical power was applied to the brake its electromagnet over-
296 came the mechanical force from a spring, permitting the driveshaft to
297 turn freely; when power was turned off the spring forced friction plates
298 together, clamping the driveshaft in place. This type of “power-off” or
299 “fail-safe” brake was desirable because it would immediately lock the
300 driveshaft if power were lost.
- 301 • A Polyclutch EFS 16 “slip-ease” clutch was connected to the driveshaft
302 between the motor and the brake. In the unlikely event that the cable
303 became caught, the clutch slipped at 4 kg weight equivalent, far below
304 the cable’s approximately 45 kg breaking strength. Moreover, the mo-
305 tor itself slipped at roughly 4.5 kg weight equivalent, so the system was
306 incapable of generating sufficient tension to break the cable.
- 307 • An Automation Direct 12-mm round stainless steel inductive proximity
308 sensor was installed just below the z-axis pulley to prevent the weight
309 from being raised too high and colliding with the pulley superstructure.
310 The upstop sensor was triggered by a small 416 stainless steel collar
311 installed at the end of the cable just above the weight. When the
312 sensor was triggered it sent a signal directly to the motor that blocked
313 its ability to execute further upward motion. (The motor remained
314 capable of downward motion.)
- 315 • The cable length was chosen so that even at maximum extension an
316 attached source could not come into contact with the bottom of the
317 KamLAND balloon.

- 318 • The GUI enforced restrictions on acceptable user-entered values to pre-
319 vent the system from operating outside safe limits.
- 320 • The software continuously monitored the status of the system, most
321 notably the motion of the motor and z-axis pulley. If the software
322 observed any motion when the system was supposed to be stopped, or
323 if the driveshaft or pulley rotation speeds exceeded certain limits, or if
324 there was any disagreement between the motor encoder and the z-axis
325 pulley encoder (e.g., due to cable slippage), the software immediately
326 stopped the motor and engaged the safety brake to prevent the cable
327 spool from turning. The system would therefore self-arrest if the motor
328 failed.

329 In the unlikely event that the motor failed during a source deployment, the
330 source could be retrieved by removing the motor assembly and replacing
331 it with a special ratcheted hand crank. The software possessed a special
332 emergency mode for this situation.

333 3. Operating protocols

334 The MiniCal system was designed to be safe, simple, and capable of
335 operation in all aspects by a single person. Operators were responsible for
336 exchanging sources, managing the flow of nitrogen gas through the system,
337 and conducting calibration deployments.

338 3.1. Source exchanges

339 The first step in preparing for a calibration was to attach the desired
340 radioactive source to the end of the MiniCal cable. A list of the sources used
341 and their energies is given in Table 1.

342 To exchange sources, the weight and its attached source were first raised
343 to the uppermost possible position inside the MiniCal housing, and the chim-
344 ney’s upper gate valve was closed as a safety measure. The operator then
345 removed the front access door and installed a special nylon plug in the floor
346 opening of the housing. This plug contained a rotatable disk that could
347 be closed around the source rod to securely capture it and prevent it from
348 being dropped down the detector access tube. At this point the operator
349 released the source from the weight by pulling the ring on the spring-loaded
350 attachment pin, allowing the source to fall out and be caught by the plug
351 (Figure 6).

Source	Half-life	Radiation	Energy (MeV)
^{203}Hg	46.61 d	γ	0.279
^{137}Cs	30.07 a	γ	0.662
^{68}Ge	270.8 d	β^+	1.022
^{65}Zn	244.3 d	γ	1.116
^{241}Am - ^9Be	432.2 a	n	2.223 [†]
^{60}Co	5.271 a	γ	2.506 [‡]

[†] From delayed capture by hydrogen. Some prompt γ rays are also seen.

[‡] From successive 1.173 MeV and 1.333 MeV γ rays.

Table 1: Radioactive sources used in detector calibrations, ordered by energy. These particular sources were chosen because their radiation spans the low-energy range of the neutrino spectrum observed in KamLAND.

Figure 6: Illustrations of the weight and its source attachment mechanism. An internal spring-loaded pin is used to capture source rods inserted into the weight; the source rods have a D-shaped profile that ensures correct alignment. The spring pin has two small tines (highlighted above in red) to provide an unambiguous visual indicator of when a source has been securely captured inside the weight, and for anchoring the spring-loaded pin in its retracted position. A nylon plug with a rotatable disk (shown above, in red, in its open position) was used for safely capturing a source released from the weight.

352 To install a source, the procedure was reversed. The source was lifted
353 up by hand and inserted in the bottom of the weight; the source shaft's
354 D-shaped cross section ensured alignment with the attachment pin. Once
355 the source was fully inserted, the spring-loaded attachment pin was released
356 to capture the source inside the weight. The pin had two small tines that
357 provided unambiguous visual confirmation of a successful attachment; when
358 the tines disappeared from view inside the weight, the source and weight
359 were securely connected and the plug could be removed.

360 After the source exchange was complete, the operator reinstalled the door
361 of the housing, reopened the chimney's upper gate valve, and configured
362 the system so that purified nitrogen gas continually flowed up the chimney
363 through the MiniCal housing and out of the glove box, to purge the volumes
364 of any radon. After several hours had passed (typically by the morning of
365 the following day), the operator ended the nitrogen gas purge, sealed the
366 MiniCal housing off from the glove box by closing the purge valves, opened
367 the chimney's lowermost gate valve to permit access to the detector, and
368 proceeded with the source deployment.

369 *3.2. Calibration deployments*

370 Deployments were generally conducted "remotely" from the experiment's
371 nearby control room, where the operator established a virtual network com-
372 puting (VNC) connection to the MiniCal computer to manipulate the system
373 using the GUI and to monitor the live camera feed.

374 Before starting a deployment, the operator had to calibrate the system by
375 zeroing the source at a known position. This was accomplished by moving
376 the weight to the position where a notch on its neck was visually aligned
377 with a horizontal reference line in the center of the camera backdrop, a
378 water-jetted sheet of Teflon attached to an electropolished titanium backing
379 plate for contrast (Fig. 7). The operator then pressed the "Tare" button in
380 the GUI and the software calculated the source's center of activity, using the
381 premeasured source lengths and the known location of the reference line with
382 respect to the detector.

383 After its position had been established by a tare operation, the source was
384 typically lowered to each desired position in succession, beginning with the
385 uppermost position. When moving between positions, the operator watched
386 the cable as it passed through the camera's field of view, in order to verify
387 that the system was behaving correctly and to monitor the cable's condition
388 (e.g., check for frayed wires). After the source came to a stop at a deployment

Figure 7: Two images of the weight in its “tare” position, in which the notch in the weight’s neck is aligned with the long centerline in the camera backdrop. Photo (a) shows the weight and ruled backdrop inside the MiniCal housing, while screenshot (b) shows the same scene as viewed through the camera. The backdrop’s hash marks are spaced at 5 mm intervals.

position, the operator turned off the infrared lights, set the driveshaft brake for security, and commenced taking data. A separate data file was recorded for each calibration point (Figure 8).

To enable consistency checks of the system’s position, two small sleeves (“beads”) were swaged onto the cable at the time of its manufacture, and the exact positions of the beads were found by hanging the cable under its expected load in a controlled environment at LBNL and measuring it with a precision tape measure. By comparing the known bead positions with the positions reported by the MiniCal system, the operator could verify the system was accurately reporting the cable payout; this was the only precise means of verifying the system’s performance in situ. The beads had a negligible effect on the system’s measurement of cable payout.

Coarse assessments of the source’s position and the detector’s contamination levels were provided in near real time by an automated online data analysis which processed most of the incoming data and displayed the results. The online software was configured for general-purpose analysis and the information it provided was useful primarily for monitoring for any gross abnormalities while a deployment was in progress.

Figure 8: Activity from a ^{60}Co source deployed to $z = +5, +3, 0, -3, -5$ m along the detector's z -axis, as reconstructed from the data. The colors correspond to the intensity of detected activity.

407 Routine detector calibrations were typically performed once every two
 408 weeks. A complete source deployment lasted between 5–8 hours, depend-
 409 ing upon the type and intensity of the source and the number of deploy-
 410 ment positions. For example, a standard calibration using a ~ 200 Bq ^{60}Co
 411 source consisted of placing it at 0.5-meter intervals between $z = 6.0$ m and
 412 $z = -6.0$ m (where $z = 0$ m is the center of the LS balloon) and leaving it at
 413 each point for ~ 15 minutes.

414 4. Performance

415 MiniCal was operated routinely from February 2009 until June 2011,
 416 when it was dismounted to permit a final deployment of the full-volume cal-
 417 ibration system. During its operational period MiniCal performed 65 source
 418 deployments and (including tests) executed more than 90 round trips into
 419 the detector. Immediately before being uninstalled, MiniCal was used to
 420 continuously deploy a CdWO_4 crystal assembly to the center of the detector
 421 for a special study lasting several days.

422 *4.1. Positioning accuracy and reproducibility*

423 Upon being installed in the KamLAND glove box, MiniCal exhibited
424 near-perfect reproducibility in positioning. However, the cable payout ratio
425 that had been established during system testing no longer appeared to be
426 correct, as the position of the single bead reported by the system disagreed
427 by 2.9 cm with prior tape measurements of the loaded hanging cable—that
428 is, MiniCal reported the cable to be almost 3 cm shorter than we believed
429 was the case. After accounting for the effects on cable stretch from buoyancy
430 (-0.1 cm) and the precise value of the attached weight (-0.7 cm) there
431 was still a persistent 2.1-cm discrepancy. It thus appeared the system’s
432 payout ratio had somehow been altered in the course of being disassembled,
433 cleaned, reassembled, and installed in the glove box. We made the decision
434 to recalibrate the payout ratio to the premeasured position of the bead; this
435 entailed increasing the payout ratio from 11.298 cm/rev to 11.315 cm/rev,
436 which corresponds to an increase of 0.0027 cm in the effective radius of the
437 z-axis pulley.

438 In January 2011 the original single-beaded cable was replaced in situ
439 with a similar cable possessing two evenly spaced beads which provided an
440 additional reference point over a longer length. The positions of the two
441 beads had been measured with care beforehand using a precision tape on
442 the hanging cable under load. The new, double-beaded cable verified the
443 correctness of the recalibrated cable payout ratio established roughly two
444 years earlier. The reason for the change in the payout ratio between the
445 system’s offsite testing and onsite operation remains unknown.

446 A small hysteresis of 2–3 mm of undershoot was consistently observed
447 when the weight returned to its tare position after being deployed to its
448 maximum depth in the detector. This was likely due to a small degree of
449 cable slippage on the z-axis pulley from the lubricating effects of the LS
450 during reel-in. The effect was small, but to minimize the risk of positioning
451 errors we typically placed a source at progressively lower positions during a
452 calibration and only raised it at the conclusion of the deployment.

453 It was observed that small white crystals sometimes formed on the portion
454 of the cable near the weight when the system was idled for weeks or more.
455 We believe the crystals were PPO from the LS brought up by the system,
456 and their formation was likely promoted by the drying effects of the constant
457 nitrogen gas flux through the MiniCal housing. We observed that the crystals
458 dissolved immediately upon submersion in the LS and did not affect the cable
459 payout accuracy.

Figure 9: ^{222}Rn activity in the KamLAND detector over the period MiniCal was in use. The radon activity level is determined from the efficiency-corrected number of ^{214}Bi - ^{214}Po decay coincidences inside a 5.5-m-radius spherical volume; the statistical error is reflected in the width of the black line. The red intervals indicate MiniCal deployments into the detector; no correlation between radon activity and deployments is apparent. The prominent feature beginning in July 2010 is due to a disruption in the detector's water cooling system which produced strong convection in the LS and brought contaminants from the balloon's surface into the fiducial volume.

4.2. Contamination assessment

The KamLAND detector itself provides the most sensitive means of measuring radioactivity inside it. The level of ^{222}Rn is of particular interest because it was known to have been introduced into the detector by previous calibration systems, and its long-lived daughter ^{210}Pb would have presented a problematic background to detecting ^7Be solar neutrinos during the high-purity phase of the experiment.

The level of ^{222}Rn activity inside the LS can be determined via its daughters ^{214}Bi and ^{214}Po , whose successive decays occur close together in time (~ 1 ms) and therefore generate a robust delayed-coincidence signal. The measured ^{222}Rn activity level vs. time is plotted in Fig. 9 for the period when MiniCal was in use. As the figure shows, there is no apparent correlation between MiniCal deployments and changes in ^{222}Rn activity. Indeed, most of the features in the ^{222}Rn activity history can be attributed to fluctuations in detector operating conditions, usually changes in temperature that generated convection currents which circulated contaminants from the balloon surface

476 into the fiducial volume. It is worth noting that in Fig. 9 we present the
477 radon activity inside a 5.5-m-radius spherical volume primarily for purpose
478 of comparison with data from the previous calibration system [11], but we
479 find the fundamental result is the same if we consider instead a smaller-radius
480 cylindrical volume centered on the path the MiniCal cable traveled along the
481 detector’s z-axis.

482 In short, we performed a variety of data-analysis studies and found no
483 indication that MiniCal introduced any contamination, radon or otherwise—
484 even during extended multi-day deployments—above the background levels
485 existing in the LS following purification [15].

486 5. Conclusions

487 We successfully designed, built, and operated an ultra-clean calibration
488 system that enabled accurate, precise positioning of radioactive sources along
489 the z-axis of the KamLAND detector. The main device is simple in concept,
490 but its realization was challenging due to the need to make it compact and
491 precise in its operations while also ensuring it would not contaminate or
492 degrade the detector’s highly radiopure liquid scintillator. The system was
493 routinely used to deploy sources inside the detector over a period of more than
494 two years, and no adverse effects on the liquid scintillator were observed. We
495 are now in the process of modifying the system for use in KamLAND-Zen,
496 an experiment utilizing the KamLAND detector to search for neutrinoless
497 double-beta decay of ^{136}Xe [16–18].

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