Open Aquarium Project

OPEN AQUARIUM PROJECT SPECIFICATION

Probe Interface

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> **Draft.** This is the agreed basis for further work, not yet approved; it changes only for defects, results of the bench tests, and decisions of the Project Lead. Many electrical values are provisional until breadboard tests 6 and 7, and the bench tests of the first probe module, are done (Appendix D). Comment by opening an issue with the `probe-interface` label.

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Notes:

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2 Compliance with Open Aquarium Tenets

2.1 Openness

The Specification is published under the Community Specification License 1.0, and its probe types file, checks file, schema, test vectors, and examples under the Apache License 2.0. It adopts connectors, sensors, and methods that anyone can use without a license: the BNC connector, the PT1000 element of IEC 60751, temperature sensors that use the 1-Wire protocol, the Practical Salinity Scale 1978, and the IUPAC pH standards. Every calculation a probe port makes, from pH to salinity to a calibration's slope, is published with a reference implementation and test vectors, so that owners can check a reading by hand and makers can check their products. Every requirement that can be tested has a published test procedure (Section 19.5).

2.2 Interoperability

Any conforming probe works with any conforming port, whoever made them. pH and ORP electrodes, and many conductivity cells, already use BNC connectors, and this Specification keeps them; it adds what BNC alone does not say: the input's characteristics, its isolation, and what each contact carries. Calibration follows one procedure, with one set of acceptance limits and one way of computing the result, so a probe calibrated on one maker's port reads the same on another's, and a smart probe carries its calibration between them (Sections 14 and 16). Readings and calibrations use the Device Classes `sensor` class, Data Model parameters, units, reference electrodes, and Calibration Records, and Fail-Safe Behavior terms, and add no parallel vocabulary.

2.3 Local Control

Probes, ports, and calibrations work with no network service, account, or vendor. A calibration is computed and checked on the device, and recorded by the controller in the owner's own history (Section 14.9). A smart probe stores its own record, which any conforming device can read; no maker's app or cloud is needed to use it (Section 16).

2.4 Safety

Probe readings drive heaters, chillers, CO2, ozone, and top-off, so a wrong reading can harm livestock as surely as a failed output. This Specification removes the common causes of wrong readings:

- Every pH, ORP, and conductivity port is galvanically isolated, so probes in the same water cannot disturb each other, and stray voltage from equipment in the water does not shift readings (Section 12). A temperature probe's conductors are insulated from the water, so a temperature port that is not isolated still has no path to it (Section 10.4).
- Ports survive static discharge, short circuits, voltages from miswired or wrong cables, and the wrong kind of probe, without damage and without reporting a false reading as good (Section 13).
- A probe being calibrated, a temperature probe beside it in the reference, or a probe just put back in the water never drives control: its input is unavailable from the start of a calibration until a person says the probe is back and its readings have settled, and after a fault until its readings have settled again (Sections 14.7 and 14.8).
- A calibration never holds a critical alarm, and its hold of other alarms ends when the calibration ends (Section 14.7).
- A calibration that fails its acceptance limits is never applied, and one that changes the reading in the system more than a probe type allows needs a person's confirmation (Sections 14.6 and 14.8).
- A controller never writes a compensation temperature it does not have, so a probe whose temperature is lost stops reading `good` (Section 7.4).
- A smart probe's calibration never moves to another probe, and a new probe is never trusted until a person has seen it (Section 16.4).
- A reading beyond the measuring range of a conductivity or temperature port is reported, with its qualifier, so that range alarms and interlocks act on it; a pH or ORP reading beyond the range, which an unplugged electrode gives, is never `good` (Section 7.3).

Electrical safety is not at stake: everything in this Specification runs at safety extra-low voltage, and probe isolation is functional, not protective (Section 12.3).

2.5 Sustainability

Because any probe works with any port, owners can replace a worn probe with any maker's, and keep their controller. Calibration records and the prediction of a pH electrode's end of life let owners replace probes when they are worn, not on a schedule or after a failure (Section 14.10). Probes are consumables; ports and modules are not, and the protection requirements of Section 13 keep a port working through the mistakes an owner makes over its life.

Revision History

Revision	Date	Description	Authors
0.1	2026-10-15	Initial Pre-Draft.	Trent Scholl
0.2	2026-10-16	Readings beyond the measuring range of conductivity and temperature ports reported as `good`, with a qualifier, and those of electrode ports never `good` (issue 26); temperature ports that may rely on their probes' insulation (issue 24); 1-Wire sensors described by their behavior rather than a family code (issue 25); a calibration that never holds a critical alarm, and whose hold of other alarms ends with it (issue 23); the Device Classes attributes `lastCalibration`, `probeNominal`, `tdsFactor`, `compensationSalinity`, `compensationMethod`, `compensationCoefficient`, and `port`, and the `selectable` feature, with the provisional names of revision 0.1 kept only for reading older devices;	Trent Scholl

Revision	Date	Description	Authors
		calibration records as Data Model Calibration Records, and the Data Model's reference electrodes; inputs held after any fault, not only after a disconnection; no compensation temperature written from an unavailable input; `resetCalibration` required; a temperature stability limit of 0.1 °C, more than one step of a 1-Wire sensor; a short across a conductivity cell reported as a fault; ZoBell's solution at 20 °C from the USGS tables; tests of dissolved oxygen and PAR, and the times of tests stated in their requirements; a test procedure, mapped to its requirements, for every requirement; references cited by tag, with IEC 61076-2-104 added; one sentence per line; every open issue given a status.	
0.3	2026-10-17	The Project Lead's decisions of 17 October 2026 applied: a port refuses to begin a calibration while its clock is not valid, because every record needs the time; a calibration that a restart interrupts ends as cancelled, with the reason `other`, and its record is reported; `resetCalibration` clears `calibration-failed`, and is refused during a calibration; and an electrode port resolves 0.1 mV rather than 0.01 mV.	Trent Scholl
0.4	2026-10-18	The Project Lead's decisions of 17 October 2026 applied: a connector for smart probes left to a later revision, with the probe record defined now; BNC for conductivity cells, provisionally; the M8 three-contact temperature connector, with the contacts of Table 10, no longer provisional; calibration before use, and a person's confirmation after every calibration, unchanged and no longer provisional, with the readings of a probe not yet calibrated shown, marked; a calibration record's `time` in the record itself, as Data Model revision 0.4 allows, in place of its extension, with the time of an older record read from its extension; the schema's `$id` `https://openaquariumproject.org/schemas/probe-interface/0.4`. Also: a temperature probe put in the reference held as the calibrated probe is, so that heaters, chillers, and compensated ports never act on the reference's temperature; a calibration that ends without a command, which a controller learns when the probe's endpoints stop reporting `calibrating`; a probe replaced on any port that does not list `resetCalibration`, or refuses it, held until a calibration; `lastCalibration` and `calibrationDue` required of ports; a conductivity or temperature port's reading beyond its range, which is `good`, held after no fault, and a limit only for comparisons; tests that take each port beyond its own range; "A pass criterion that checks what a SHOULD asks applies to a product that does it"; a test for each new requirement; references to the final revisions of the other specifications; issues 13 to 22 deferred beyond revision 1.0.	Trent Scholl
0.4	2026-10-19	Adopted as Draft by the Project Lead, with the corrections of the final check before Draft: a temperature probe in a calibration's reference held also when a person says it is there; the insulation test limited to temperature probes; corrected references.	Trent Scholl

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3 Scope

This Specification defines, for water-quality probes and the device ports they plug into:

- port kinds for pH and ORP electrodes, conductivity cells, and temperature probes, with their connectors and what each contact carries;
- the input characteristics of each port kind, including input impedance, bias current, excitation, measuring ranges, and accuracy;
- how pH, conductivity, salinity, and temperature are computed from what a port measures, and how they are compensated for temperature;
- the use of electrode ports for galvanic dissolved oxygen probes and PAR sensors with millivolt outputs;
- galvanic isolation between probe channels, and its test methods;
- protection against electrostatic discharge, wiring faults, and the wrong probe, and its test methods;
- calibration procedures for pH, ORP, conductivity, salinity, temperature, dissolved oxygen, and PAR probes, mapped to the calibration commands of the Device Classes `sensor` class: points, reference solutions, temperature correction, acceptance limits, and records;
- what a controller does while a probe is calibrated, and after;
- smart probes, which store their identity and calibrations, and how devices use them; and
- a test procedure for every requirement that can be tested.

This Specification does not define:

- the `sensor` class, which the Device Classes specification defines [OAP-DC Section 11.1];
- how readings are carried, which the Module Bus and Device Protocol specifications define [OAP-MB] [OAP-DP];
- what a controller does when an input is unavailable, which the Fail-Safe Behavior and Automation specifications define [OAP-FS Section 10] [OAP-AU Section 9.8];
- the connector of the module bus, or the enclosure of a probe module;
- a connector for smart probes, which a later revision may define (Section 16.6);
- interfaces for optical dissolved oxygen sensors, PAR sensors with digital outputs, thermistors, and four-electrode conductivity cells;
- level, leak, flow, and analog inputs, which the Device Classes specification and the reference controller cover;
- analyzers, which the Water Testing specification covers [OAP-WT]; or
- the values a parameter should have.

4 References

4.1 Normative References

- **[RFC 2119]** Bradner, S., “Key words for use in RFCs to Indicate Requirement Levels”, BCP 14, RFC 2119, March 1997.
- **[RFC 8174]** Leiba, B., “Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words”, BCP 14, RFC 8174, May 2017.
- **[RFC 8259]** Bray, T., Ed., “The JavaScript Object Notation (JSON) Data Interchange Format”, STD 90, RFC 8259, December 2017.
- **[JSON Schema]** “JSON Schema: A Media Type for Describing JSON Documents” and “JSON Schema Validation”, draft 2020-12, https://json-schema.org/draft/2020-12.
- **[IEC 61169-8]** IEC 61169-8, “Radio-frequency connectors — Part 8: Sectional specification for RF coaxial connectors with inner diameter of outer conductor 6.5 mm (0.256 in) with bayonet lock — Characteristic impedance 50 ohms (type BNC)”.
- **[IEC 61076-2-104]** IEC 61076-2-104:2014, Edition 2.0, “Connectors for electronic equipment — Product requirements — Part 2-104: Circular connectors — Detail specification for circular connectors with M8 screw-locking or snap-locking”.

- **[IEC 60751]** IEC 60751:2022, "Industrial platinum resistance thermometers and platinum temperature sensors".
- **[IEC 61000-4-2]** IEC 61000-4-2:2008, "Electromagnetic compatibility (EMC) — Part 4-2: Testing and measurement techniques — Electrostatic discharge immunity test".
- **[PSS-78]** UNESCO, "Algorithms for computation of fundamental properties of seawater", Fofonoff, N. P. and Millard, R. C., Unesco Technical Papers in Marine Science 44, 1983, https://unesdoc.unesco.org/ark:/48223/pf0000059832.
- **[IUPAC pH]** Buck, R. P., et al., "Measurement of pH. Definition, standards, and procedures (IUPAC Recommendations 2002)", Pure and Applied Chemistry 74(11), 2169–2200, 2002, https://doi.org/10.1351/pac200274112169.
- **[OAP-DM]** Open Aquarium Project, "Open Aquarium Data Model", Revision 0.4, `specs/data-model/spec.md`.
- **[OAP-DC]** Open Aquarium Project, "Open Aquarium Device Classes", Revision 0.5, `specs/device-classes/spec.md`.
- **[OAP-FS]** Open Aquarium Project, "Open Aquarium Fail-Safe Behavior", Revision 0.4, `specs/fail-safe-behavior/spec.md`.
- **[OAP-MB]** Open Aquarium Project, "Open Aquarium Module Bus", Revision 0.4, `specs/module-bus/spec.md`.
- **[OAP-DP]** Open Aquarium Project, "Open Aquarium Device Protocol", Revision 0.3, `specs/device-protocol/spec.md`.
- **[OAP-AU]** Open Aquarium Project, "Open Aquarium Automation", Revision 0.3, `specs/automation/spec.md`.
- **[OAP-AN]** Open Aquarium Project, "Open Aquarium Alarms and Notifications", Revision 0.3, `specs/alarms-and-notifications/spec.md`.
- **[OAP-SA]** Open Aquarium Project, "Open Aquarium Security and Access", Revision 0.3, `specs/security-and-access/spec.md`.

The IEC standards are available for purchase; every other normative reference is free.

4.2 Informative References

- **[P0001]** Open Aquarium Project, "Proposal 0001: Reference Controller Architecture", `proposals/0001-reference-controller-architecture.md`.
- **[Breadboard]** Open Aquarium Project, "Breadboard Prototype", `hardware/controller/breadboard/README.md`.
- **[Enclosure]** Open Aquarium Project, "Controller Enclosure", `hardware/controller/enclosure/README.md`.
- **[Firmware]** Open Aquarium Project, breadboard firmware, pH calibration, `hardware/controller/firmware/components/oap_core/src/ph_cal.c`.
- **[USGS]** U.S. Geological Survey, "National Field Manual for the Collection of Water-Quality Data", Techniques of Water-Resources Investigations, Book 9, Chapter A6: sections 6.1 (temperature), 6.2 (dissolved oxygen), 6.3 (specific conductance), and 6.4 (pH), https://www.usgs.gov/mission-areas/water-resources/science/national-field-manual-collection-water-quality-data-nfm; and section 6.5, Nordstrom, D. K. and Wilde, F. D., "Reduction-Oxidation Potential (Electrode Method)", Version 1.2, September 2005, https://doi.org/10.3133/twri09A6.5, whose Table 6.5–2 gives the potentials of silver chloride reference electrodes, and Table 6.5–3 the potential of ZoBell's solution, against the standard hydrogen electrode.
- **[Benson]** Benson, B. B. and Krause, D., "The concentration and isotopic fractionation of oxygen dissolved in freshwater and seawater in equilibrium with the atmosphere", Limnology and Oceanography 29(3), 620–632, 1984. Its equations, in the form USGS uses, give Section 15.5's reference values.
- **[TEOS-10]** IOC, SCOR and IAPSO, "The international thermodynamic equation of seawater – 2010", https://www.teos-10.org/. Its function `gsw_SP_from_C` computes practical salinity as Section 9.5 does.
- **[Dickson]** Dickson, A., lecture on seawater pH scales, 2009, https://www.us-ocb.org/wp-content/uploads/sites/43/2020/05/ADickson-2_53806.pdf.
- **[EPA ORP]** US EPA Region 4, Field Measurement of ORP, https://www.epa.gov/sites/default/files/2017-07/documents/field_measurement_of_orp113_af.r2.pdf.
- **[IEEE 1451.4]** IEEE 1451.4-2004, a mixed-mode interface for a transducer's analog signal and its electronic data sheet (TEDS), listed by IEEE as inactive, https://standards.ieee.org/ieee/1451.4/2168/.

- **[VIM]** Joint Committee for Guides in Metrology, "International vocabulary of metrology — Basic and general concepts and associated terms (VIM)", JCGM 200:2012, https://www.bipm.org/documents/20126/2071204/JCGM_200_2012.pdf.
- **[OAP-WT]** Open Aquarium Project, "Open Aquarium Water Testing", Revision 0.3, `specs/water-testing/spec.md`.

5 Terms, Definitions, and Conventions

5.1 Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC 2119] [RFC 8174] when, and only when, they appear in all capitals, as shown here.

5.2 Terms and Definitions

Terms defined in the Device Classes specification [OAP-DC], such as device, endpoint, controller, class, and feature, in the Fail-Safe Behavior specification [OAP-FS], such as unavailable input, and in the Automation specification [OAP-AU], such as input and function, have the same meaning here.

Probe: A sensor that is placed in the water, or above it for a PAR sensor, with its cable and connector: a pH or ORP electrode, a conductivity cell, a temperature probe, a dissolved oxygen probe, or a PAR sensor.

Probe type: One of the kinds of probe that `probe-types.json` lists, each with its parameters, the ports it plugs into, and its calibration procedure (Table 3).

Port: A connector on a device that a probe plugs into, with the circuit behind it. A port presents one `sensor` endpoint for each parameter it can report (Section 7.1).

Port kind: One of the kinds of port that Table 2 lists: electrode, conductivity, PT1000, or 1-Wire.

Electrode: A pH or ORP probe whose signal is the potential between a measuring electrode and a reference electrode. A **combination electrode** holds both in one body, as aquarium electrodes do.

Measuring electrode: The glass membrane of a pH electrode, or the platinum or gold surface of an ORP electrode.

Reference electrode: The part of an electrode that keeps a fixed potential, such as silver and silver chloride in potassium chloride, and meets the water through a junction.

Signal: What a port measures before it applies a calibration: an electrode's potential in mV, a cell's conductivity at the water's temperature with its nominal cell constant, or a temperature, oxygen, or PAR reading before correction. Each probe type names its signal (Table 3).

Measuring range: The values a port measures within its accuracy, from its endpoint's `rangeMin` to its `rangeMax` [OAP-DC Section 11.1].

Cell constant: The ratio of a conductivity cell's conductance to the conductivity of the water it is in, in 1/cm, written K. A cell's **nominal** cell constant is the value its maker states, such as K = 1.0.

Compensation: Correcting a reading for the temperature of the water: the electrode slope for pH, and the conversion to 25 °C for conductivity (Section 7.4).

Isolated domain: A circuit that is galvanically isolated from every other circuit of its device, from the module bus, and from earth (Section 12.2).

Probe common: The circuit common of an isolated domain, to which an electrode's reference electrode or a cell's electrode connects.

Calibration: Determining, with references of known value, the correction a port applies to a probe's signal, and applying it [VIM 2.39].

Calibration point: One reference value, the signal the port measured in it, and the reference's temperature (Section 14.2).

Calibration record: What a calibration did, as a Data Model Calibration Record with this Specification's details (Section 14.9).

Reference solution: A solution of known value at a known temperature, such as a pH buffer or a conductivity standard. For temperature, dissolved oxygen, and PAR, the reference may be a reference instrument, water-saturated air, or darkness instead (Section 15).

Offset: For pH, the electrode's potential at pH 7, in mV. For other probe types, what a calibration adds to the signal after the gain, in the signal's unit.

Slope: For pH, the change of an electrode's potential with pH, as a percentage of the Nernst slope at the same temperature (Section 8.4).

Gain: What a calibration multiplies the signal by, for probe types other than pH.

Acceptance limits: The limits within which a calibration's result must fall for it to be applied (Section 14.6).

Stable: Readings that change by no more than a probe type's limit over its window (Section 14.3).

Calibration hold: The time from the start of a calibration until a person confirms that the probe is back in place and its readings have settled, during which its input is unavailable (Section 14.8).

Settle time: How long a probe's readings must be `good` and stable before a hold of its inputs ends (Section 14.8).

Shift: The change in a probe's reading in the system that a calibration causes (Section 14.8).

Smart probe: A probe that stores its own probe record, which a port reads (Section 16).

Probe record: What a smart probe stores: its identity, its nominal characteristics, and its latest calibrations (Section 16.1).

5.3 Notation

JSON member names, probe types, port kinds, and the names of attributes, commands, and faults appear in `monospace`. Units are Data Model unit codes [OAP-DM], except where a quantity has no Data Model unit, such as resistance in Ω or capacitance in pF. References to other Open Aquarium specifications name them, as in "Fail-Safe Behavior Section 10.1", or use their tags from Section 4, as in "[OAP-FS Section 10.1]". A section number with a third part refers to a numbered item of that section: "Section 14.2.4" means item 4 of Section 14.2. Values marked provisional are to be confirmed by the breadboard tests [Breadboard], by bench tests of the first probe module, or by owners' experience (Appendix D). Temperatures are on the International Temperature Scale of 1990.

6 Introduction

6.1 Purpose

A controller is only as good as its probes. pH steers CO2 and calcium reactors, ORP steers ozone, temperature steers heaters and chillers, and salinity steers top-off; a reading that is wrong, but looks right, can harm a system faster than a failed pump.

Four widely used commercial controller ecosystems all measure pH, ORP, temperature, and conductivity or salinity, and two of them also measure dissolved oxygen. pH and ORP probes already plug in with BNC connectors, but what a port does with them is each maker's own: some makers isolate their inputs, and others do not say whether they do. Conductivity, temperature, dissolved oxygen, and PAR probes use whatever connector each maker chose, and calibration is a different procedure on every product, with different acceptance limits and records that stay in each maker's app. An owner who changes controller often has to change probes, and an owner who moves a probe has to calibrate it again.

This Specification defines one set of ports, one isolation requirement, and one calibration procedure for each probe type, so that any probe works on any port, a calibration means the same everywhere, and a probe's record can move with it.

6.2 Design Principles

1. **Adopt what exists.** BNC for electrodes and conductivity cells, PT1000 elements of IEC 60751, temperature sensors that use the 1-Wire protocol, IUPAC pH standards, and PSS-78 salinity are already used across the industry; this Specification defines only what they leave open (Sections 8 to 10).
2. **Every electrode floats.** Each pH, ORP, and conductivity probe has an isolated domain of its own, so the only path between it and anything else is through its own measurement (Section 12).
3. **No mistake does harm.** Static, short circuits, wrong cables, and the wrong probe damage nothing, and never produce a reading marked good that is not a reading of the water (Section 13).
4. **One calibration everywhere.** Each probe type is calibrated with the same references, computed the same way, and accepted within the same limits, on every product (Sections 14 and 15).
5. **A calibration never steers control unseen.** A probe in a buffer is never read as the system's water, and a calibration that moves the reading a lot needs a person (Sections 14.7 and 14.8).
6. **The record travels with the probe.** A smart probe carries its calibrations; every other probe still works, with its calibration kept by its port (Section 16).

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6.3 Overview

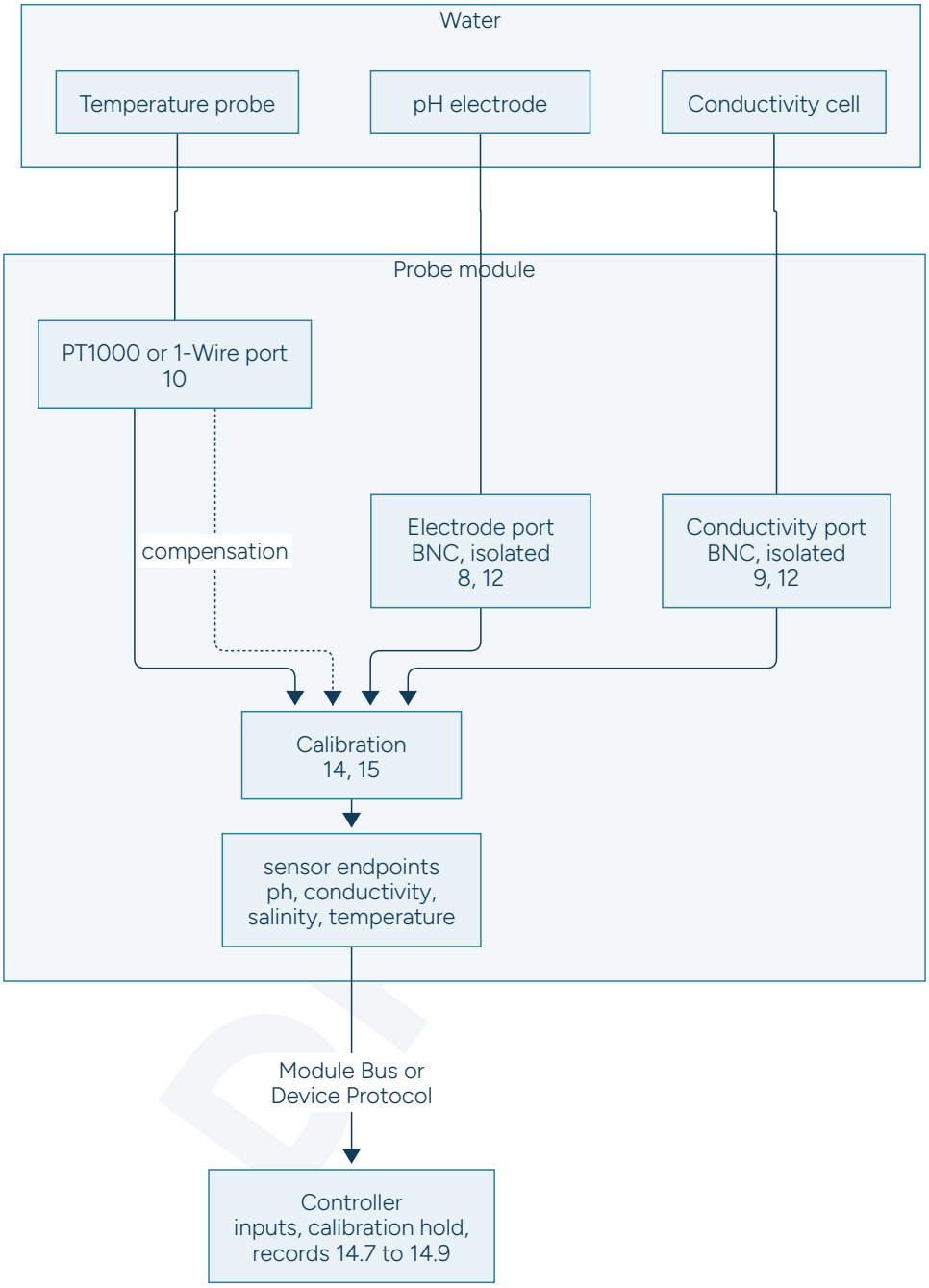

Figure 1 — From a probe to an input

A probe plugs into a port of a matching port kind (Table 2). The port measures the probe's signal, applies the probe's calibration and temperature compensation, and reports the reading as a `sensor` endpoint [OAP-DC Section 11.1]. A controller reads the endpoint as an input [OAP-AU Section 9], guides people through calibrations, and records them.

Table 1 — Parts of this Specification

Part	What it does	Section
Common requirements	Ports, probe types, readings, compensation, documentation, and the provisional names of revision 0.1.	7
Electrode ports	The BNC input for pH and ORP electrodes, and for dissolved oxygen and PAR sensors with millivolt outputs.	8

Part	What it does	Section
Conductivity ports	The BNC input for two-electrode conductivity cells; salinity and total dissolved solids.	9
Temperature ports	PT1000 and 1-Wire inputs.	10
Dissolved oxygen and PAR	Which of these probes this revision covers, and how.	11
Isolation	Isolated domains, their ratings, and their tests.	12
Protection	Static, wiring faults, the wrong probe, and connecting while powered.	13
Calibration	The calibration commands on the device and on the controller, stability, references, results, acceptance, the calibration hold, records, and end of life.	14
Calibration procedures	Points, references, and limits for each probe type.	15
Smart probes	Probe records, and how ports read and write them.	16

6.4 Example

A reef's probe module has a pH probe on an electrode port, and a temperature probe in the same sump. The pH input steers the CO2 of a calcium reactor. Its owner calibrates the pH probe on a Sunday morning.

1. The owner starts the calibration in the controller's app. The controller sends `beginCalibration`, the endpoint's `quality` becomes `calibrating`, and its input is unavailable, so the calcium reactor's CO2 stops [OAP-FS Section 10.3] (Section 14.7). The input's `input-unavailable` alarm is a warning, so the controller holds its sound and notifications while the calibration lasts.
2. The app asks for the temperature probe to go into the buffer cups beside the pH probe, so that buffers and compensation use the buffers' temperature, 21.6 °C, rather than the sump's 25.8 °C (Section 14.4).
3. The pH probe goes into a technical pH 7.00 buffer. Its reading settles; once it changes by less than 0.6 mV in 30 s, the app sends `calibratePoint` with `reference` 7.01, the buffer's value at 21.6 °C, and `solution` `technical-7` (Sections 14.3 and 14.4).
4. After a rinse, the same in a pH 10.01 buffer, whose value at 21.6 °C is 10.04.
5. The app sends `completeCalibration`. The port computes a slope of 97.2 % and an offset of −4.1 mV, both within the acceptance limits of 85 % to 105 % and ±35 mV, applies them, and reports the calibration's record as `lastCalibration` (Sections 15.1, 14.6, and 14.9). The calibration has ended, so the hold of the alarm ends too: had the input's alarm still been active, it would sound now.
6. The owner puts both probes back in the sump and confirms it in the app. The input stays unavailable for another 120 s while the electrode settles (Section 14.8).
7. The sump read pH 8.12 before the calibration, and reads 8.19 after: a shift of 0.07, within the 0.2 that pH allows, so the input becomes available, and the CO2 resumes. Had the owner used a pH 10 buffer left open for months, which takes up carbon dioxide and falls, the slope might have been 83 %, and the port would have refused the calibration and kept the previous one; or the shift might have been 0.5, and the input would have stayed unavailable until the owner confirmed it (Sections 14.6 and 14.8).
8. The controller records the calibration in the owner's history, and sets the next one due in 30 days (Section 14.9).

7 Common Requirements

7.1 Ports and Endpoints

1. A port MUST present one `sensor` endpoint for each parameter it reports [OAP-DC Section 7.1.4]. For example, a conductivity port that reports conductivity and salinity presents two endpoints. A port that can read probes of more than one type, such as an electrode port that reads a pH or an ORP electrode (Section 8.2), MUST present an endpoint for each parameter it can read, each with the `selectable` feature, of which one is `active` at a time [OAP-DC Section 11.1].
2. A port's endpoints MUST declare the features that Table 3 lists for their probe type, and the `isolated` feature when, and only when, the port meets Section 12 (Section 12.5).

3. Every endpoint of a port MUST give the port's identifier as its `port` [OAP-DC Section 11.1], which no other port of the device has.
4. Endpoints that read one probe, such as a conductivity cell's conductivity and salinity, share one calibration: calibrating either calibrates both, and both report the same `lastCalibrated` and `lastCalibration` (Section 14.2.9). Selectable endpoints of one port read probes of different types, and each keeps a calibration of its own.
5. When a person makes another endpoint of a port `active`, a controller MUST hold that endpoint's inputs as after a probe is reconnected (Section 14.8.6), because another probe may now be in the port.
6. A port SHOULD implement the `identify` command [OAP-DC Section 8.2], with an indicator beside its connector, so that an owner can tell which port is which.
7. A device SHOULD label each port with its port kind and the endpoint identifiers it presents, and SHOULD mark ports of each port kind so that they can be told apart by touch and sight, not by color alone [Enclosure].

7.2 Port Kinds and Probe Types

Table 2 lists the port kinds, and Table 3 the probe types and the ports they plug into. They are published in machine-readable form in `probe-types.json`.

Table 2 — Port kinds

Port kind	Name	Connector	Probe types	Isolation	Section
`electrode`	Electrode port	BNC jack, 50 Ω: centre to the measuring electrode or a sensor's output, shell to the reference electrode or its return	`ph`, `orp`, `dissolved-oxygen`, `par`	REQUIRED	8
`conductivity`	Conductivity port	BNC jack, 50 Ω (provisional): one electrode on the centre, the other on the shell	`conductivity`	REQUIRED	9
`rtd`	PT1000 port	M8 jack, 3 contacts, A-coded	`temperature`	RECOMMENDED	10.2
`one-wire`	1-Wire port	M8 jack, 3 contacts, A-coded	`temperature`	RECOMMENDED	10.3

Table 3 — Probe types

Probe type	Name	Parameters	Port kinds	Required features	Signal	Procedure
`ph`	pH electrode	`ph`	`electrode`	`calibration`, `temperature-compensation`	Electrode potential, in mV	15.1
`orp`	ORP electrode	`orp`	`electrode`	`calibration`	Electrode potential, in mV	15.2
`conductivity`	Conductivity cell	`conductivity`, `salinity`, `total-dissolved-solids`	`conductivity`	`calibration`, `temperature-compensation`	Conductivity at the water's temperature, with the nominal cell constant, in mS/cm	15.3
`temperature`	Temperature probe	`temperature`	`rtd`, `one-wire`	`calibration`	Temperature before calibration, in °C	15.4
`dissolved-oxygen`	Dissolved oxygen probe	`dissolved-oxygen`, `dissolved-oxygen-saturation`	`electrode`	`calibration`, `temperature-compensation`	Reading before calibration, in the reading's unit	15.5
`par`	PAR sensor	`ppfd`	`electrode`	`calibration`	Reading before	15.6

Probe type	Name	Parameters	Port kinds	Required features	Signal	Procedure
					calibration, in µmol/m²/s	

1. A port MUST be of one port kind, and MUST meet the section of Table 2 for that kind.
2. A probe MUST plug into the port kinds Table 3 lists for its type, and MUST meet the requirements for probes in that port kind's section.
3. A port's endpoint MUST report a parameter that Table 3 lists for a probe type the port kind accepts. An electrode port, for example, reports `ph`, `orp`, `dissolved-oxygen`, `dissolved-oxygen-saturation`, or `ppfd`.
4. Several commercial ports accept either a pH or an ORP electrode, and every electrode port can read either (Section 8.2). A port that lets its owner choose presents an endpoint for each, with `selectable` (Section 7.1.1); one that does not reports the one parameter its maker gives it.

7.3 Readings and Quality

1. A port MUST measure at least once every 2 s (provisional), so that no reading it reports is more than 2 s old, and a port that stops measuring is found within 6 s, when its reading goes stale [OAP-FS Section 10.2].
2. A port MUST report `quality` as the Device Classes specification requires [OAP-DC Section 11.1], and MUST NOT report `good`:
   - while it reports `sensor-disconnected` or `hardware-failure`;
   - while a calibration is in progress, when `quality` is `calibrating` (Section 14.2);
   - while the compensation temperature it uses is unavailable, for a probe type that needs compensation (Section 7.4);
   - before it has a calibration, for a probe type that needs one (Section 14.2.11); or
   - for a reading of an electrode port beyond its measuring range (item 4).
3. While a reading is beyond the port's measuring range, the port MUST report `out-of-range`, and MUST give `qualifier`: `>` above the range, with `value` its `rangeMax`, and `<` below it, with `value` its `rangeMin`.
4. Whether such a reading is `good` depends on the port kind:
   - a conductivity, PT1000, or 1-Wire port MUST report it as `good`, with its `qualifier`, unless item 2 keeps it from `good`, because such a port can tell a missing or faulty probe from a reading of the water (Sections 9.7 and 10), and range alarms and interlocks then act on it [OAP-AU Section 9.2.2] [OAP-AN Section 9.3.5];
   - an electrode port MUST NOT report it as `good`, because an electrode that is unplugged, or whose cable is broken, drifts off scale, and the reading is then not a reading of the water.
5. A port MUST report `rangeMin`, `rangeMax`, and `resolution` for each endpoint.
6. A reading is reported in the endpoint's `unit`, which MUST be accepted for its parameter [OAP-DM Section 9.2]. pH is reported at the temperature of the water, never converted to another temperature; conductivity at 25 °C, as the Data Model defines it [OAP-DM Section 9.2]; and ORP against the probe's own reference electrode (Section 8.5).

7.4 Temperature Compensation

1. pH, conductivity, salinity, total dissolved solids, and dissolved oxygen endpoints MUST implement the `temperature-compensation` feature [OAP-DC Section 11.1].
2. The compensation temperature is the temperature of the water the probe is in. With `compensationSource` `internal`, it comes from a temperature sensor in the probe or the same port; with `external`, from a value the controller writes to `compensationTemperature`; and with `fixed`, it is `compensationTemperature`.
3. A controller that writes `compensationTemperature` MUST take it from a temperature input in the same water as the probe, and MUST write it at least every 60 s, and within 2 s of each change of 0.1 °C or more (provisional).
4. A controller MUST NOT write a compensation temperature while the temperature input it comes from is unavailable [OAP-FS Section 10.1], so that the port's compensation temperature goes stale (item 5), rather than its readings staying `good` with a temperature that is no longer true. The one exception is the temperature of a reference, which a controller writes to the port being calibrated in it (Section 14.4.5).

5. A port with `compensationSource` `external` MUST treat its compensation temperature as unavailable when it has not been written for 300 s (provisional), and MUST then report `quality` `stale`. It MUST use a value written again from its next reading.
6. `fixed` is NOT RECOMMENDED except for a probe in water whose temperature is held within 1 °C, because a pH reading compensated for the wrong temperature is wrong by about 0.003 pH per °C for each pH unit away from 7, and a conductivity reading by about 2 % per °C (Sections 8.4 and 9.4).
7. While a calibration is in progress, the compensation temperature is the temperature of the reference, not of the system (Section 14.4).

7.5 Probes

1. A probe MUST be insulated, except at its measuring surfaces, so that no conductor of its cable or connector touches the water. A temperature probe's wetted parts, including a metal sheath, MUST be insulated from its conductors (Section 10.4).
2. A probe's documentation MUST give its probe type, connector, measuring range, operating temperatures, cable length, and nominal characteristics: an electrode's reference system, as a Data Model reference electrode [OAP-DM Table 27]; a cell's nominal cell constant and number of electrodes; a PT1000's tolerance class; or a millivolt sensor's nominal output.
3. A probe's documentation SHOULD give its expected life, its storage, and how to clean it.

7.6 Documentation of Ports

A device's documentation MUST give, for each port: its port kind; the parameters it reports; its measuring ranges, resolution, and accuracy; the cell constants it accepts, for a conductivity port; its compensation methods; whether it is isolated, and its isolation ratings (Section 12.3); and the probes it was tested with.

7.7 Operating Conditions

1. A port MUST meet its requirements with the device at an ambient temperature of 0 °C to 40 °C, the highest cabinet temperature the reference enclosure is designed for (provisional) [Enclosure].
2. A port MUST meet its requirements for water from 0 °C to 40 °C at the probe; ranges beyond these are the probe's and port's documented choice.
3. A port's connector SHOULD resist splashing when mated, or face downward with a sealing boot, as the reference enclosure's BNC ports do [Enclosure].

7.8 Checks

Table 4 — Common checks

Check	Presence	Applies to	What it requires	Section
Endpoints	REQUIRED	Devices	A port presents one `sensor` endpoint for each parameter it can report, each with its probe type's features and the port's `port`, as `selectable` endpoints where the port reads probes of more than one type; the endpoints of one probe share one calibration; and the port gives the Device Classes attributes, not the provisional names of revision 0.1.	7.1
Changing the active endpoint	REQUIRED	Controllers	When a person makes another selectable endpoint of a port active, a controller holds that endpoint's inputs until their readings have been `good` and stable for the settle time.	7.1
Readings and quality	REQUIRED	Devices	A port measures at least every 2 s, reports its range and resolution, and never reports `good` with a fault, while calibrating, without its compensation temperature, or before a calibration its probe type needs.	7.3
Readings beyond the range	REQUIRED	Devices	A reading beyond the measuring range is reported with `out-of-range` and a `qualifier`; it is `good` on a conductivity or temperature port, and never `good` on an electrode port.	7.3
Compensation temperature	REQUIRED	Devices, controllers	A controller writes an external compensation temperature from the same water at least every 60 s and within 2 s of every change of 0.1 °C, and never from an unavailable input; a port treats one not written for 300 s as unavailable.	7.4

Check	Presence	Applies to	What it requires	Section
Probes	REQUIRED	Probes	A probe is insulated except at its measuring surfaces, plugs into a port kind its type allows, and its documentation gives its type, connector, range, operating temperatures, cable length, and nominal characteristics, with an electrode's reference as a Data Model reference electrode.	7.5
Documentation of ports	REQUIRED	Devices	A device's documentation gives each port's kind, parameters, ranges, resolution, accuracy, cell constants, compensation methods, isolation and its ratings, and the probes it was tested with.	7.6
Operating conditions	REQUIRED	Devices	A port meets its requirements at ambient temperatures of 0 °C to 40 °C, and with water at the probe from 0 °C to 40 °C.	7.7

7.9 Provisional Names of Revision 0.1

Revision 0.1 of this Specification carried some configuration and records under provisional extension names, which Device Classes revision 0.2 replaces with attributes of the `sensor` class [OAP-DC Section 7.11]:

- `org.openaquariumproject.probe-calibration`, in an endpoint's `extensions`, by `lastCalibration`, a calibration record of Section 14.9;
- `org.openaquariumproject.probe-nominal` by `probeNominal`, except its members `tdsFactor` and `salinity`, which `tdsFactor` and `compensationSalinity` replace; and
- `org.openaquariumproject.compensation-method` and `org.openaquariumproject.compensation-coefficient` by `compensationMethod` and `compensationCoefficient`, in `%/degC`.

1. A port that conforms to this revision MUST implement the Device Classes attributes, and MUST NOT give the provisional names.
2. A controller SHOULD read the provisional names of a device of Device Classes revision 0.1 as their replacements.
3. A calibration record of revision 0.1 is an object with the members `probeType`, `parameter`, `unit`, `time`, `outcome`, `reason`, and `points`, each point with `reference`, `signal`, `temperature`, `time`, `solution`, and `pressure`; `result` and `previous`, with `offset`, `slope`, `gain`, and `cellConstant` as numbers; and `compensation`, `nominalCellConstant`, `tdsFactor`, `probe`, `device`, `shift`, `notes`, and `extensions` (`$defs/calibrationRecord01` of the schema). It holds what a record of Section 14.9 holds, as plain numbers in the units of the record's parameter and the probe type's signal.
4. A controller SHOULD read such a record, from a device of Device Classes revision 0.1, from the `extensions["org.openaquariumproject.probe-calibration"]` of a calibration event in a Data Model document, or from a probe record of revision 0.1, as the record of Section 14.9 that holds the same values. The reference implementation's `record` function converts one (Section 19.4).

8 Electrode Ports

An electrode port reads the potential of a pH or ORP electrode. Because it is a high-impedance millivolt input, it also reads galvanic dissolved oxygen probes and PAR sensors with millivolt outputs (Section 11).

8.1 Connector

1. An electrode port MUST be a BNC jack of 50 Ω [IEC 61169-8]. Electrodes have BNC plugs, as commercial aquarium electrodes do.
2. The centre contact connects to the measuring electrode, and the shell to the reference electrode. For a millivolt sensor, the centre carries the positive output and the shell its return.
3. The shell is the probe common of the port's isolated domain (Section 12.2). It MUST be insulated from every panel, enclosure part, and other port, because a metal panel would join the probe commons of every port it touches [Enclosure]. Bulkhead jacks isolated from their panels, which several connector makers sell, or jacks in a plastic panel, meet this.
4. An electrode's cable SHOULD be a low-noise coaxial cable whose screen is the reference conductor.

5. A port whose connector does not resist splashing SHOULD face downward and take a sealing boot [Enclosure].

8.2 Input Characteristics

Table 5 — Electrode port input (provisional)

Characteristic	Requirement
Measuring range	At least −1000 mV to +1000 mV between centre and shell.
Input resistance	At least 10^{12} Ω (1 TΩ).
Input bias current	At most 1 pA, over the port's operating temperatures (Section 7.7).
Resolution	0.1 mV or finer.
Accuracy	Within ±(0.1 mV + 0.2 % of the reading), before any calibration with a probe.
Source resistance	Putting 1 GΩ in series with the source changes the reading by at most 1 mV.
Noise	At most 0.2 mV peak to peak over 60 s, from a source of 100 MΩ.
Drift	At most 0.2 mV over 24 h at a constant ambient temperature.
Settling	Within 0.5 mV of a step of 400 mV from a source of 100 MΩ, within 5 s.

1. A port MUST meet Table 5.
2. The input resistance and bias current matter because a glass electrode's membrane has a resistance of tens to hundreds of megohms, rising as it cools and ages: 1 pA through 500 MΩ is 0.5 mV, or 0.008 pH.
3. The range covers pH 0 to 14 at 40 °C, with an electrode's offset, and every ORP an aquarium shows, so any electrode port can read either kind of electrode (Section 7.2.4).

8.3 The Reference Electrode and Bias

1. A port MUST NOT pass a current through an electrode other than its input bias current and the diagnostic signal of item 3. A current through the reference electrode shifts its potential and uses it up.
2. A port MAY hold the probe common at any potential within its measuring circuit, for example at mid-supply so that negative potentials can be measured from one supply, because the whole domain floats (Section 12.2).
3. A port MAY measure an electrode's impedance, as industrial instruments do to find a cracked or missing membrane. Its test signal MUST average no current over each test, MUST NOT be applied more than once a minute, and MUST NOT change the reading by more than 0.6 mV (0.01 pH) from 10 s after the test ends.
4. This interface has no solution ground: a third contact to the water, which industrial instruments use for differential measurement, would connect the domain to the water a second time.

8.4 Computing pH

1. An electrode's potential E, in mV, at a temperature t, in °C, is modelled as

   $E = E_0 - (s / 100) \times S_N(t) \times (pH - 7)$

   where E_0 is the offset, the potential at pH 7; s is the slope, in % of the Nernst slope; and $S_N(t)$ is the Nernst slope:

   $S_N(t) = (R \times \ln 10 / F) \times (t + 273.15) = 0.198\,421 \text{ mV/K} \times (t + 273.15)$,

   with the gas constant R = 8.314 462 618 J/(mol·K) and the Faraday constant F = 96 485.332 12 C/mol, which gives 59.159 mV per pH at 25 °C.
2. A port MUST compute pH as

   $pH = 7 - (E - E_0) / ((s / 100) \times S_N(t))$,

   with t the compensation temperature (Section 7.4), and E_0 and s from its calibration (Section 14.5).
3. Compensation corrects the electrode's response for its temperature. It does not convert the water's pH to another temperature: the pH of the water itself changes with temperature, and the port reports it as it is at the water's temperature (Section 7.3.6).

4. pH 7 as the point where the potential does not depend on temperature suits the combination electrodes that aquariums use; this revision does not cover an electrode whose maker gives another point.
5. Electrodes calibrated with the buffers of Section 15.1 measure on the scale those buffers define. In seawater, such readings are about 0.15 pH higher than on the total scale that oceanographers use, so they are comparable between aquariums, but not directly with published ocean data [Dickson].

8.5 Computing ORP

1. A port MUST report ORP as the electrode's potential plus its calibration's offset, in mV, against the electrode's own reference electrode, without temperature compensation.
2. An ORP electrode's documentation MUST name its reference system, as a Data Model reference electrode [OAP-DM Table 27], such as `ag-agcl-3m`, silver and silver chloride in 3 mol/L potassium chloride. Readings against a silver chloride reference are about 200 mV lower than against the standard hydrogen electrode, depending on its filling [USGS].
3. The `reference` of an ORP endpoint's `probeNominal` names its electrode's reference, with the same values (Section 16.1). A controller that records ORP readings as Data Model observations SHOULD give it as their Method's `referenceElectrode` [OAP-DM Section 8.4].

8.6 Missing and Faulty Probes

1. A port whose endpoint is `ph` SHOULD find a missing or broken electrode, and report `sensor-disconnected`, within 60 s, for example by measuring its impedance (Section 8.3.3). An impedance above 20 GΩ means no electrode or a broken cable; one below 1 MΩ means a cracked membrane, a short, or a probe that is not a pH electrode, such as a conductivity cell (Section 13.3) (provisional).
2. A port MUST report `out-of-range`, with `qualifier`, and no `good` reading, while its input is beyond its measuring range, as an unconnected input often drifts to be (Section 7.3.4).
3. A port MUST report `hardware-failure`, and no `good` reading, when its own circuit fails, such as a converter that does not respond.

8.7 Cables

1. A port MUST meet Table 5 with electrodes whose cables are up to 5 m long (provisional). Aquarium electrodes come with cables of about 1 m to 3 m.
2. Longer cables need an amplifier at the electrode, which this revision does not define.

8.8 Checks

Table 6 — Electrode port checks

Check	Presence	Applies to	What it requires	Section
BNC connector	REQUIRED	Devices	An electrode port is a BNC jack of 50 Ω whose centre is the measuring input and whose shell is the probe common, insulated from every panel, enclosure part, and other port.	8.1
Input characteristics	REQUIRED	Devices	The port meets Table 5: range, input resistance, bias current, resolution, accuracy, source resistance, noise, drift, and settling.	8.2
No current through the electrode	REQUIRED	Devices	The port passes no current through an electrode but its bias current and diagnostic signals that average no current, come at most once a minute, and leave the reading within 0.6 mV from 10 s after.	8.3
Computing pH	REQUIRED	Devices	The port computes pH from the potential by the Nernst equation, at the compensation temperature, with its calibration's offset and slope.	8.4
Computing ORP	REQUIRED	Devices, probes	The port reports ORP as the potential plus its calibration's offset, without temperature compensation, and an ORP electrode's documentation names its reference as a Data Model reference electrode.	8.5

Check	Presence	Applies to	What it requires	Section
Missing electrodes	RECOMMENDED	Devices	A pH port finds a missing electrode, a short, or a probe that is not a pH electrode, and reports `sensor-disconnected`, within 60 s.	8.6
Faults	REQUIRED	Devices	The port reports `out-of-range` with `qualifier`, and no `good` reading, beyond its range, and `hardware-failure` with no `good` reading when its circuit fails.	8.6
Cables	REQUIRED	Devices	The port meets Table 5 with 5 m of electrode cable.	8.7

9 Conductivity Ports

A conductivity port measures the conductivity of the water between the two electrodes of a cell, and reports conductivity, salinity, or total dissolved solids.

9.1 Cells

1. A conductivity port accepts two-electrode cells. Four-electrode cells, which avoid polarization errors at high conductivity, need more contacts, and this revision does not cover them.
2. A port's documentation MUST give the nominal cell constants it accepts, with the measuring range for each. A port SHOULD accept cells of K = 0.1, 1.0, and 10.
3. Cells with a higher cell constant suit higher conductivity, because the cell's resistance stays high enough to measure without polarization error:

Table 7 — Cell constants and their uses (informative)

Nominal cell constant	Typical range	Cell resistance at the top of the range
K = 0.1	RO/DI water, about 0.1 µS/cm to 100 µS/cm	1 kΩ
K = 1.0	Fresh water, about 100 µS/cm to 10 mS/cm	100 Ω
K = 10	Brackish water and seawater, 10 mS/cm and above	190 Ω at 53 mS/cm

4. A port MUST know the nominal cell constant of the cell connected to it, from a smart probe's record (Section 16) or from the `cellConstant` of `probeNominal` [OAP-DC Section 11.1], which the owner sets.

9.2 Connector

1. A conductivity port MUST be a BNC jack of 50 Ω [IEC 61169-8], with one electrode on the centre contact and the other on the shell, which is the probe common (provisional; Appendix D, issue 3). Two widely used commercial controllers use BNC conductivity cells; a third uses a four-pin Mini-DIN connector.
2. The shell MUST be insulated as Section 8.1.3 requires.
3. Electrode ports and conductivity ports share a connector, so the wrong probe can be plugged into either; Section 13.3 makes that harmless.
4. Cells with a temperature sensor in their body, which compensate best, need more contacts than BNC has. This revision does not define their connector. Until it does, a conductivity port takes its compensation temperature from a temperature port in the same water (Section 7.4).

9.3 Excitation and Measurement

Table 8 — Conductivity port (provisional)

Characteristic	Requirement
Excitation	Alternating and symmetrical, with no average current through the cell; its DC component at most 1 mV.
Excitation amplitude	At most 1 V peak across the cell; 0.4 V is typical.
Excitation frequency	Chosen by the port for each range, higher for higher conductivity, and documented; about 100 Hz to a few kHz is typical.

Characteristic	Requirement
Accuracy	Within ±(1 % of the reading + 0.1 % of the range), measured with precision resistors in place of the cell, over each documented range.
Temperature input	Within ±0.2 °C, when the port measures temperature itself.

1. A port MUST meet Table 8.
2. The excitation alternates because a direct current through a cell electrolyses the water and polarizes the electrodes, and component makers warn that even a small one damages a cell over time. Its amplitude is limited so that a pH electrode plugged in by mistake is not expected to come to harm; the wrong-probe check of Section 13.5 confirms it (Section 13.3).
3. The signal is the conductivity at the water's temperature, computed with the cell's nominal cell constant; the calibration's gain corrects it to the cell's true cell constant (Section 14.5).

9.4 Temperature Compensation

1. A conductivity endpoint MUST report conductivity at 25 °C [OAP-DM Section 9.2], compensated by one of two methods:
   - **`pss-78`:** the water is treated as seawater. The port computes the practical salinity from the conductivity at the water's temperature (Section 9.5), and reports the conductivity that seawater of that salinity has at 25 °C. This is RECOMMENDED for marine and brackish water.
   - **`linear`:** $C_{25} = C_t / (1 + \alpha \times (t - 25\ °C))$, with α the coefficient in % per °C. This is RECOMMENDED for fresh water and RO/DI water, with α = 2.0 % per °C unless the owner sets another [USGS].
2. The method and coefficient are the endpoint's `compensationMethod` and `compensationCoefficient`, in `%/degC` [OAP-DC Section 11.1].
3. Neither method matches a potassium chloride standard exactly: at 20 °C, 0.1 mol/L potassium chloride reads about 12.96 mS/cm by either method, not the 12.88 mS/cm of its label, because its own coefficient is about 1.9 % per °C. This is why a calibration's reference is computed with the port's own method (Section 14.4.4).

9.5 Salinity

1. A salinity endpoint MUST report practical salinity, in `psu`, computed by the Practical Salinity Scale 1978 [PSS-78] at atmospheric pressure, from the conductivity at the water's temperature and that temperature, as [TEOS-10]'s `gsw_SP_from_C` does with a pressure of 0 dbar, including its extension below salinity 2.
2. Temperatures are converted from ITS-90 to IPTS-68 by multiplying by 1.00024, as [TEOS-10] does.
3. PSS-78 holds for water of the composition of seawater, from salinity 2 to 42. Artificial seawater mixes are close to it. A salinity endpoint's `rangeMax` MUST NOT be more than 42, so that a higher salinity is reported as beyond the range, with `qualifier >` (Section 7.3.3).
4. A port reports no specific gravity in this revision.

9.6 Total Dissolved Solids

1. A total dissolved solids endpoint MUST report, in mg/L, the conductivity at 25 °C in µS/cm multiplied by its `tdsFactor` [OAP-DC Section 11.1].
2. The factor SHOULD be 0.5, which matches the sodium chloride scale of most RO/DI meters (provisional).
3. A port's documentation MUST give the factor it uses by default, because readings with different factors differ by up to 40 %.

9.7 Missing and Faulty Probes

1. A cell in air reads almost no conductivity, as it would in very pure water, so a port often cannot tell a dry or missing cell from RO/DI water. A port SHOULD report `sensor-disconnected` where it can tell, and controllers use plausibility instead (Section 17.2).
2. A short circuit across the cell reads more than any water conducts. A port MUST report `sensor-disconnected`, and no `good` reading, while it measures more than 300 mS/cm at the water's temperature (provisional), which is more than saturated brine conducts.

3. A port MUST report `hardware-failure`, and no `good` reading, when its excitation or converter fails.

9.8 Checks

Table 9 — Conductivity port checks

Check	Presence	Applies to	What it requires	Section
Cell constants	REQUIRED	Devices	A port's documentation gives the nominal cell constants it accepts, with their ranges, and the port reads with the nominal cell constant of the cell connected.	9.1
BNC connector	REQUIRED	Devices	A conductivity port is a BNC jack of 50 Ω whose shell is the probe common, insulated as an electrode port's.	9.2
Excitation	REQUIRED	Devices	The excitation alternates symmetrically, with a DC component of at most 1 mV and at most 1 V peak across the cell.	9.3
Accuracy	REQUIRED	Devices	Readings are within ±(1 % of the reading + 0.1 % of the range) over each documented range.	9.3
Compensation	REQUIRED	Devices	Conductivity is reported at 25 °C by the `pss-78` or `linear` method, as Section 9.4 defines.	9.4
Salinity	REQUIRED	Devices	Salinity is practical salinity by PSS-78 at atmospheric pressure, with its extension below 2, and a salinity endpoint's range ends at 42 or below.	9.5
Total dissolved solids	REQUIRED	Devices	Total dissolved solids is the conductivity at 25 °C in µS/cm times the endpoint's `tdsFactor`, and the documentation gives the factor the port uses by default.	9.6
Faults	REQUIRED	Devices	A short across the cell, which reads more than 300 mS/cm, is `sensor-disconnected`, and a failed excitation or converter is `hardware-failure`, each with no `good` reading.	9.7

10 Temperature Ports

10.1 Two Interfaces

This revision defines two temperature port kinds:

- **PT1000 ports**, for platinum resistance elements, whose resistance at each temperature is fixed by IEC 60751, so any element works with any port; and
- **1-Wire ports**, for digital sensors that measure and convert at the probe, and communicate by the 1-Wire protocol.

Both are provisional until breadboard test 7 compares them for accuracy, noise, and behavior on a 5 m cable [Breadboard], as Proposal 0001 asks [P0001] (its open question 6). The Working Group may then keep both, or one (Appendix D, issue 2). Thermistors, which one commercial controller uses, follow curves that differ between families and that no standard fixes, so a port must know a probe's curve; this revision does not cover them.

Both port kinds use one connector, so that ports and cables are alike; the contact assignment makes a probe of either kind harmless in a port of the other (Section 13.3).

Table 10 — Temperature port contacts

Contact	PT1000 port	1-Wire port
1	Element, first terminal, excitation	Supply, VDD
4	Element, first terminal, sense	Data, DQ
3	Element, second terminal	Ground

1. A temperature port MUST be an M8 jack with three contacts, A-coded [IEC 61076-2-104], with the contacts of Table 10 [Enclosure] (Appendix D, issue 4). Three widely used commercial controllers each use a different temperature connector.
2. The assignment follows the usual one for three-wire sensors: supply on 1, ground on 3, and signal on 4.

10.2 PT1000 Ports

1. A PT1000 port MUST read platinum elements of IEC 60751 with a resistance of 1000 Ω at 0 °C, and MUST convert resistance to temperature with the Callendar–Van Dusen equation and coefficients of [IEC 60751]:

   $R(t) = R_0 \times (1 + A \times t + B \times t^2)$ for $t \geq 0$ °C, adding $C \times (t - 100\ °C) \times t^3$ below 0 °C,

   with $R_0 = 1000\ \Omega$, $A = 3.9083 \times 10^{-3}\ °C^{-1}$, $B = -5.775 \times 10^{-7}\ °C^{-2}$, and $C = -4.183 \times 10^{-12}\ °C^{-4}$. At 25 °C, R = 1097.35 Ω.
2. A port MUST read three-wire probes, which have two leads on contacts 1 and 4 and one on contact 3, compensating the resistance of the leads, and two-wire probes, whose plug joins contacts 1 and 4. A two-wire probe's leads add to its reading: 5 m of 0.25 mm² copper is about 0.4 Ω in each lead, so the two add about 0.8 Ω, or 0.2 °C, which a calibration removes.
3. A port MUST meet Table 11.

Table 11 — PT1000 port (provisional)

Characteristic	Requirement
Measuring range	At least −5 °C to 60 °C.
Resolution	0.05 °C or finer.
Accuracy	Measured with precision resistors in place of the element, three-wire, over 0 °C to 40 °C: within ±0.3 °C, and within ±0.1 °C after a one-point calibration at 25 °C.
Self-heating	The power in the element, averaged over each measurement interval, at most 0.2 mW.
Open and short	A resistance above 2000 Ω or below 500 Ω is reported as `sensor-disconnected` within 5 s.

4. Self-heating is limited because an element warmed by its own excitation reads high: 0.2 mW, which is 0.45 mA through 1000 Ω, warms even a small element in still air by less than 0.1 °C, and much less in water. Component makers' application notes give a small thin-film element about 1 °C of warming for each 2.5 mW it dissipates, so 0.2 mW warms it by 0.08 °C.
5. A resistance between the ends of the measuring range and the limits of Table 11 is a reading beyond the range, which the port reports as Section 7.3.4 says.

10.3 1-Wire Ports

1. A 1-Wire port MUST read a digital temperature sensor that communicates by the 1-Wire protocol, is powered from the supply contact rather than through its data line, and behaves as follows:
   - it has a 64-bit ROM code: an 8-bit family code, a 48-bit serial number, and an 8-bit CRC;
   - it starts a conversion on the command 0x44, which takes at most 750 ms at 12-bit resolution;
   - it returns its 9-byte scratchpad on the command 0xBE: the temperature in its first two bytes, least significant first, as a two's-complement number of 0.0625 °C steps at 12-bit resolution; the configuration, which sets the resolution, in its fifth byte; and a CRC of the first eight bytes in its last byte;
   - both CRCs use the polynomial $x^8 + x^5 + x^4 + 1$; and
   - its scratchpad reads 85 °C from when it starts until its first conversion ends.
2. A port MUST supply between 3.0 V and 5.5 V on contact 1, limited to 20 mA (provisional), so that a short circuit, or a probe of the other kind, does no harm (Section 13).
3. A port reads one sensor. It MUST read the sensor's 64-bit ROM code, and MUST check the CRC of the ROM code and of every reading, discarding a reading whose CRC fails.
4. A port MUST convert at 12-bit resolution (0.0625 °C), and SHOULD start a new conversion at least every 2 s.
5. A sensor reads 85 °C after it restarts, which a disturbed cable can cause. A port MUST NOT report 85.0 °C as a `good` reading unless the reading before it was within 5 °C of 85 °C, or a second conversion confirms it.
6. A port MUST report `sensor-disconnected` within 5 s (provisional) when no sensor answers, and after three readings in a row fail their CRC.
7. A port MUST work with cables up to 5 m (provisional); longer cables need the care that application notes on long 1-Wire networks describe.

8. Sensors of this kind are commonly specified as accurate to ±0.5 °C from −10 °C to 85 °C. A port's documentation SHOULD give the accuracy of the sensors it was tested with, and a calibration (Section 15.4) improves it.

10.4 Probes

1. A temperature probe's sensing element and conductors MUST be insulated from the water, with an insulation resistance of at least 100 MΩ at 500 V DC between its contacts, joined, and the water it is immersed in (provisional). This keeps a temperature probe from connecting the water to its port's circuit, which a port that is not isolated relies on (Section 10.5).
2. A probe's wetted parts SHOULD be titanium, glass, or a plastic that suits seawater, because stainless steel, even type 316, can corrode in seawater.
3. A PT1000 probe MUST use an element of tolerance class B or better: within ±(0.3 + 0.005 × |t|) °C [IEC 60751].

10.5 Isolation

1. A temperature port SHOULD be an isolated domain (Section 12.2). A temperature port that is not isolated relies instead on the insulation of its probe (Section 10.4.1), which keeps the water out of its circuit.
2. A temperature port that is not isolated MUST be used only with probes that meet Section 10.4.1, and its endpoint MUST NOT declare `isolated`.
3. A temperature sensor in the body of a pH probe or a conductivity cell shares that probe's isolated domain.

10.6 Choosing an Interface (Informative)

Table 12 — PT1000 and 1-Wire

	PT1000	1-Wire
Standard	IEC 60751 fixes the element; any element works with any port.	The 1-Wire protocol and the sensor's commands come from its maker; compatible sensors come from several makers.
Accuracy	Class B: ±0.43 °C at 25 °C; class A: ±0.2 °C; improved by calibration.	±0.5 °C; improved by calibration.
Cable	Lead resistance adds to two-wire readings; three wires cancel it.	Digital, so the cable adds no error, but long cables need care.
Identity	None.	A unique ROM code, so a port can tell one probe from another (Section 16.5).
Port cost	An RTD converter per port.	A pull-up and a microcontroller pin.
In the breadboard	An RTD converter with a PT1000 probe.	A probe with a digital sensor that uses the 1-Wire protocol.

10.7 Checks

Table 13 — Temperature port checks

Check	Presence	Applies to	What it requires	Section
M8 connector	REQUIRED	Devices, probes	A temperature port is an M8 jack with three contacts, A-coded, with the contacts of Table 10, and probes match it.	10.1
PT1000 readings	REQUIRED	Devices	A PT1000 port converts by IEC 60751, compensates three-wire leads, reads two-wire probes, and meets Table 11.	10.2
PT1000 open and short	REQUIRED	Devices	Above 2000 Ω or below 500 Ω, the port reports `sensor-disconnected` within 5 s.	10.2
1-Wire readings	REQUIRED	Devices	A 1-Wire port reads a sensor that behaves as Section 10.3.1 says, supplies 3.0 V to 5.5 V limited to 20 mA, checks every CRC, converts at 12 bits, never reports the start-up value of 85 °C as `good`, and reports `sensor-disconnected` within 5 s when no sensor answers.	10.3
Probe insulation	REQUIRED	Probes	A temperature probe's contacts, joined, are insulated from the water by at least 100 MΩ at 500 V DC, and a PT1000 probe's element is of class B or better.	10.4

11 Dissolved Oxygen and PAR

11.1 Dissolved Oxygen

1. Dissolved oxygen probes are galvanic, polarographic, or optical. Galvanic probes produce their own millivolt output, roughly proportional to the oxygen in the water. Two commercial controllers connect their dissolved oxygen probes by BNC, and a widely used maker of probe circuits offers its galvanic probes with BNC. This revision covers galvanic probes with millivolt outputs, on electrode ports (provisional).
2. A port that reports dissolved oxygen MUST be an electrode port, MUST read the probe's output as its signal, and MUST document the probes it supports, because how a galvanic probe's output changes with temperature is its maker's.
3. A port MUST report `dissolved-oxygen-saturation` in %, and MAY also report `dissolved-oxygen` in mg/L. Saturation is relative to water in equilibrium with water-saturated air at the standard pressure of 101.325 kPa; mg/L is the saturation multiplied by the solubility of oxygen at the water's temperature and salinity at that pressure [Benson].
4. A port that reports mg/L MUST use the water's salinity, its `compensationSalinity` [OAP-DC Section 11.1], set by the owner or the controller, because seawater holds about a fifth less oxygen than fresh water.
5. Polarographic probes need a polarizing voltage, and optical probes are digital, most often with RS-485 or SDI-12 outputs; neither is covered by this revision. Such a probe can be a device of its own that presents `sensor` endpoints, and still follows Sections 14 to 16.

11.2 PAR

1. A PAR sensor measures photosynthetic photon flux density, the Data Model parameter `ppfd`, in µmol/m²/s.
2. Self-powered sensors with millivolt outputs are common, and one commercial controller's PAR sensor is reported to use the same connector as a pH electrode. This revision covers them, on electrode ports (provisional).
3. A port that reports PAR MUST convert its signal with the sensor's nominal factor, in µmol/m²/s per mV, from a probe record or from the `gain` of `probeNominal` [OAP-DC Section 11.1] (provisional).
4. A sensor calibrated in air reads low under water, by an immersion factor its maker gives, such as 1.25 for one maker's sensor. The nominal factor a port uses MUST be the one for the medium the sensor is in: for a sensor under water, its factor in air times its immersion factor. A sensor's documentation MUST give its factor in air and its immersion factor.
5. PAR sensors with current outputs, or with digital outputs such as USB, RS-485, or SDI-12, are not covered by this revision.
6. A sensor with an output of 40 mV at full scale gives 100 µmol/m²/s per mV, so an electrode port's resolution of 0.1 mV (Table 5) resolves 10 µmol/m²/s, and a port that resolves 0.01 mV resolves 1 µmol/m²/s.

12 Isolation

12.1 Why Probes Are Isolated (Informative)

A pH electrode, an ORP electrode, and a conductivity cell each touch the water electrically, through a reference junction or bare electrodes. If two of them share a circuit common, current flows between them through the water: a conductivity cell's excitation, or a difference in ground potential between modules, then appears at the pH electrode as a false potential. The errors are large: 1 µA through a reference junction of 10 kΩ is 10 mV, or 0.2 pH, and one maker of process instruments warns that a steady current through a reference electrode can damage it. Equipment adds more: a pump or heater with failing insulation, or a grounding probe connected to earth, can put volts into the water, and owners report measuring several volts, sometimes tens of volts, between their water and earth. Commercial makers isolate their probe inputs for this reason, and one maker of probe circuits tells designers never to build a commercial product without isolation.

Isolation gives each probe a circuit of its own, whose only connection to the water is through that probe. A potential in the water then moves the whole circuit with it, and does not appear in the measurement.

A temperature probe touches the water through no conductor, because its element and conductors are insulated from the water (Section 10.4), so a temperature port may rely on that insulation instead of an isolated domain (Section 10.5).

Breadboard test 6 measures how much this matters [Breadboard].

12.2 Isolated Domains

1. Each electrode port and each conductivity port MUST be an isolated domain of its own, galvanically isolated from:
   - every other port of the device;
   - the module bus, its power, and every other power or data connection of the device; and
   - earth, and every metal part of the device's enclosure.
2. An isolated domain holds its port's connector, measuring circuit, and probe common. Power and data cross its barrier only through isolating parts, such as an isolated DC-DC converter and a digital isolator.
3. One isolated domain MAY hold more than one port only when they serve one probe, such as a conductivity cell and the temperature sensor in its body.
4. Nothing in an isolated domain may connect to anything outside it except through its barrier.

12.3 Ratings

Table 14 — Isolation ratings (provisional)

Characteristic	Requirement
Withstand	500 V AC rms, or 707 V DC, for 60 s, between each isolated domain and every other domain, and between each isolated domain and the module bus contacts, joined, with no breakdown.
Insulation resistance	At least 100 MΩ at 500 V DC, between the same points.
Barrier capacitance	At most 100 pF between each isolated domain and the rest of the device (RECOMMENDED).
Disturbance	In the tests of Table 15, readings change by at most 0.02 pH, 2 mV of ORP, 1 % of conductivity, and 0.1 °C. These are the disturbance limits.
Wet surfaces	The ratings hold, and the tests of Table 15 pass, with the outside of the device wet with artificial seawater.

1. A port MUST meet Table 14.
2. These are functional ratings, which protect measurements. They are not a protective insulation for people: everything in this Specification runs at safety extra-low voltage, and protecting people from faulty mains equipment in the water is the job of a residual-current device on that equipment.
3. Common isolating parts are rated far beyond these values, often at 2500 V rms or more. The ratings are low so that a port can be built from many parts, and they are checked by test, because what spoils isolation in practice is a salt film or a metal panel, not a failed isolator.

12.4 Outside the Device

1. A salt film across the outside of a device can join neighbouring probe connectors. A device SHOULD lengthen the surface path between the connectors of different isolated domains, for example with ribs between them, and SHOULD use no metal that could join them [Enclosure].
2. A device MUST pass the wet tests of Table 15.

12.5 The `isolated` Feature

An endpoint MUST declare the `isolated` feature [OAP-DC Section 11.1] when, and only when, its port meets Sections 12.2 to 12.4.

12.6 Checks

Table 15 — Isolation checks

Check	Presence	Applies to	What it requires	Section
Withstand and insulation	REQUIRED	Devices	Each isolated domain withstands 500 V AC rms, or 707 V DC, for 60 s, and has at least 100 MΩ at 500 V DC, to every other domain and to the module bus.	12.3
Barrier capacitance	RECOMMENDED	Devices	Each isolated domain has at most 100 pF to the rest of the device.	12.3
Probes in the same water	REQUIRED	Devices	Probes on different ports in the same water do not disturb each other.	12.2
Potentials in the water	REQUIRED	Devices	A potential between the water and the device's ground does not disturb readings.	12.2
Wet surfaces	REQUIRED	Devices	Isolation holds with the outside of the device wet with artificial seawater.	12.4
The isolated feature	REQUIRED	Devices	An endpoint declares `isolated` when, and only when, its port meets Sections 12.2 to 12.4.	12.5

13 Protection

13.1 Electrostatic Discharge

1. Every port MUST withstand electrostatic discharges, as [IEC 61000-4-2] defines them, of ±4 kV by contact and ±8 kV through air, to its connector and to the connector of a mated probe (provisional).
2. During discharges, a port's readings MAY be disturbed, but MUST NOT be reported as `good` while they are wrong by more than the disturbance limits of Table 14, and the port MUST recover within 10 s (provisional) without a person's help. Other ports and endpoints of the device MUST keep working, and the device MUST NOT restart.
3. After the discharges, a port MUST still meet its requirements, including the bias current of Table 5, and MUST keep its calibration.
4. Protecting an electrode input without adding leakage needs care, such as low-leakage clamps, guard rings, and a series resistor that is small beside an electrode's resistance.

13.2 Wiring Faults

1. A port MUST withstand, indefinitely and without damage, a short circuit between any two of its contacts, and MUST work again within 10 s (provisional) after it ends. While the short lasts, the port MUST report `sensor-disconnected`, and no `good` reading, where it can tell a short: a conductivity port (Section 9.7.2), a PT1000 port (Table 11), a 1-Wire port, whose sensor no longer answers (Section 10.3.6), and an electrode port that measures its electrode's impedance (Section 8.6.1). An electrode port that does not measure its impedance reads a short as 0 mV, which is pH 7 (Section 13.3.3).
2. A port MUST withstand, indefinitely and without damage, any voltage from −30 V to +30 V DC between any two of its contacts, and, for a port that is not isolated, between any contact and the device's ground (provisional). 30 V is the highest voltage of the module bus [OAP-MB Section 7.3], and such voltages can reach probe ports: some security cameras are powered over their coaxial cable, with 12 V to 24 V on its BNC connectors, and the M8 cables of industrial 24 V sensors fit temperature ports.
3. While a fault of item 1 or 2 lasts, other ports and endpoints of the device MUST keep working.

13.3 The Wrong Probe

1. A probe of any type in Table 3 plugged into any port whose connector it fits MUST NOT damage the probe or the port. In particular:
   - a pH electrode in a conductivity port receives at most 1 V peak of alternating excitation (Table 8);
   - a conductivity cell in an electrode port receives only bias current (Section 8.3);

- a 1-Wire probe in a PT1000 port presents almost no current path between contacts 1 and 3, and is reported as `sensor-disconnected`;
- a PT1000 probe in a 1-Wire port draws at most the port's limited supply current, and holds the data line high through contact 4, so no sensor answers, and the port reports `sensor-disconnected`.

2. A port MUST NOT report `good` readings from a probe it can tell is of the wrong type: an electrode port whose endpoint is `ph` that measures an impedance below 1 MΩ, or a temperature port that finds no element or sensor of its kind.
3. A port cannot always tell: a conductivity cell in an electrode port reads near 0 mV, which is pH 7. Controllers SHOULD catch this with plausibility (Section 17.2), and owners with labels (Section 7.1.7).

13.4 Connecting While Powered

1. Probes are plugged and unplugged while everything runs. Connecting or disconnecting a probe MUST NOT damage any part, restart the device, or change another port's reading by more than the disturbance limits of Table 14.
2. A port MUST report a newly connected probe's readings as `good` only once they are stable (Section 14.3), and, on an electrode port, within its measuring range.
3. After a probe is disconnected and connected again, the controller holds its inputs as Section 14.8.6 says.

13.5 Checks

Table 16 — Protection checks

Check	Presence	Applies to	What it requires	Section
Electrostatic discharge	REQUIRED	Devices	Ports withstand ±4 kV contact and ±8 kV air discharges to their connectors and to mated probes' connectors, recover within 10 s, and keep their calibration.	13.1
Short circuits	REQUIRED	Devices	A short between any two contacts of a port does no damage, is reported as `sensor-disconnected` where the port can tell, and leaves other ports working.	13.2
Wrong voltages	REQUIRED	Devices	Any voltage from −30 V to +30 V DC between any two contacts of a port, or between a contact of a port that is not isolated and ground, does no damage.	13.2
The wrong probe	REQUIRED	Devices, probes	A probe in a port of another kind whose connector it fits damages nothing, and a port does not report `good` readings from a probe it can tell is wrong.	13.3
Connecting while powered	REQUIRED	Devices	Plugging and unplugging probes damages nothing, restarts nothing, and disturbs other ports by no more than the disturbance limits; a probe's readings are `good` again only once stable.	13.4

14 Calibration

14.1 Overview

A probe is calibrated with the commands of the Device Classes `calibration` feature [OAP-DC Section 11.1]: `beginCalibration`, `calibratePoint` with a `reference` and, optionally, a `solution`, `completeCalibration`, `cancelCalibration`, and `resetCalibration`, which this Specification requires (Section 14.2.11). This section defines what a port and a controller do with them; Section 15 gives the points, references, and limits for each probe type.

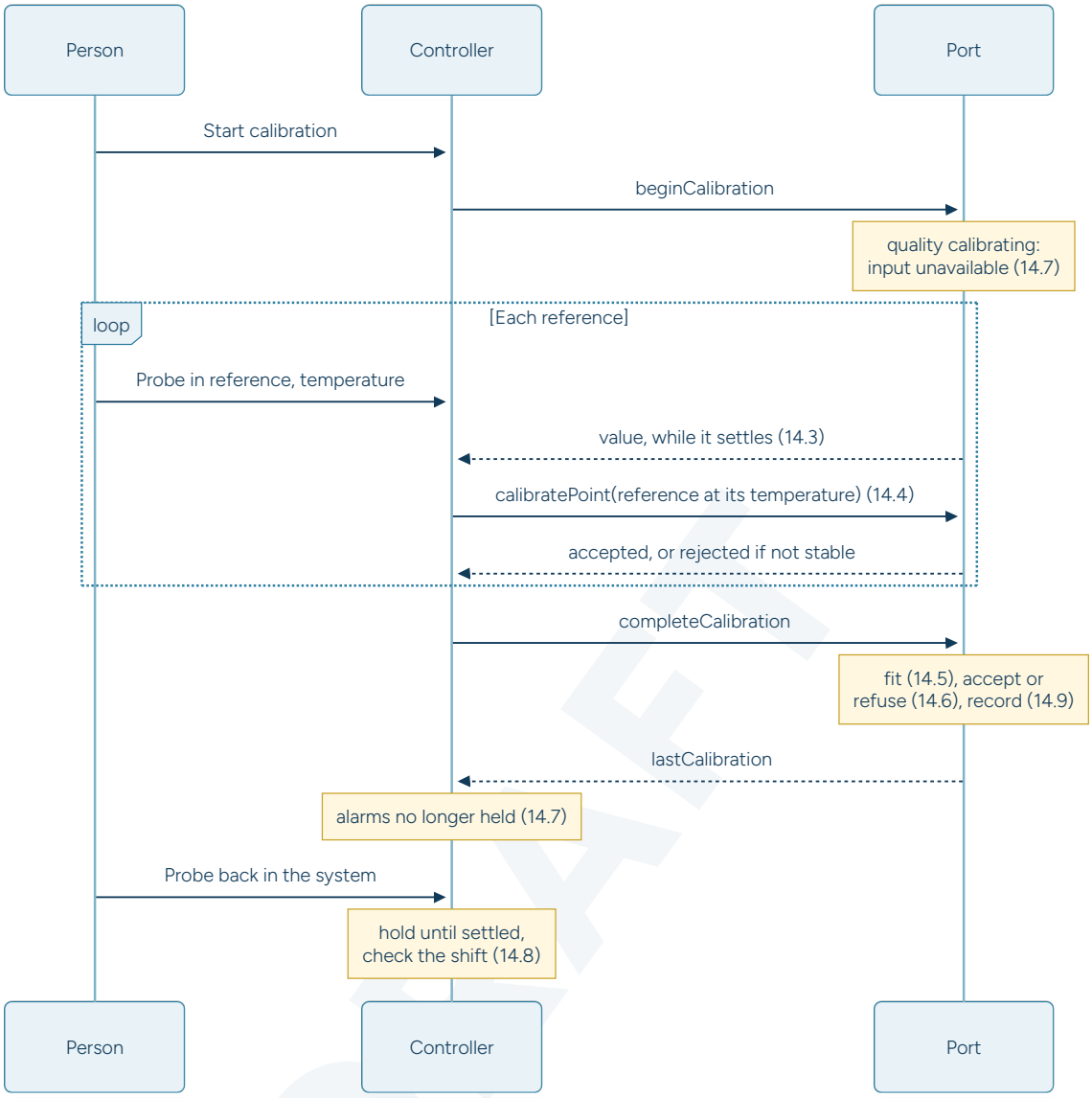

Figure 2 — A calibration

14.2 On the Port

1. `beginCalibration` starts a calibration of the probe, discarding the points of any calibration already in progress. Every endpoint of the probe reports `quality calibrating` until the calibration ends. A port MUST refuse `beginCalibration`, with the status for a bad state, while its clock is not valid [OAP-FS Section 10.5.4], because the record of every calibration needs the time (Section 14.9).
2. While calibrating, a port MUST keep measuring, and MUST keep reporting `value` and `updated`, computed with the calibration in use, so that a person can watch the reading settle.
3. `calibratePoint` records a point: the `reference`; the probe's signal averaged over at least the last 5 s (provisional); the compensation temperature; the time; and the `solution`, if the command names one.
4. A port MUST reject `calibratePoint`, and record nothing:
   - with the status for a bad state (`STATUS_BAD_STATE` on the module bus [OAP-MB], `bad-state` in the Device Protocol [OAP-DP]), when no calibration is in progress, when the readings are not stable (Section 14.3), or when the compensation temperature is unavailable for a probe type that needs one; and
   - with the status for a bad parameter (`STATUS_BAD_PARAMETER`, `bad-parameter`), when the reference is outside the probe type's range of references (Table 19).

5. A point whose reference differs from an earlier point's by no more than half the probe type's spacing, or, for a probe type without a spacing, by no more than 5 % of the earlier reference, replaces that point. A port MUST reject, with the status for a bad state, a new point beyond the probe type's maximum number of points.
6. `completeCalibration` computes the result (Section 14.5) and checks it (Section 14.6).
   - If the calibration is accepted, the port MUST apply it to every endpoint of the probe, set `lastCalibrated` to the time of completion, keep it across power loss, write it to a smart probe first (Section 16.3), and clear `calibration-failed` and `calibration-due`.
   - Otherwise, the port MUST keep the calibration in use, and MUST raise `calibration-failed`, which stays until a calibration is accepted or the calibration is reset (item 11). Either way, the calibration ends, and the port MUST report its record as `lastCalibration` of every endpoint of the probe (Section 14.9).
7. `cancelCalibration` ends the calibration, discarding its points and keeping the calibration in use, and its record has the reason `person`.
8. A port MUST cancel a calibration that has received no calibration command for 1800 s (provisional), within 5 s, with the reason `timeout`, so that a calibration a person walked away from does not hold a probe forever.
9. A calibration of a probe applies to every endpoint of the probe: calibrating salinity also calibrates conductivity, and calibrating dissolved oxygen in % also calibrates it in mg/L. It does not apply to a selectable endpoint of the same port that reads a probe of another type (Section 7.1.4).
10. A port MUST keep its calibrations across power loss, restarts, and firmware updates. A factory reset MAY clear them, and then acts as `resetCalibration`.
11. A port MUST implement `resetCalibration`, and list it among its endpoints' optional elements [OAP-DC Section 7.2.4], so that a controller can make sure that a new probe is never read with an old probe's calibration (Section 16.5). `resetCalibration` restores the factory calibration of a smart probe, or the nominal values: slope 100 % and offset 0 mV for pH, and gain 1 and offset 0 for other probe types. A probe type marked in Table 19 as needing a calibration before use reports no `good` reading, and reports `calibration-due`, until it has a factory calibration or an accepted calibration (Appendix D, issue 5). `resetCalibration` clears `calibration-failed`, because a calibration that failed no longer describes the calibration in use. A port MUST refuse `resetCalibration`, with the status for a bad state, while a calibration is in progress.
12. A port with a local control for calibration, such as a button, MUST follow the same rules, and SHOULD let its controller know, through the same `quality` and record.
13. A port that restarts during a calibration MUST end it as cancelled, with the reason `other`, and MUST report its record after the restart. The calibration in use stays. The record's time is that of the calibration's last command, when the port does not know when it restarted. So a controller learns that the calibration has ended, and ends the hold of its alarms (Section 14.7.5), even though no command ended it.

14.3 Stable Readings

1. Readings are stable when, over the probe type's window, the highest and lowest differ by no more than its limit (Table 19): for pH, 0.6 mV in 30 s, or about 0.01 pH. Limits marked relative are a percentage of the readings' mean.
2. The window and limit apply to the signal for pH and ORP, and to the reading for other probe types.
3. A temperature probe's limit, 0.1 °C, is more than one step of a 1-Wire sensor, 0.0625 °C, so that a reading that flickers between two steps is stable.
4. A controller SHOULD show a person whether the readings are stable, and SHOULD send `calibratePoint` only once they are.

14.4 References and Their Temperature

1. The `reference` of `calibratePoint` is what a perfect probe would read in the reference at that moment, in the endpoint's unit.
2. For a solution, it is the solution's value at its temperature, from its maker's table, which governs, or, for common solutions, from Table 20. A pH 10.01 buffer at 20 °C, for example, is pH 10.06.

3. The temperature of a solution SHOULD be measured, by putting a temperature probe in the solution beside the probe being calibrated; a controller SHOULD ask for the system's own temperature probe to be put there, and then holds its inputs (Section 14.7.8), and MAY otherwise let the person enter the temperature.
4. For conductivity, a perfect probe reads at 25 °C, by the port's own compensation method (Section 9.4). So the reference is the standard's conductivity at its temperature, from its table, compensated by the port's method: for 0.1 mol/L potassium chloride at 20 °C, which conducts 11.67 mS/cm, a port with the linear method at 2.0 % per °C reads 12.97 mS/cm, not the 12.88 mS/cm of the label. At 25 °C the reference is the label's value; for a seawater standard on a salinity endpoint, it is the standard's salinity.
5. While a calibration is in progress, a controller that writes `compensationTemperature` MUST write the temperature of the reference, not of the system, and MUST restore the system's temperature when the calibration ends.
6. A controller SHOULD send `calibratePoint` with the `solution` the person used, as an identifier of Table 20 or an extension name, so that the port can record it, and use its own table for it.
7. A person SHOULD use fresh portions of each solution, never pour a used portion back, rinse the probe with clean water between solutions, and use no solution past its use-by date. An open pH 10 buffer takes up carbon dioxide from the air and falls; it SHOULD be used within the time its maker gives.

14.5 Computing a Calibration

1. A port MUST compute a calibration's result from its points as Table 17 says, and MUST then compute its readings with the result as Sections 8.4, 8.5, 9.4, 9.5, and 10.2 say.

Table 17 — Calibration models

Model	Probe types	Result	One point	Two or more points
`nernst`	pH	Offset E_0, in mV; slope s, in % (Section 8.4).	E_0 from the point, keeping the slope in use, or 100 % if there is none.	E_0 and s by least squares, fitting each point's signal E against $S_N(t) \times (pH - 7) / 100$ at the point's own temperature t.
`linear`	All others	Gain g and offset b: the true signal is g × signal + b, in the signal's unit.	The gain or the offset, as Table 19 says, keeping the other from the calibration in use, or 1 and 0 if there is none.	g and b by least squares, fitting each point's true signal against its signal.

2. The true signal of a point is its reference expressed as a signal at the point's temperature: for conductivity, the conductivity at that temperature of water whose reading is the reference, by the port's method (Section 9.4); for salinity, the conductivity at that temperature of seawater of that salinity; for every other probe type, the reference itself.
3. For conductivity, the cell's cell constant is the gain multiplied by its nominal cell constant.
4. Because each pH point is fitted at its own temperature, buffers at different temperatures give the same result as buffers at one temperature.
5. The reference implementation's `fit` and `reading` functions, in `tools/probe_reference.py`, compute Table 17, and `test-vectors.json` holds their results for each probe type. After each calibration of the vectors, a port's readings MUST agree with the vectors' readings within the tolerance each vector gives.

14.6 Acceptance

1. A port MUST NOT apply a calibration that fails any limit of its probe type in Table 19:
   - the number of points;
   - each reference within the range of references;
   - for pH and temperature, references at least the spacing apart;
   - for pH, the slope, with two or more points; the offset; and, with three or more points, every point within the linearity limit of the fitted line;
   - for other probe types, the gain and offset; and, with two or more points, an offset no larger than the zero limit times the largest true signal.

2. A failed calibration has the first reason that applies, in the order of item 1: `points`, `reference`, `spacing`, `slope`, `gain`, `offset`, or `linearity`. A port MAY fail a calibration for a reason of its own, with the reason `probe` or `other`.
3. A port MAY apply stricter limits than Table 19, and MUST document them. It MUST NOT apply looser ones.
4. A controller SHOULD tell a person why a calibration failed, and what to do: use fresh solutions, clean the probe, or replace it.
5. The reference implementation's `problems` function computes item 1 and item 2.

14.7 On the Controller

1. Calibrating needs the `calibrate` operation, of the `full-control` role [OAP-SA Table 6].
2. A controller MUST guide a person through a calibration: the references to use, in order; rinsing; putting a temperature probe in the reference, and asking whether it is one of the system's temperature probes, and which (Section 14.4.3); waiting until the readings are stable (Section 14.3); and the reference's value at its temperature, which the controller SHOULD compute from Table 20 or the solution's table, and the person confirms.
3. Before it starts a calibration, a controller SHOULD show which functions use the probe's inputs, and what they will do while the inputs are unavailable, such as "CO2 stops".
4. From `beginCalibration` until the calibration hold ends (Section 14.8), the inputs of every endpoint of the probe are unavailable [OAP-FS Section 10.1], and the functions that use them apply their behavior for an unavailable input [OAP-FS Section 10.3].
5. The `input-unavailable` alarms of those inputs, and of the inputs of a temperature probe in the reference (item 8), are expected while the calibration lasts. A controller holds their sound and notifications from `beginCalibration` until the calibration ends, completed, failed, cancelled, or timed out, as Alarms and Notifications Sections 12.8.6 and 12.8.7 say [OAP-AN]. It MUST NOT hold a `critical` alarm, or any alarm but these, and MUST end the hold when the calibration ends, sounding and notifying those of the held alarms that are still active and unacknowledged, although the inputs stay unavailable until the calibration hold ends (Section 14.8).
6. A controller that starts, or restarts, and finds an endpoint calibrating MUST hold its inputs as Section 14.8 says, and MUST NOT end the hold without a person.
7. A device that controls equipment from its own probe, such as a heater with a built-in probe, MUST treat the probe as unavailable during a calibration, and until a person confirms, on the device or through its controller, that the probe is back.
8. A controller that asks for a temperature probe of the system to be put in the reference (Section 14.4.3), or that a person tells that one is there (item 2), MUST hold that probe's inputs from when it asks, or is told, until the person has confirmed that the probe is back in the system, and its readings have been `good` and stable for the settle time since, as Section 14.8.1 holds the calibrated probe's. So heater and chiller functions, and ports compensated from the probe, never act on the reference's temperature (Section 7.4.4).
9. A controller MUST treat a calibration as ended when the port reports its record, or when no endpoint of the probe reports `quality calibrating` any more, whichever comes first, so that a calibration that ended without a command, such as one that a port of an earlier revision lost in a restart, never keeps alarms held (item 5).
10. A controller SHOULD show people the readings of a probe that needs a calibration before use and has none, marked as not calibrated, so that an owner can see that the probe works (Section 14.2.11).

14.8 After a Calibration

1. The calibration hold of a probe's inputs starts with `beginCalibration`, and ends when all of these hold:
   - the calibration has ended, by completion, failure, cancellation, or timeout, or as Section 14.7.9 treats it;
   - a person has confirmed to the controller that the probe is back in the system; and
   - the probe's readings have been `good` and stable (Section 14.3) for the settle time, by default 120 s (provisional), since the person confirmed.
2. During the hold, a controller MUST treat the inputs as unavailable, whatever their `quality`.

3. A controller MUST record the last `good` reading of each endpoint of the probe before `beginCalibration`, and the first reading when the hold would end. If they differ by more than the probe type's shift (Table 19), the hold MUST continue until a person confirms the new reading. The controller SHOULD show both readings, and SHOULD suggest checking the water with another instrument, such as a test kit or refractometer.
4. A shift is not always wrong: a probe that had drifted reads differently once calibrated, and the water may have changed during a long calibration. The shift check makes a person look; it does not refuse the calibration.
5. A controller records the readings, and whether a person confirmed the shift, in the calibration's record, as its `shift` (Section 14.9).
6. Outside a calibration and its hold, when an endpoint of a probe has reported `sensor-disconnected` or `hardware-failure`, or a `quality` other than `good`, such as an electrode port's reading beyond its measuring range, a controller MUST hold the probe's inputs from when that ends until their readings have been `good` and stable for the settle time (provisional). A reading of a conductivity or temperature port beyond its measuring range is `good` (Section 7.3.4), so its `out-of-range` starts no hold: the probe still reads the water. After `sensor-disconnected`, the controller SHOULD also ask a person to confirm that the probe is back in the system and whether it was replaced (Section 16.5). A probe unplugged for cleaning may come back still in a cleaning solution, and one that a fault interrupted may not yet read the water.

14.9 Calibration Records

1. When a calibration ends, a port MUST report its record, whatever its outcome, as `lastCalibration` of every endpoint of the probe [OAP-DC Section 11.1]. A port MUST implement `lastCalibration` and `calibrationDue`, and list both among its endpoints' optional elements [OAP-DC Section 7.2.4], so that a controller can read its records and set when the next calibration falls due (item 4).
2. A calibration record is a Data Model Calibration Record [OAP-DM Section 8.12], valid against `$defs/calibrationRecord` of `schema/probe-interface.schema.json`, with these members:
   - `outcome`: `completed`, `failed`, or `cancelled`; and, for a failed or cancelled calibration, `reason` (Section 14.6.2; Data Model Table 29);
   - `parameter`, the endpoint's parameter, and `model`, its probe type's (Table 17);
   - `points`, in the order they were taken, each with `reference`, the value sent with `calibratePoint`, in the endpoint's unit; `reading`, the signal the port measured (Section 14.2.3), in the probe type's signal unit (Table 3); `temperature`, the compensation temperature; `time`; and, in its `extensions["org.openaquariumproject.probe-calibration"]`, `solution`, the reference solution, and `pressure`, the barometric pressure in kPa of a dissolved oxygen point in water-saturated air (Section 15.5);
   - `result`, what the calibration computed (Section 14.5), when it computed one, and `previous`, the result it replaced, which is still in use after a failed or cancelled calibration: for the `nernst` model, `offset`, in mV, and `slope`, in %; for `linear`, `gain`, and `offset`, in the signal's unit;
   - `time`, when the calibration ended [OAP-DM Section 8.12];
   - `due`, when the next calibration falls due, once the controller has set it (item 4); and
   - in its `extensions["org.openaquariumproject.probe-calibration"]`, what belongs to a probe calibration alone: `probeType`; for a conductivity cell, `compensation`, its method and coefficient, `nominalCellConstant`, and, for total dissolved solids, `tdsFactor`; for dissolved oxygen in mg/L, `salinity`; `probe`, the maker, model, and serial number of the probe, where the port knows them; `device`, the maker, model, serial number, and endpoint of the device that calibrated it; and `shift` (Section 14.8.5).
3. A controller MUST record each calibration of a probe it controls, completed, failed, or cancelled, as a Data Model event of the type `calibration` [OAP-DM Section 8.6], whose `time` is when the calibration ended, whose `equipment` is the probe, or the device if the controller does not know the probe, and whose `calibration` is the port's record, with `shift` added.
4. After an accepted calibration, a controller MUST set `calibrationDue` to the time of completion plus the probe type's interval (Table 19), unless the owner has chosen another interval, and gives the record's `due` the same time. The port raises `calibration-due` when that time passes [OAP-DC Section 11.1].
5. Records belong to the owner, who can export them with the rest of their history [OAP-DM].

6. The record a port reports is the record a controller stores, and the record a smart probe keeps (Section 16.1), so its details are in the record's own extensions rather than the event's. The reference implementation's `record` function writes a record from a calibration's points and result, and its `compact` function reads one.
7. Revisions 0.2 and 0.3 of this Specification gave a record's time as `time` in its extension, because a Data Model Calibration Record had no `time` of its own before Data Model revision 0.4. A port that conforms to this revision MUST give `time` in the record itself, and MUST NOT give it in the extension. A controller SHOULD read the `time` in the extension of a record of revision 0.2 or 0.3 as the record's `time`.

14.10 Probe Condition and End of Life

1. A controller SHOULD show the condition of a pH electrode from its latest calibration (provisional):
   - **good:** slope from 95 % to 105 %, and offset within ±15 mV;
   - **clean it:** slope from 90 % to 95 %, or offset from ±15 mV to ±35 mV; cleaning often restores it;
   - **replace it soon:** slope from 85 % to 90 %; or
   - **replace it:** a calibration that fails its slope or offset after cleaning.

   These are the bands one maker of laboratory meters publishes.
2. A port with the `smart-probe` feature, and a controller for a probe whose calibrations it has recorded, SHOULD predict the end of a pH electrode's life, and report it as `probeEndOfLife` (port) or show it (controller). A controller SHOULD also record it as the `endOfLife` of the probe's Data Model Equipment [OAP-DM Section 8.3].
3. The prediction fits a straight line to the slope of each accepted calibration of the last 365 days, against time, by least squares. It needs at least three calibrations, spread over at least 30 days, and a falling slope. The end of life is the day the line reaches the lowest slope accepted, 85 %. The reference implementation's `end_of_life` function computes it.
4. A port SHOULD report `expired` when `probeEndOfLife` has passed.
5. pH electrodes usually last 12 to 18 months [USGS]; a prediction lets owners buy one before it is needed.

14.11 Checks

Table 18 — Calibration checks

Check	Presence	Applies to	What it requires	Section
Calibration sessions	REQUIRED	Devices	`beginCalibration` is refused while the port's clock is not valid, and otherwise starts afresh and makes every endpoint of the probe `calibrating`; readings keep updating; a calibration that ends, or that a restart interrupts, reports its record; `cancelCalibration` keeps the calibration in use.	14.2
Calibration points	REQUIRED	Devices	A port rejects points without a calibration, while readings are not stable, without a compensation temperature, outside the range of references, or beyond the maximum number, and replaces a point close to an earlier one.	14.2
Computing a calibration	REQUIRED	Devices	A port's results and readings agree with the test vectors.	14.5
Acceptance	REQUIRED	Devices	A calibration outside its limits is not applied, raises `calibration-failed` with its reason, and keeps the calibration in use; a port documents limits stricter than Table 19, and applies none looser.	14.6
Abandoned calibrations	REQUIRED	Devices	A calibration with no command for 1800 s is cancelled within 5 s, with the reason `timeout`.	14.2
Calibrations kept	REQUIRED	Devices	Calibrations survive power loss, restarts, and firmware updates.	14.2
Calibration before use	REQUIRED	Devices	A port implements `resetCalibration`, refuses it during a calibration, and clears `calibration-failed` with it; and a probe type that needs a calibration before use reports no `good` reading, and reports `calibration-due`, until it has one.	14.2

Check	Presence	Applies to	What it requires	Section
Calibration from the device	REQUIRED	Devices	A calibration started from a port's own control follows the same rules as one started by commands.	14.2
References at their temperature	REQUIRED	Controllers	A controller guides each calibration, proposes each reference's value at its temperature, compensated by the port's method for conductivity and converted to the electrode's reference for ORP, and writes the reference's temperature for compensation during the calibration.	14.4
Alarms during a calibration	REQUIRED	Controllers	A calibration holds the sound and notifications of only the `input-unavailable` alarms of its probe's inputs, and of a temperature probe put in its reference, never a critical one, and only until the calibration ends, which a controller also learns when the probe's endpoints stop reporting `calibrating`.	14.7
The calibration hold	REQUIRED	Controllers	A probe's inputs, and those of a temperature probe put in its reference, are unavailable from `beginCalibration`, or from when the controller asks for the temperature probe, or is told that it is there, until a person confirms the probe is back and its readings have been `good` and stable for the settle time.	14.8
The shift check	REQUIRED	Controllers	A calibration that moves the reading in the system by more than the probe type's shift keeps the hold until a person confirms the new reading, and the record holds the shift.	14.8
A restart during a calibration	REQUIRED	Controllers	A controller that finds an endpoint calibrating when it starts holds its inputs until a person ends the hold.	14.7
A device's own probe	REQUIRED	Devices	A device that controls equipment from its own probe treats the probe as unavailable during a calibration, and until a person confirms that it is back.	14.7
A probe after a fault	REQUIRED	Controllers	After `sensor-disconnected`, `hardware-failure`, or a loss of `good` ends, such as an electrode port's reading beyond its range, a controller holds the probe's inputs until their readings have been `good` and stable for the settle time; a conductivity or temperature port's reading beyond its range, which is `good`, starts no hold.	14.8
Calibration records	REQUIRED	Devices, controllers	A port implements `lastCalibration` and `calibrationDue`, and reports each calibration's record, with its `time`, as `lastCalibration`; a controller records it as a Data Model `calibration` event and sets `calibrationDue` and the record's `due`.	14.9
End of life	RECOMMENDED	Devices, controllers	The end of a pH electrode's life is predicted from its calibrations' slopes by Section 14.10.3.	14.10

15 Calibration Procedures

Table 19 summarizes each probe type's procedure, and Table 20 gives the values of common reference solutions. Both are published in `probe-types.json`. Every limit and interval is provisional.

Table 19 — Calibration procedures

Probe type	Points	One point corrects	Before use	References	Stable when	Accepted when	Interval	Shift
`ph`	1 to 3; 2 recommended	The offset	Calibrate first	pH 1 to pH 13, at least 2 pH apart	Change of at most 0.6 mV in 30 s	Slope 85 % to 105 %; offset −35 mV to 35 mV; every point within 0.05 pH of the line	30 days	0.2 pH
`orp`	1	The offset	May be used	−1000 mV to 1000 mV	Change of at	Offset −50 mV to 50 mV	90 days	50 mV

Probe type	Points	One point corrects	Before use	References	Stable when	Accepted when	Interval	Shift
					most 2 mV in 60 s			
`conductivity`	1 to 3; 1 recommended	The gain	Calibrate first	0 mS/cm or more	Change of at most 0.5 % in 30 s	Gain 0.8 to 1.25; zero at most 2.0 % of the largest true signal	90 days	3 %
`temperature`	1 to 2; 1 recommended	The offset	May be used	−5 °C to 60 °C, at least 10 °C apart	Change of at most 0.1 °C in 30 s	Gain 0.98 to 1.02; offset −1 °C to 1 °C	365 days	0.5 °C
`dissolved-oxygen`	1 to 2; 1 recommended	The gain	Calibrate first	0 mg/L or more	Change of at most 1 % in 60 s	Gain 0.7 to 1.4; zero at most 5.0 % of the largest true signal	30 days	10 %
`par`	1 to 2; 1 recommended	The gain	May be used	0 µmol/m²/s or more	Change of at most 1 % in 10 s	Gain 0.8 to 1.25; zero at most 2.0 % of the largest true signal	365 days	20 %

Table 20 — Reference solutions (informative: a solution's own table governs)

Solution	For	Values	Source
`iupac-phthalate`: Potassium hydrogen phthalate, 0.05 mol/kg	`ph`	15 °C: 3.998; 20 °C: 4.000; 25 °C: 4.005; 30 °C: 4.011	IUPAC
`iupac-phosphate`: Phosphate, 0.025 mol/kg KH2PO4 and 0.025 mol/kg Na2HPO4	`ph`	15 °C: 6.900; 20 °C: 6.881; 25 °C: 6.865; 30 °C: 6.853	IUPAC
`iupac-borax`: Disodium tetraborate (borax), 0.01 mol/kg	`ph`	15 °C: 9.276; 20 °C: 9.225; 25 °C: 9.180; 30 °C: 9.139	IUPAC
`iupac-carbonate`: Carbonate, 0.025 mol/kg NaHCO3 and 0.025 mol/kg Na2CO3	`ph`	15 °C: 10.118; 20 °C: 10.062; 25 °C: 10.012; 30 °C: 9.966	IUPAC
`technical-4`: Technical buffer pH 4.01	`ph`	15 °C: 4.00; 20 °C: 4.00; 25 °C: 4.01; 30 °C: 4.01	Typical; the maker's table governs
`technical-7`: Technical buffer pH 7.00	`ph`	15 °C: 7.04; 20 °C: 7.02; 25 °C: 7.00; 30 °C: 6.99	Typical; the maker's table governs
`technical-10`: Technical buffer pH 10.01	`ph`	15 °C: 10.12; 20 °C: 10.06; 25 °C: 10.01; 30 °C: 9.97	Typical; the maker's table governs
`zobell-3.5m`: ZoBell's solution, against Ag/AgCl in 3.5 mol/L KCl	`orp`	15 °C: 243 mV; 20 °C: 235 mV; 25 °C: 225 mV; 30 °C: 217 mV	USGS Tables 6.5–2 and 6.5–3
`zobell-saturated`: ZoBell's solution, against Ag/AgCl in saturated KCl	`orp`	15 °C: 246 mV; 20 °C: 239 mV; 25 °C: 231 mV; 30 °C: 224 mV	USGS Tables 6.5–2 and 6.5–3
`kcl-0.01`: Potassium chloride, 0.01 mol/L	`conductivity`	15 °C: 1147 µS/cm; 20 °C: 1278 µS/cm; 25 °C: 1413 µS/cm; 30 °C: 1552 µS/cm	Typical; the maker's table governs
`kcl-0.1`: Potassium chloride, 0.1 mol/L	`conductivity`	15 °C: 10.48 mS/cm; 20 °C: 11.67 mS/cm; 25 °C: 12.88 mS/cm; 30 °C: 14.12 mS/cm	Typical; the maker's table governs
`seawater-35`: Seawater standard, salinity 35	`salinity`	15 °C: 35 psu; 20 °C: 35 psu; 25 °C: 35 psu; 30 °C: 35 psu	PSS-78
`ice-point`: Ice and water	`temperature`	0 °C: 0.0 °C	Physics

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Solution	For	Values	Source
`saturated-air`: Water-saturated air	`dissolved-oxygen-saturation`	Computed or measured at the time	Section 15.5
`zero-oxygen`: Zero-oxygen solution	`dissolved-oxygen-saturation`	Computed or measured at the time	Section 15.5
`darkness`: Darkness	`ppfd`	Computed or measured at the time	Section 15.6
`reference-sensor`: A reference quantum sensor beside the sensor	`ppfd`	Computed or measured at the time	Section 15.6

15.1 pH

1. **Points.** Two points, which bracket the water's pH, are RECOMMENDED: pH 7 and pH 10 for marine water and for fresh water above pH 7; pH 4 and pH 7 for fresh water below pH 7. One point, at pH 7, corrects the offset only, and keeps the slope in use; it suits a check between two-point calibrations. Three points, at pH 4, 7, and 10, give one slope by least squares, and test the electrode's linearity.
2. **References.** IUPAC standard buffers [IUPAC pH] or technical buffers, at their value at their temperature (Section 14.4).
3. **Temperature.** Each point is fitted at its own temperature (Section 14.5.4), so buffers need not be warmed to the system's temperature; they SHOULD be between 15 °C and 30 °C.
4. **Limits.** Slope from 85 % to 105 %, offset within ±35 mV, references at least 2 pH apart, and, with three points, every point within 0.05 pH of the line [USGS].
5. **Interval.** 30 days. An owner whose electrode holds its calibration may choose a longer interval; the shifts in the calibration records show how far each calibration moved the reading (Section 14.9).
6. **Care.** An electrode SHOULD be kept wet, in its storage solution when it is out of the system, and SHOULD be cleaned as its maker says when its condition is "clean it" (Section 14.10).

15.2 ORP

1. **Points.** One point, which corrects the offset.
2. **References.** A commercial ORP standard, or ZoBell's solution, at its value against the electrode's reference system at its temperature. ZoBell's solution is 430 mV against the standard hydrogen electrode at 25 °C, which is about 225 mV against silver chloride in 3.5 mol/L potassium chloride, and 231 mV against silver chloride in saturated potassium chloride [USGS]. Table 20 gives its values at other temperatures from the same tables. A value given against another reference MUST be converted first.
3. **Stability.** ORP electrodes settle slowly in standards; readings are stable when they change by no more than 2 mV in 60 s.
4. **Limits.** Offset within ±50 mV. An electrode that needs more is dirty or failing; USGS accepts an electrode within 5 mV of a standard, and the US EPA within 10 mV [USGS] [EPA ORP].
5. **Interval.** 90 days.

15.3 Conductivity, Salinity, and Total Dissolved Solids

1. **Points.** One standard, close to the water's value, which corrects the gain: a seawater standard of salinity 35, or about 53.0 mS/cm at 25 °C, for marine water; 0.01 mol/L potassium chloride, 1413 µS/cm at 25 °C, for fresh water. A dry point first, with the clean cell dry in air and a reference of 0, also corrects the zero. Two standards, low and high, correct gain and offset.
2. **References.** For a salinity endpoint, the standard's salinity; for a conductivity endpoint, its conductivity compensated by the port's method (Section 14.4.4); for a total dissolved solids endpoint, that conductivity in µS/cm times the factor.
3. **Temperature.** The standard SHOULD be between 20 °C and 30 °C.
4. **Limits.** Gain from 0.8 to 1.25, so that the cell constant is within −20 % to +25 % of its nominal value, and a zero no larger than 2 % of the largest true signal.
5. **Interval.** 90 days. Salt creep, biofilm, and coralline algae on the electrodes change a cell's constant; a cell SHOULD be cleaned before it is calibrated.

15.4 Temperature

1. **Points.** One point, which corrects the offset: the probe beside a reference thermometer, both in stirred water near the system's temperature. The system's own water serves, without taking the probe out. A second point, at least 10 °C away, such as an ice point, also corrects the gain.
2. **References.** A thermometer whose uncertainty is 0.1 °C or less, such as a calibrated digital thermometer. An ice point is crushed ice from pure water, with enough pure water to fill the gaps, stirred: 0.0 °C [USGS].
3. **Limits.** Offset within ±1.0 °C; with two points, gain from 0.98 to 1.02. A larger offset means a fault, such as a two-wire probe on a very long cable, or a damaged element.
4. **Interval.** 365 days.

15.5 Dissolved Oxygen

1. **Points.** One point in water-saturated air, which corrects the gain: the probe held above a little water in a closed or shaded container, without touching it, at a steady temperature, until it is stable. A zero point first, in a fresh zero-oxygen solution, such as about 2 g of sodium sulfite in a litre of water, or with the maker's zero adapter, also corrects the zero; a probe should read no more than 0.2 mg/L in it [USGS].
2. **References.** In water-saturated air, at temperature t and barometric pressure P:
   - in %, 100 × C(t, 0, P) / C(t, 0, 101.325 kPa), about 100 × P / 101.325 kPa; and
   - in mg/L, C(t, S, P),

   where C(t, S, P) is the solubility of oxygen in mg/L at temperature t, salinity S, and pressure P, by [Benson] in the form of [USGS], and S is the salinity the port uses (Section 11.1.4). The reference implementation's `saturated_air_reference` function computes them.
3. **Pressure.** P is the barometric pressure where the probe is, not the pressure adjusted to sea level that weather reports give. Without a barometer, $P = 101.325\ \text{kPa} \times (1 - 2.25577 \times 10^{-5} \times h)^{5.25588}$, with h the altitude in metres.
4. **Limits.** Gain from 0.7 to 1.4, and a zero no larger than 5 % of the largest true signal.
5. **Interval.** 30 days for galvanic probes, whose membranes and electrolyte need regular care.
6. **Flow.** A galvanic probe uses up the oxygen next to its membrane, so it reads low in still water; it needs water moving past it, at about 0.3 m/s, in the system and in a zero solution [USGS].

15.6 PAR

1. **Points.** PAR sensors are calibrated by their makers. An owner can check one, and correct its gain, against a reference quantum sensor beside it in the same water, under steady light without effects. A point in darkness, with the sensor covered, corrects the zero.
2. **References.** The reference sensor's reading, with its own immersion factor (Section 11.2.4).
3. **Limits.** Gain from 0.8 to 1.25, and a zero no larger than 2 % of the largest true signal.
4. **Interval.** 365 days, as a check against a reference sensor. A sensor whose gain falls outside the limits goes back to its maker for calibration.

16 Smart Probes

A smart probe stores its own probe record, so that it keeps its identity and calibrations wherever it is plugged in. One aquarium maker's probes store their own calibrations, and laboratory and industrial instruments have used such probes for years.

16.1 Probe Records

A probe record has the members of Table 21. Its JSON form [RFC 8259] is `$defs/probeDocument` in `schema/probe-interface.schema.json`.

Table 21 — Members of a probe record

Member	Type	Presence	Description
`oapProbe`	string	REQUIRED	The revision of this Specification: `"0.4"`. A record of revision `"0.2"` or `"0.3"` has the same members, with calibration records that give their time in their extension (Section 14.9.7); one of revision `"0.1"` holds calibration records of that revision (Section 7.9).
`probe.type`	string	REQUIRED	The probe type (Table 3).
`probe.manufacturer`, `probe.model`, `probe.serialNumber`	string	REQUIRED	Who made the probe, its model, and its serial number, unique for the maker and model.
`probe.manufactured`	date	OPTIONAL	When the probe was made.
`probe.useBy`	date	OPTIONAL	The date by which the probe should be put into use, for electrodes that age on the shelf.
`probe.installed`	date	OPTIONAL	When the probe was first used.
`probe.endOfLife`	date	OPTIONAL	The probe's predicted end of life (Section 14.10).
`probe.nominal`	object	OPTIONAL	The probe's nominal characteristics: `slope` and `offset` for pH; `cellConstant` and `electrodes` for conductivity; `gain`, in the reading's unit per mV, for dissolved oxygen and PAR; and `reference`, the reference system of an electrode, as a Data Model reference electrode [OAP-DM Table 27]. A port without a smart probe takes the same members as its endpoints' `probeNominal`.
`probe.temperatureSensor`	string	OPTIONAL	The temperature sensor in the probe's body, if any.
`factory`	object	OPTIONAL	The maker's calibration, as a calibration record (Section 14.9).
`calibrations`	array	OPTIONAL	The probe's latest calibrations, oldest first, as calibration records; at most 8.
`extensions`	object	OPTIONAL	Extensions.

1. The calibration in use is the last completed calibration of `calibrations`, or, if there is none, `factory`.
2. A record keeps at most 8 calibrations, as one industrial smart-probe system does; when a ninth is added, the oldest is dropped. `factory` is never dropped.
3. How a record is stored in a probe's memory, and how it is protected against corruption, depends on the smart-probe connector, which this revision does not define (Section 16.6).

16.2 Reading a Probe

1. A port with the `smart-probe` feature MUST read a probe's record when the probe is connected, and when the port starts.
2. It MUST reject a record that fails its integrity check, or whose probe type the port does not accept, and then report `sensor-disconnected`.
3. It MUST use the record's calibration in use (Section 16.1.1), and report `probeSerialNumber`, `probeInstalled`, `probeEndOfLife`, `lastCalibrated`, and `lastCalibration` from the record.
4. When `probe.installed` is empty, it MUST write the current date, once it has a valid clock.
5. A probe whose record has no calibration in use, of a probe type that needs a calibration before use, is treated as Section 14.2.11 says.

16.3 Writing a Probe

1. A port MUST write an accepted calibration to the probe's record before it applies it. If it cannot, the calibration fails with the reason `probe`, so that a probe and its port never disagree about the calibration in use.
2. A port MAY also write failed calibrations, which help predict the end of life.
3. A port MUST NOT change `probe`, other than `installed` and `endOfLife`, or `factory`.

16.4 A Different Probe

1. When a smart probe is connected whose maker, model, or serial number differs from the last probe on the port, the port MUST NOT use the previous probe's calibration.

2. A controller that sees `probeSerialNumber` change MUST hold the probe's inputs as after a calibration (Section 14.8), until a person confirms the new probe, and SHOULD record the change as a Data Model event of the type `maintenance` [OAP-DM Section 8.6].

16.5 Probes Without Memory

1. A port keeps the calibration of a probe without memory, and cannot tell when the probe is replaced.
2. When a person tells a controller that a probe was replaced (Section 14.8.6), the controller MUST send `resetCalibration`, so that the new probe is not read with the old probe's calibration, and SHOULD record the change as a `maintenance` event. For a port that does not list `resetCalibration` among its optional elements [OAP-DC Section 7.2.4], such as one of an earlier revision, or that refuses it, the controller MUST instead hold the probe's inputs until a calibration of the probe is accepted.
3. A 1-Wire port knows each sensor's ROM code. It MAY declare the `smart-probe` feature, report the ROM code, in hexadecimal, as `probeSerialNumber`, and keep each sensor's calibration by its ROM code, so that it acts as Sections 16.2 and 16.4 say for the sensors it has seen. The calibration stays in the port, not in the sensor.

16.6 Connectors for Smart Probes

This revision defines what a smart probe stores, but not the connector through which a port reads it. A later revision may define one, once probe modules are built and makers of smart probes take part; the record is defined now, so that every smart probe agrees on what it stores (Appendix D, issue 1).

1. A connector with extra contacts could carry a memory chip, such as a 1-Wire memory, beside a probe's analog signal, as the paid standard [IEEE 1451.4] does; BNC has no room for it.
2. A smart probe could digitize its signal in its head, as one aquarium maker's smart probes and several industrial systems do. Such a probe is a device in its own right: a module on the module bus, or a device on a digital probe connector yet to be defined, that presents a `sensor` endpoint with the `smart-probe` feature, isolates its own probe from its power and data (Section 12), and follows Sections 14 to 16.
3. Until a connector is defined, a port MAY read records through a connector of its maker's choosing, and still conforms if it meets this section.

16.7 Checks

Table 22 — Smart probe checks

Check	Presence	Applies to	What it requires	Section
Reading a probe	REQUIRED	Devices	A port reads a smart probe's record when the probe is connected and at start, rejects a corrupt record or a wrong probe type, and uses the record's calibration and dates.	16.2
Writing a probe	REQUIRED	Devices	An accepted calibration is written to the probe before it is applied; a calibration that cannot be written fails with the reason `probe`; a record keeps at most 8 calibrations and its factory calibration, and the port changes nothing else of it but `installed` and `endOfLife`.	16.3
A different probe	REQUIRED	Devices, controllers	A port never uses one probe's calibration for another, and a controller holds a new probe's inputs until a person confirms it, and records the change.	16.4
Probes without memory	REQUIRED	Controllers	When a person says a probe without memory was replaced, a controller resets the port's calibration, or, for a port that does not list `resetCalibration` or refuses it, holds its inputs until a calibration, and records the change.	16.5

17 Fail-Safe Behavior and Alarms

17.1 Unavailable Probes

A probe's input is unavailable when its endpoint's `quality` is not `good`, or its endpoint reports `sensor-disconnected` or `hardware-failure` [OAP-FS Section 10.1], and so whenever:

- the probe is disconnected or faulty, or, on an electrode port, its reading is beyond the measuring range (Sections 7.3, 8.6, 9.7, and 10);
- it is being calibrated, or held after a calibration, a fault, or a reconnection (Sections 14.7 and 14.8);
- its compensation temperature is unavailable (Section 7.4); or
- it needs a calibration and has none (Section 14.2.11).

Functions that use it then apply their behavior for an unavailable input [OAP-FS Section 10.3]. A reading of a conductivity or temperature port beyond its measuring range is `good`, with its qualifier (Section 7.3.4), and starts no hold (Section 14.8.6). An input treats it as a limit for the comparisons that it decides, such as those of range alarms and interlocks, and as unavailable for anything else, such as a setpoint function [OAP-AU Section 9.2.2].

17.2 Readings That Look Good but Are Not

Some failures give readings a port cannot tell from real ones: a conductivity cell out of the water reads like RO/DI water, a pH electrode in air drifts slowly, and a probe of the wrong type may read a plausible value (Section 13.3).

1. A controller SHOULD warn when a reading is outside the values its system can have, such as a marine system's conductivity below 10 mS/cm, using the owner's danger ranges [OAP-AN Section 9].
2. Where a probe's failure could cause serious harm, a controller SHOULD use two probes, as Fail-Safe Behavior Section 10.4 recommends for heaters.
3. A reading that does not change at all for hours SHOULD be suspected; every real probe shows some noise.

17.3 Alarms

The faults a port reports, `sensor-disconnected`, `out-of-range`, `calibration-due`, `calibration-failed`, `expired`, and `hardware-failure`, become alarms with the default severities of the Alarms and Notifications specification [OAP-AN Section 8.4]. This Specification adds no condition codes.

18 Provisional Values

Table 23 gives the values of this Specification's limits and defaults that are not given for each probe type in Table 19. Every one is provisional, and they are published in machine-readable form in `checks.json`.

Table 23 — Provisional values

Area	Value	Provisional value	Kind	Why
Common requirements	Measurement interval	2 s	Limit	No reading a port reports is more than 2 s old, and a port that stops measuring is found within 6 s, when its reading goes stale.
Common requirements	Compensation write interval	60 s	Limit	Water temperature changes slowly; a write each minute, and on every change of 0.1 °C, keeps pH within 0.001 and conductivity within 0.2 %.
Common requirements	Compensation change	0.1 °C	Limit	0.1 °C changes a compensated conductivity by 0.2 %, and a pH one unit from 7 by 0.0003.
Common requirements	Compensation write delay	2 s	Limit	A change of 0.1 °C is written within 2 s, which allows for the controller's evaluation interval of 1 s.
Common requirements	Compensation maximum age	300 s	Limit	Five missed writes mean the controller is gone, not late.
Electrode ports	Electrode cable	5 m	Limit	Covers electrodes on long cables in a stand with a sump; commercial electrodes come with about 1 m to 3 m.
Conductivity ports	Short circuit	300 mS/cm	Limit	More than saturated brine conducts, so no water reads as much; a reading above it is a short across the cell.
Temperature ports	Temperature probe cable	5 m	Limit	The length breadboard test 7 measures; two-wire PT1000 leads of 5 m add about 0.2 °C, which calibration removes.

Area	Value	Provisional value	Kind	Why
Temperature ports	1-Wire disconnection	5 s	Limit	Two missed conversions at the recommended interval of 2 s, as a PT1000 port reports an open element.
Protection	Recovery	10 s	Limit	Long enough for a port to restart its converter after a discharge or a short, short enough that a function barely notices.
Calibration	Signal averaging	5 s	Limit	Averages out noise without hiding drift, which the stability check catches.
Calibration	Calibration timeout	1800 s	Default	Long enough for a three-point calibration with cleaning, short enough that a forgotten calibration ends the same session.
Calibration	Settle time	120 s	Default	pH electrodes settle within 1 to 2 minutes after moving between solutions, and other probes faster.
Smart probes	Calibrations kept	8	Limit	As one industrial smart-probe system keeps; eight monthly pH calibrations, more than the three that predict an electrode's end of life (Section 14.10).

19 Conformance

19.1 Ports

A conforming port:

1. is of one port kind, and meets Section 7 and its port kind's section (Sections 8 to 11);
2. if it is an electrode port or a conductivity port, meets Section 12;
3. meets Section 13;
4. implements calibration as Sections 14.2 to 14.6, 14.9.1, 14.9.2, and 15 define;
5. if it declares `smart-probe`, meets Section 16; and
6. passes the test procedures of Section 19.5 that apply to devices.

A device with conforming ports also meets the Device Classes and Fail-Safe Behavior specifications [OAP-DC Section 13.1].

19.2 Probes

A conforming probe meets Section 7.5 and the requirements for probes of its port kind's section, and, if it is a smart probe, Section 16.1. It passes the test procedures of Section 19.5 that apply to probes.

19.3 Controllers

A conforming controller:

1. writes compensation temperatures as Section 7.4 says;
2. guides calibrations, holds inputs and alarms, and checks shifts as Sections 7.1.5, 14.4, 14.7, and 14.8 say;
3. records calibrations as Section 14.9 says;
4. meets Section 16.4.2 and Section 16.5.2; and
5. passes the test procedures of Section 19.5 that apply to controllers.

19.4 Schema and Tools

- `probe-types.json` is normative for Tables 2, 3, 19, and 20, which are generated from it by `tools/render_spec_tables.py`; the values of Table 20 are informative.
- `checks.json` is normative for the checks, their test procedures, the other tests, and the provisional values; the check tables, Table 23, and Table 24 are generated from it, and the generator checks that every check has a test procedure, and that every MUST and MUST NOT of Sections 7 to 20 is checked by a test.
- `schema/probe-interface.schema.json`, a JSON Schema [JSON Schema], is normative for the structure of probe records (at its root), calibration records (`$defs/calibrationRecord`, with the Data Model schema), the

calibration records of revision 0.1 (`$defs/calibrationRecord01`), and test vectors (`$defs/vectors`). Where it and this document differ, this document governs.

- `tools/probe_reference.py` is a reference implementation of the computations of Sections 8.4, 9.4, 9.5, 10.2, 14.3 to 14.6, 14.8, 14.9, 14.10, and 15.5.
- `test-vectors.json` holds calibrations and conversions computed by it; Section 14.5.5 makes them normative for ports.
- `tools/validate_probe_interface.py` checks probe records, device descriptions of probe ports, Data Model documents with calibration records, and the test vectors. It recomputes every calibration record's result and outcome, and warns about choices this Specification advises against. It is informative.

```
python tools/validate_probe_interface.py specs/probe-interface/examples/*.json specs/probe-interface/test-vectors.json
```

19.5 Test Procedures

Tests of ports use a device with its ports, and the probes and instruments each test names. Tests of controllers use a controller with a simulated port whose readings, `quality`, faults, and records the tester can set. "Within 2 s" allows for the controller's evaluation interval of 1 s [OAP-AU Section 17.1]. Every check of Tables 4, 6, 9, 13, 15, 16, 18, and 22 has a test in Table 24, which follows the checks with tests of the other requirements. Each test names the requirements it checks, as sections or as numbered items of sections, and every MUST and MUST NOT of Sections 7 to 20 is checked by at least one test, which `tools/render_spec_tables.py` checks. A pass criterion that checks what a SHOULD asks applies to a product that does it.

Table 24 — Test procedures

Test	Applies to	Requirements	Method	Pass criteria
Endpoints (7.1)	Devices	7.1.1, 7.1.2, 7.1.3, 7.1.4, 7.2.1, 7.2.3, 7.3.6, 7.4.1, 7.9.1	Check the device's description with the validator. Then begin a calibration on the salinity endpoint of a conductivity port that also reports conductivity, and complete it. On a port that reads a pH or an ORP electrode, with its pH endpoint active, calibrate pH.	The validator reports no errors: every endpoint gives its `port`, the features its probe type requires, and a unit accepted for its parameter, and a port that reads pH or ORP has a `selectable` endpoint for each, one of them `active`. Both conductivity endpoints report `calibrating` during the calibration, and the same `lastCalibrated` and `lastCalibration` after it. The ORP endpoint's `lastCalibration` does not change when pH is calibrated.
Changing the active endpoint (7.1)	Controllers	7.1.5	On a port that reads a pH or an ORP electrode, bind its ORP endpoint to an input of a function, with ORP active. Plug in an ORP electrode in the sump, make the ORP endpoint active through the controller, and record when the input becomes available.	The input stays unavailable from the change until the ORP readings have been `good` and stable for 120 s.
Readings and quality (7.3)	Devices	7.3.1, 7.3.2, 7.3.5	Record a port's readings and `updated` for 10 minutes. Then begin a calibration; stop writing its external compensation temperature; reset the calibration of a pH port; and make each port report `sensor-disconnected` and `hardware-failure`, as its faults checks do.	`updated` advances at least every 2 s, and each endpoint reports `rangeMin`, `rangeMax`, and `resolution`. In each case that follows, `quality` is not `good`; after the reset, the port reports `calibration-due`.
Readings beyond the range (7.3)	Devices	7.3.3, 7.3.4	Take each port beyond its own measuring range, as its endpoint's `rangeMin` and `rangeMax` give it, by a tenth of the range's width: an electrode port's input, with a voltage source, to potentials that read beyond each end; a conductivity port, with	Each reading is reported with `out-of-range`, and with `qualifier` `>` and `value` the endpoint's `rangeMax` above the range, or `<` and its `rangeMin` below it. The conductivity and temperature readings have

Test	Applies to	Requirements	Method	Pass criteria
			precision resistors, beyond its `rangeMax`; a PT1000 port, with precision resistors, to the resistances of temperatures beyond each end; and a 1-Wire port, with a sensor emulator, to a temperature above its `rangeMax`, where the sensor can report one.	`quality good`; the electrode port's have not.
Compensation temperature (7.4)	Devices, controllers	7.4.3, 7.4.4, 7.4.5	Bind a pH endpoint with `compensationSource external` to a temperature input in the same sump, and record what the controller writes while the water warms by 1 °C. Unplug the temperature probe for 10 minutes, and plug it in again. Then stop the controller from writing.	The controller writes at least every 60 s, and within 2 s of each change of 0.1 °C. It writes nothing while the temperature input is unavailable, and the pH endpoint reports `stale` 300 s after the last write; it reports `good` again from its next reading after the controller writes again. 300 s after the controller stops writing, the pH endpoint reports `stale`.
Probes (7.5)	Probes	7.2.2, 7.5.1, 7.5.2	Inspect the probe, its connector, and its documentation. Immerse it to its greatest depth in artificial seawater, and measure at 500 V DC between the water and each contact of its connector that is not a measuring surface's.	The probe's connector is of a port kind Table 3 gives its type. No conductor of its cable or connector touches the water, and, for a temperature probe, each measurement is at least 100 MΩ (Section 10.4.1). The documentation gives every item of Section 7.5.2.
Documentation of ports (7.6)	Devices	7.6	Read the device's documentation, and compare it with its description and its ports.	Every item of Section 7.6 is given for every port, and agrees with the description.
Operating conditions (7.7)	Devices	7.7.1, 7.7.2	Repeat the input checks of each port at ambient temperatures of 0 °C and 40 °C, and the tests of computing pH, compensation, and PT1000 readings with the reference at 0 °C and at 40 °C.	Every check passes at each temperature.
BNC connector (8.1)	Devices	8.1.1, 8.1.3	Inspect the port and plug in a standard BNC plug. With the device unpowered, measure at 500 V DC between the port's shell and each other port's shell, the module bus contacts, and every exposed metal part.	The plug mates and locks. Every insulation resistance is at least 100 MΩ.
Input characteristics (8.2)	Devices	8.2.1	In a shielded box, connect a precision voltage source to the port directly, then through 100 MΩ, then through 1 GΩ. Step it from −1000 mV to +1000 mV in steps of 100 mV, recording 60 s at each step; then hold 400 mV for 24 h. Repeat at ambient temperatures of 0 °C and 40 °C.	Direct readings are within ±(0.1 mV + 0.2 %) and resolve 0.1 mV; readings through 1 GΩ are within 1 mV of the direct ones; through 100 MΩ, noise is at most 0.2 mV peak to peak, and each step settles within 0.5 mV within 5 s; the 24-hour drift is at most 0.2 mV.
No current through the electrode (8.3)	Devices	8.3.1, 8.3.3	Measure the current into the port with an electrometer for 10 minutes. Then record a pH electrode's readings in a pH 7 buffer for 10 minutes.	The average current is at most 1 pA. Any diagnostic signals are at least 60 s apart, and readings from 10 s after each are within 0.6 mV of those before it.
Computing pH (8.4)	Devices	8.4.2	With `compensationSource fixed`, and a voltage source in place of an electrode, run the pH calibrations of `test-vectors.json`, setting the compensation temperature of each point; then apply each reading's potential at its temperature.	Each reading is within its vector's tolerance of 0.005 pH.

Test	Applies to	Requirements	Method	Pass criteria
Computing ORP (8.5)	Devices, probes	8.5.1, 8.5.2	Calibrate an ORP endpoint with a source giving 215 mV and a reference of 225 mV. Then apply 100 mV, 400 mV, and −200 mV, at compensation temperatures of 15 °C and 30 °C. Read an ORP electrode's documentation.	The readings are 110 mV, 410 mV, and −190 mV, within ±(0.1 mV + 0.2 %), at both temperatures. The documentation names the electrode's reference as a reference electrode of Data Model Table 27.
Missing electrodes (8.6)	Devices	8.6.1	With a pH electrode in a pH 7 buffer, unplug it. Then plug in a 100 kΩ resistor. Then plug in a conductivity cell in seawater.	Each time, the port reports `sensor-disconnected` within 60 s, and no `good` reading after it.
Faults (8.6)	Devices	8.6.2, 8.6.3	Apply potentials that read beyond the endpoint's `rangeMax`, and then below its `rangeMin`, by a tenth of the range's width. Then make the port's converter stop responding, for example by holding it in reset.	The port reports `out-of-range`, with `qualifier >` and then `<`, and then `hardware-failure`, with no `good` reading in any case.
Cables (8.7)	Devices	8.7.1	Repeat the noise and settling tests of the input check with 5 m of coaxial electrode cable between the 100 MΩ source and the port, laid beside the cable of a running mains-powered aquarium pump.	Noise and settling meet Table 5.
Cell constants (9.1)	Devices	9.1.2, 9.1.4	Read the port's documentation. Connect 10 kΩ in place of the cell, with a fixed compensation temperature of 25 °C, and set the `cellConstant` of `probeNominal` to 1.0, and then to 10, for each that the port accepts.	The documentation gives each cell constant the port accepts, with its measuring range. The readings are 0.1 mS/cm with K = 1.0, and 1.0 mS/cm with K = 10, within the accuracy of Table 8.
BNC connector (9.2)	Devices	9.2.1, 9.2.2	As the electrode port's connector check.	As the electrode port's connector check.
Excitation (9.3)	Devices	9.3.1	In place of a cell, connect 100 Ω, 1 kΩ, 10 kΩ, and 100 kΩ in turn, and then nothing. Record the voltage across the port with an oscilloscope, and its average with a voltmeter through a low-pass filter.	In every case, the peak is at most 1 V, and the average at most 1 mV.
Accuracy (9.3)	Devices	9.3.1	For each documented cell constant K, connect precision resistors of K / κ for conductivities κ at 10 %, 50 %, and 90 % of each range, with the compensation temperature fixed at 25 °C.	Every reading is within ±(1 % of κ + 0.1 % of the range).
Compensation (9.4)	Devices	9.4.1	With a resistor in place of the cell, set the compensation temperature to 15 °C, 20 °C, 25 °C, and 30 °C, with `compensationMethod pss-78`, and with `linear` and a `compensationCoefficient` of 2.0.	Every reading is within 0.1 % of the reference implementation's `compensate` for the same conductivity and temperature.
Salinity (9.5)	Devices	9.5.1, 9.5.3	Apply the conductivities and temperatures of the salinity conversions of `test-vectors.json` with resistors and a fixed compensation temperature. Then apply a conductivity giving salinity 45.	Every salinity is within 0.01 of the vector. The endpoint's `rangeMax` is at most 42, and salinity 45 is reported with `out-of-range`, `qualifier >`, and `quality good`.
Total dissolved solids (9.6)	Devices	9.6.1, 9.6.3	Apply 500 µS/cm at 25 °C with `tdsFactor` 0.5 and 0.7. Read the port's documentation.	The readings are 250 mg/L and 350 mg/L, within 1 %. The documentation gives the default factor.

Test	Applies to	Requirements	Method	Pass criteria
Faults (9.7)	Devices	9.7.2, 9.7.3	Short the port. Then make its excitation or converter stop, for example by holding it in reset.	The port reports `sensor-disconnected` during the short, and then `hardware-failure`, with no `good` reading in either case.
M8 connector (10.1)	Devices, probes	10.1.1	Inspect the port and a probe of each kind, and measure which contacts of each probe's plug connect to its element or sensor.	The jack is an A-coded M8 jack of IEC 61076-2-104. The contacts are as Table 10 says; a two-wire PT1000 probe joins contacts 1 and 4.
PT1000 readings (10.2)	Devices	10.2.1, 10.2.2, 10.2.3	Connect precision resistors of the IEC 60751 resistances at −5 °C, 0 °C, 10 °C, 25 °C, 40 °C, and 60 °C, three-wire, first with short leads and then with 2 Ω in each lead; then two-wire, with contacts 1 and 4 joined. Measure the voltage across the resistor and the current through it.	Each reading resolves 0.05 °C and, from 0 °C to 40 °C, is within ±0.3 °C, and within ±0.1 °C after a one-point calibration at 25 °C; three-wire readings with 2 Ω leads are within 0.05 °C of those without, and two-wire readings are higher by the leads' resistance. The power in the resistor, averaged over a measurement interval, is at most 0.2 mW.
PT1000 open and short (10.2)	Devices	10.2.3	Disconnect the probe; then connect 2200 Ω; then 400 Ω; then short contacts 1 and 3.	Each time, `sensor-disconnected` within 5 s, and no `good` reading.
1-Wire readings (10.3)	Devices	10.3.1, 10.3.2, 10.3.3, 10.3.4, 10.3.5, 10.3.6, 10.3.7	Connect a probe whose sensor behaves as Section 10.3.1 says, on 5 m of cable, in water at 25 °C, and record its readings. Corrupt one reading's CRC with a sensor emulator, and then three in a row. Interrupt the sensor's supply for 10 ms while the port runs. Then remove the sensor; then short contacts 1 and 3 and measure the current.	The port reads the sensor's ROM code, and its readings resolve 0.0625 °C. The single corrupted reading is discarded; after three in a row, the port reports `sensor-disconnected`. 85.0 °C is never reported as `good`. Within 5 s of removal, the port reports `sensor-disconnected`. The supply is between 3.0 V and 5.5 V, and the short draws at most 20 mA.
Probe insulation (10.4)	Probes	10.4.1, 10.4.3	Immerse the probe to its greatest depth in artificial seawater for 24 h, then measure at 500 V DC between its joined contacts and an electrode in the water. For a PT1000 probe, measure its reading in stirred water at 0 °C and 40 °C against a reference thermometer.	At least 100 MΩ. A PT1000 probe's readings are within ±(0.3 + 0.005 ×
Withstand and insulation (12.3)	Devices	12.2.1, 12.3.1	With the device unpowered, join the contacts of each isolated domain, and the module bus contacts. Apply the withstand voltage for 60 s between each domain and every other, and between each domain and the bus; then measure insulation resistance at 500 V DC.	No breakdown, and every resistance at least 100 MΩ. The device then passes its other checks.
Barrier capacitance (12.3)	Devices	12.3	With the device unpowered, measure the capacitance between each domain's joined contacts and all the device's other contacts, joined.	At most 100 pF.
Probes in the same water (12.2)	Devices	12.2.1, 12.3.1	Put a pH electrode and an ORP electrode in stirred artificial seawater of salinity 35 at 25 °C, and record for 5 minutes. Then add a conductivity cell, measuring, on the same device, and record for 5 minutes more. This is breadboard test 6 [Breadboard].	pH changes by at most 0.02, and ORP by at most 2 mV, when the cell is added.

Test	Applies to	Requirements	Method	Pass criteria
Potentials in the water (12.2)	Devices	12.2.1, 12.3.1	With pH, ORP, conductivity, and temperature probes in stirred artificial seawater, put a titanium electrode in the water, and connect it through 1 kΩ to a source referred to the module bus ground: +24 V DC, then −24 V DC, then 10 V rms at 50 Hz, then at 60 Hz, for 5 minutes each.	Compared with the readings before, pH changes by at most 0.02, ORP by at most 2 mV, conductivity by at most 1 %, and temperature by at most 0.1 °C, and no fault is reported.
Wet surfaces (12.4)	Devices	12.4.2	Mount the device as intended, spray its underside and connectors with artificial seawater until a film covers the surface between the probe ports, and repeat the tests of probes in the same water and of potentials in the water. This is enclosure test 5 [Enclosure].	As in those tests.
The isolated feature (12.5)	Devices	10.5.2, 12.5	Compare the device's description with the ports that passed the isolation checks.	Every endpoint of a port that passed declares `isolated`; no other endpoint does, a temperature port that is not isolated among them.
Electrostatic discharge (13.1)	Devices	13.1.1, 13.1.2, 13.1.3	With probes connected and in water, and again with no probes, apply ten discharges of each polarity to each port's connector and to each mated probe's connector, by contact at 4 kV and through air at 8 kV, as IEC 61000-4-2 defines.	No reading is reported as `good` while it is wrong by more than the disturbance limits of Table 14; each port recovers within 10 s; the device does not restart, and its other endpoints keep working. Afterwards, every port passes its input checks and keeps its calibration.
Short circuits (13.2)	Devices	13.2.1, 13.2.3	Short each pair of contacts of each port for 1 hour, while the device's other ports measure.	During each short that Section 13.2.1 says the port can tell, the port reports `sensor-disconnected`, and no `good` reading; it works again within 10 s after the short. Other ports keep working. Nothing is damaged.
Wrong voltages (13.2)	Devices	13.2.2, 13.2.3	From a supply limited to 1 A, apply +30 V and −30 V DC between each pair of contacts of each port, and, for ports that are not isolated, between each contact and ground, for 1 hour each.	Other ports keep working throughout. Afterwards, every port passes its input checks.
The wrong probe (13.3)	Devices, probes	13.3.1, 13.3.2	Calibrate a pH electrode, then leave it in a conductivity port in seawater for 24 h, and calibrate it again. Plug a conductivity cell in seawater into a pH port. Plug a 1-Wire probe into a PT1000 port, and a PT1000 probe into a 1-Wire port, for 24 h each.	The pH electrode's second calibration is within 1 % of slope and 3 mV of offset of its first. The pH port reports no `good` reading from the cell if it implements Section 8.6.1. Both temperature ports report `sensor-disconnected`. Every probe and port then works normally.
Connecting while powered (13.4)	Devices	13.4.1, 13.4.2	With every port measuring probes in the same water, unplug and plug each probe 50 times.	The device does not restart. Other ports' readings stay within the disturbance limits of Table 14. Each probe's readings are `good` again only once stable, and, on an electrode port, within range.
Calibration sessions (14.2)	Devices	14.2.1, 14.2.2, 14.2.6, 14.2.7, 14.2.13	Begin a pH calibration on a port whose clock is not valid. Give it the time, begin, add a point, and begin again. Watch `value` and `updated` while moving the electrode between	The first begin is refused with bad state. The second begin discards the first point. `value` and `updated` keep changing during the calibration. After the

Test	Applies to	Requirements	Method	Pass criteria
			buffers. Add two points and cancel. Begin again, add a point, and restart the port.	cancel, readings use the calibration from before, `lastCalibrated` is unchanged, and `lastCalibration` is the cancelled calibration's record, with the reason `person`. After the restart, the calibration is not in progress, readings use the calibration from before, and `lastCalibration` is the interrupted calibration's record, cancelled with the reason `other`, with its point.
Calibration points (14.2)	Devices	14.2.4, 14.2.5	Send `calibratePoint` with no calibration in progress. Begin a pH calibration and send points: while the source ramps 1 mV every 10 s; with a reference of 13.5; with the external compensation temperature unwritten for 300 s; at 7.00 and then 8.00; and at 4.00, 10.00, and then 12.50.	Bad state, bad state, bad parameter, and bad state, in turn. The point at 8.00, no more than half the spacing of 2 pH from 7.00, replaces the one at 7.00. The point at 12.50 is rejected with bad state as a fourth point.
Computing a calibration (14.5)	Devices	14.5.1, 14.5.5	For each calibration of `test-vectors.json` of a probe type the port accepts, produce its points' signals with a source or simulator at their temperatures, and send their references; then produce each reading's signal.	Each reading is within its vector's tolerance, and the port's `lastCalibration` holds the vector's result, within it.
Acceptance (14.6)	Devices	14.2.6, 14.6.1, 14.6.2, 14.6.3	Calibrate pH with points that give a slope of 80 %; then an offset of 40 mV; then references of 7.00 and 8.50; then a good calibration. Read the port's documentation of its limits.	The first three are refused, with the reasons `slope`, `offset`, and `spacing`, readings use the earlier calibration, and `calibration-failed` is raised. The fourth is applied, `calibration-failed` clears, and `lastCalibrated` is its time. Any limits the port documents are no looser than Table 19′s.
Abandoned calibrations (14.2)	Devices	14.2.8	Begin a calibration, add a point, and send nothing for 1800 s.	The calibration is cancelled within 5 s after 1800 s, its record has the reason `timeout`, and readings use the calibration from before.
Calibrations kept (14.2)	Devices	14.2.10	Calibrate a port. Remove its power; restart it; update its firmware.	After each, the port reads with the same calibration, and reports the same `lastCalibrated` and `lastCalibration`.
Calibration before use (14.2)	Devices	14.2.6, 14.2.11	Check that each endpoint's description lists `resetCalibration` among its optional elements. Make a calibration of a pH port with a probe without memory fail. Send `resetCalibration` during a calibration, and after it; then calibrate the port.	Every endpoint lists `resetCalibration`. The reset during the calibration is refused with bad state. After the other, `calibration-failed` is cleared, `quality` is not `good`, and `calibration-due` is raised; after the calibration, readings are `good` and the fault clears.
Calibration from the device (14.2)	Devices	14.2.12	Calibrate a port that has a local control for calibration from that control, first with points outside the limits, and then with good points.	The first is refused with its reason and the calibration in use is kept; the second is applied. During each, `quality` is `calibrating`, and after each, `lastCalibration` holds its record.

Test	Applies to	Requirements	Method	Pass criteria
References at their temperature (14.4)	Controllers	14.4.5, 14.7.2, 15.2.2	Calibrate a pH port with a technical pH 10.01 buffer at 20 °C; a conductivity port with the `linear` method at 2.0 % per °C with 0.1 mol/L potassium chloride at 20 °C; a salinity port with a seawater standard of salinity 35 at 22 °C; and an ORP port whose electrode's reference is `ag-agcl-3.5m` with ZoBell's solution at 25 °C, labelled 231 mV against saturated silver chloride. Record what the controller shows and writes to `compensationTemperature`.	The controller shows the references to use, rinsing, the temperature probe in the reference, and when the readings are stable, and asks whether that temperature probe is one of the system's, and which. It proposes 10.06, 12.97 mS/cm, 35, and 225 mV. It writes 20 °C, 20 °C, and 22 °C during the calibrations, and the system's temperature after them.
Alarms during a calibration (14.7)	Controllers	14.7.5, 14.7.9	Bind a pH input to a function that drives a CO2 valve, with its `input-unavailable` alarm at `warning`, and a temperature input to a heater's function, with its alarm critical through the heater's equipment group. Calibrate the pH probe, and complete the calibration; wait 10 minutes before confirming that the probe is back. Then calibrate the temperature probe, and cancel it. During the pH calibration, raise another warning, such as `calibration-failed` of another probe. Then calibrate the pH probe again, with the system's temperature probe in the buffer, its alarm now at `warning`, and make the port stop reporting `calibrating` without reporting a record, as a port of an earlier revision may after a restart.	The pH input's alarm is raised, and its sound and notifications are held until the calibration completes, when it sounds and is notified, although the input stays unavailable until the hold ends. The temperature input's critical alarm sounds and is notified when it is raised. The other warning is not held. In the second pH calibration, the alarms of the pH input and of the temperature input are held until the pH endpoint stops reporting `calibrating`, and then sound and are notified.
The calibration hold (14.8)	Controllers	7.4.4, 14.7.4, 14.7.8, 14.8.2	Bind a pH input to a function that drives a CO2 valve. Calibrate the pH port; after completing, wait 10 minutes before confirming that the probe is back. Repeat, cancelling instead of completing. Then bind the system's temperature probe to a heater's function, and to the compensation of the pH port and of a conductivity port, with `compensationSource external`; calibrate pH, putting that probe in the buffer when the controller asks, and confirm that both probes are back 10 minutes after completing. Then calibrate pH with a controller that does not ask for a temperature probe of the system, put that probe in the buffer, and tell the controller which probe it is.	The valve takes its unavailable-input behavior at `beginCalibration`, and resumes only 120 s after the confirmation, with the readings stable and `good`. The same happens after the cancellation. The heater takes its unavailable-input behavior from when the controller asks for the temperature probe until its readings have been `good` and stable for 120 s after the confirmation; meanwhile the controller writes the buffer's temperature only to the pH port, and no temperature to the conductivity port. In the last calibration, the heater takes its unavailable-input behavior from when the controller is told, in the same way.
The shift check (14.8)	Controllers	14.8.3, 14.8.5	With the sump reading pH 8.12 before a calibration, simulate readings after it of 8.19; then, in a second calibration, of 8.45.	After the first, the hold ends after the settle time. After the second, it continues until a person confirms 8.45, and the controller shows both readings. Both records hold `shift`, the second with `confirmed true`.
A restart during a calibration (14.7)	Controllers	14.7.6	Restart the controller in the middle of a pH calibration, and complete the calibration from the port's local control, or let it time out.	The pH input stays unavailable until a person confirms the probe is back, and for the settle time after.

Test	Applies to	Requirements	Method	Pass criteria
A device's own probe (14.7)	Devices	14.7.7	Calibrate the probe of a heater that controls itself from its own probe, complete the calibration, and do not confirm that the probe is back for 10 minutes.	The heater applies its behavior for an unavailable probe from the start of the calibration until the confirmation.
A probe after a fault (14.8)	Controllers	14.8.6	Unplug a pH electrode for 5 minutes, and plug it back in while it is still in a pH 4 buffer; after 2 minutes, put it in the sump. Then make the port report `hardware-failure` for 10 s. Then stop writing its compensation temperature until it reports `stale`, and write it again. Then take a temperature port's reading above its `rangeMax` for 5 minutes, and back within its range.	The input stays unavailable while the electrode is in the buffer and its readings settle, and becomes available only after its readings in the sump have been stable for 120 s; the controller asks whether the probe was replaced. After the fault and after the stale compensation temperature, the input becomes available only 120 s after the readings are `good` and stable again. The temperature input is not held when its reading returns within the range.
Calibration records (14.9)	Devices, controllers	14.9.1, 14.9.2, 14.9.3, 14.9.4, 14.9.7	Check that each endpoint's description lists `lastCalibration` and `calibrationDue` among its optional elements. Run a completed, a failed, and a cancelled calibration. Read `lastCalibration` after each, export the controller's history, and check both with the validator.	Every endpoint lists both. Each record is valid, gives its `time` itself rather than in its extension, and its result and outcome agree with its points; after the failed and cancelled ones, `previous` is the result in use. The history has three `calibration` events whose `calibration` is the record, with `shift`. `calibrationDue`, and the completed record's `due`, are its time plus the probe type's interval.
End of life (14.10)	Devices, controllers	14.10.2, 14.10.3	Calibrate a pH port, with a source, to slopes of 99 %, 97 %, 95 %, and 93 % on 15 January, 15 March, 15 May, and 15 July.	`probeEndOfLife`, or the date the controller shows and records as the probe's `endOfLife`, is within 1 day of the reference implementation's `end_of_life`, and the port reports `expired` once that date has passed.
Reading a probe (16.2)	Devices	16.2.1, 16.2.2, 16.2.3, 16.2.4	Connect a smart pH probe calibrated on another port. Then connect one whose record is corrupt; one whose record is for a conductivity cell; and a new one with no `installed` date. Restart the port with the first probe connected.	The first reads with its own calibration, and the port reports its serial number, dates, `lastCalibrated`, and `lastCalibration`, before and after the restart. The corrupt and the wrong probes give `sensor-disconnected`. The new probe's record has the date it was connected as `installed`.
Writing a probe (16.3)	Devices	16.3.1, 16.3.3	Calibrate a smart probe nine times; then calibrate it with its memory write-protected. Compare the record's `probe` and `factory` before and after.	After nine, its record holds the latest eight and its factory calibration. The write-protected calibration fails with the reason `probe`, and the port keeps the calibration in use. `probe`, apart from `installed` and `endOfLife`, and `factory` are unchanged.
A different probe (16.4)	Devices, controllers	16.4.1, 16.4.2	Swap one smart pH probe for another on a port whose input drives a CO2 valve.	The port reads the new probe with its own calibration. The input is unavailable until a person confirms the new probe, and for the settle time after; the history has a `maintenance` event.

Test	Applies to	Requirements	Method	Pass criteria
Probes without memory (16.5)	Controllers	16.5.2	Unplug a pH electrode without memory, plug in another, and tell the controller that it was replaced. Repeat on a port that does not list `resetCalibration` among its optional elements, and on one that refuses it.	The controller sends `resetCalibration`, so the port reports `calibration-due` and no `good` reading, and records a `maintenance` event. On each of the other two ports, the input stays unavailable until a calibration of the probe is accepted.
Dissolved oxygen readings	Devices	11.1.2, 11.1.3, 11.1.4	On an electrode port that reports dissolved oxygen, with a millivolt source in place of a galvanic probe, set `compensationSalinity` to 0, and calibrate in water-saturated air at 25 °C and 101.325 kPa with the source at 40 mV. Then apply 20 mV at 25 °C. Then set `compensationSalinity` to 35. Read the port's documentation.	The documentation lists the probes the port supports. With 20 mV, the port reports 50 % saturation, and, if it reports mg/L, half of the reference implementation's `oxygen_solubility` at 25 °C and salinity 0, then at salinity 35, within 1 %.
PAR readings	Devices, probes	11.2.3, 11.2.4	Give a PAR endpoint's `probeNominal` a `gain` of 125 µmol/m²/s per mV, the factor in air of 100 of a sensor under water, times its immersion factor of 1.25, and apply 2.00 mV. Read the sensor's documentation.	The port reports 250 µmol/m²/s, within ±(1 % + its resolution). The documentation gives the sensor's factor in air and its immersion factor.

20 Security Considerations

1. **Calibration changes every reading.** A calibration changes what every function that uses a probe does, so it needs the `calibrate` operation, which is audited [OAP-SA Table 6].
2. **A false calibration.** A person with `calibrate` can enter false reference values. The acceptance limits bound what such a calibration can do, and the shift check makes a person look at a large change (Sections 14.6 and 14.8), but within those limits a pH reading can be moved by up to about 0.5 pH. A controller SHOULD show the calibration history, so that an owner can see who calibrated what, and when.
3. **Remote calibration.** A calibration needs a person at the probe, so a controller SHOULD NOT let the shift of Section 14.8 be confirmed by someone who is not at the system, and SHOULD say so when it is confirmed remotely.
4. **Probe records are not authenticated.** A record can be copied to another probe, or forged. A port checks a record's integrity and limits, but cannot tell a counterfeit probe, because this revision does not sign records.
5. **Physical access.** Anyone who can reach the probes can move, swap, or unplug them; the faults and holds of Sections 14.8 and 16.4 make this visible, but cannot prevent it.
6. **Privacy.** Calibration records show how an owner looks after their system, and SHOULD be treated as the owner's data.

Appendix A — Approval Checklist

Complete this checklist before requesting Working Group approval. Link each item to the evidence.

Item	Status	Details
Section 2 describes compliance with all five tenets.	Done	
A public review period of at least 30 days has been announced and completed.	Not started	
At least two independent implementations exist, at least one from an organization not represented among the Authors.	Not started	

Item	Status	Details
The implementations have passed the test procedures in Section 19.5, including a probe port and a controller.	Not started	
A probe calibrated on one implementation's port reads within its accuracy on another's, and a smart probe's record written by one is read by another.	Not started	
Breadboard tests 6 and 7 are done, and the provisional values of Sections 8 to 13 are confirmed or changed.	Not started	
Every normative reference is publicly available.	Done	The IEC standards are available for purchase; all others are free.
The probe types file, checks file, schema, test vectors, and examples are published, and pass the validator.	Done	
Every MUST and MUST NOT is checked by a test procedure.	Done	Section 19.5.
Experienced aquarists have reviewed the calibration procedures, limits, and intervals.	Not started	
The Open Issues appendix is empty, or each open issue is explicitly deferred.	In progress	Issues 2 and 27 wait on the bench tests, and issues 12, 28, and 30 on the bench tests and owners' experience; issues 13 to 22 are deferred beyond revision 1.0.
No unresolved Exclusion Notices for this Specification are recorded in `Notices.md`.	Done	
The Maintainer has recorded consensus to approve.	Not started	

Appendix B — Examples (Informative)

The `examples` directory contains:

- `probe-module.json`: the device description of an isolated probe module, of Device Classes revision 0.3, with a pH port, a port that reads an ORP or a pH electrode, a conductivity port that reports salinity and conductivity, and a PT1000 port, each with its `port`, `probeNominal`, compensation, and `resetCalibration`.
- `calibration-history.json`: a Data Model document with a reef's probes as equipment, and the calibration records of a two-point pH calibration with a shift the owner confirmed, a failed pH calibration with an old buffer, an ORP calibration, a salinity calibration with a seawater standard, and a temperature calibration against a reference thermometer; and an ORP reading with its reference electrode.
- `smart-ph-probe.json`: the probe record of a smart pH electrode, with its factory calibration and five calibrations over eight months, whose slopes predict its end of life.

Appendix C — Commercial Features (Informative)

How the probe features of commercial controllers correspond to this Specification.

Table 25 — Commercial features

Feature	In this Specification
BNC ports that take pH or ORP electrodes	Electrode ports (Section 8), with an endpoint for each parameter and the `selectable` feature (Section 7.1.1).
Galvanically isolated probe inputs	Required for electrode and conductivity ports, with ratings and tests (Section 12).
Conductivity and salinity, in several ranges, with seawater and fresh water modes	Conductivity ports with cell constants 0.1 to 10, and the `pss-78` and `linear` compensation methods (Section 9).
Thermistor, PT1000, and digital temperature probes	PT1000 and 1-Wire ports; thermistors are not covered (Section 10).
Galvanic dissolved oxygen probes on BNC	Electrode ports (Section 11.1).
PAR sensors	Millivolt sensors on electrode ports (Section 11.2).
Guided calibration, with one, two, or three pH points	Sections 14 and 15.

Feature	In this Specification
Calibration in water-saturated air and with a zero adapter	Section 15.5.
Probes that store their calibration and calibration history, and predict their end of life	Smart probes (Section 16) and the prediction of Section 14.10.
Probes that digitize in their heads, with a common digital interface	Smart probes as devices (Section 16.6); a digital connector is left to a later revision (Appendix D, issue 1).

Appendix D — Open Issues (Informative)

Issues 1 to 22 were open in revision 0.1. The Project Lead decided issues 23 to 26 on 15 October 2026. Issues 27 to 30 arose in revision 0.2. Issues 31 to 34 came from the breadboard firmware, and the Project Lead decided them on 17 October 2026; revision 0.3 applies the decisions. On 17 October 2026 the Project Lead also froze the scope of revision 1.0, and decided issues 1 and 3 to 6; revision 0.4 applies the decisions, and resolves issue 29, which the Data Model specification settles. Issue 35 records the choices that revision 0.4 made where those decisions left them open, which the Project Lead accepted on 18 October 2026. Issues 13 to 22 are deferred beyond revision 1.0, and are tracked outside this Specification. Issues 2 and 27 stay open until the bench tests, and issues 12, 28, and 30 until the bench tests and owners' experience confirm their numbers. Each issue says how a revision resolves it, or why it stays open. Issue numbers do not change, because other specifications refer to them.

Questions for the Project Lead

1. **A digital connector for smart probes, now or later.** *Resolved in revision 0.4, as the Project Lead decided on 17 October 2026: later.* Revision 0.1 defined the probe record (Section 16.1), but no connector to read it through (Section 16.6). The alternatives were to define one now, such as a connector with a memory chip beside the analog signal, or a digital connector to probes that digitize in their heads, or to define one later, once probe modules are built and makers of smart probes take part. A connector is left to a later revision: the market is moving to probes that digitize in their heads, which the module bus can already carry as devices, and a connector chosen before any is built would likely be wrong. The probe record stays defined, so that every smart probe agrees on what it stores (Section 16.6).
2. **PT1000, 1-Wire, or both.** *Open: it waits for breadboard test 7.* Both are provisional (Section 10.1). Breadboard test 7 will compare them. The recommendation is to keep both if the test shows no problem with either: PT1000 for accuracy and a standard element, 1-Wire for its low cost and its identity.
3. **BNC for conductivity cells.** *Resolved in revision 0.4, as the Project Lead decided on 17 October 2026: BNC, provisionally.* BNC is used by two widely used commercial controllers, and lets one cable and one connector serve every probe in the water, but it is shared with electrode ports, so a cell can go into the wrong port; Section 13.3 makes that harmless, but not always detectable. A distinct connector, such as the four-pin Mini-DIN one a third uses, would key ports by function, as Proposal 0001 asks [P0001], and carry a temperature sensor and four electrodes, at the cost of a connector no other maker shares. A conductivity port is a BNC jack (Section 9.2.1), which stays provisional, because a connector for cells with temperature sensors and four-electrode cells, which BNC cannot carry, is deferred beyond revision 1.0.
4. **The temperature connector.** *Resolved in revision 0.4, as the Project Lead decided on 17 October 2026.* No temperature connector is shared across makers (Section 10.1). A temperature port is the M8 three-contact connector that the reference enclosure already uses for sensor inputs [Enclosure], with the contacts of Table 10, which make a probe of either temperature kind harmless in a port of the other (Section 10.1.1). Revision 0.4 no longer marks the connector or its contacts provisional.
5. **Calibration before use.** *Resolved in revision 0.4, as the Project Lead decided on 17 October 2026: unchanged.* Section 14.2.11 keeps pH, conductivity, and dissolved oxygen readings from being `good` until the probe is calibrated, because a new pH electrode can read several tenths of a pH off. Owners may expect a new probe to work at once; the alternative was a port that uses the nominal values until the first calibration, with a fault. The rule stays, and is no longer provisional. A controller shows such readings, marked as not calibrated, so that the owner sees the probe working (Section 14.7.10).

6. **A person's confirmation after every calibration.** *Resolved in revision 0.4, as the Project Lead decided on 17 October 2026: unchanged.* The calibration hold ends only when a person confirms that the probe is back (Section 14.8). This prevents a probe in a buffer from steering CO2 or ozone, but a person who forgets leaves those functions stopped. The alternative was a hold that ends by itself after a longer time, such as 30 minutes of stable readings in the range the system had before. The confirmation stays: a forgotten confirmation leaves CO2 and ozone stopped, which fails safe, and the alarms that the hold released when the calibration ended remind the owner (issue 23). From revision 0.4, the same confirmation ends the hold of a temperature probe put in the reference (Section 14.7.8), whose heater and chiller functions apply their behavior for an unavailable input meanwhile, and whose alarms also remind the owner.

For other specifications

7. **Device Classes.** *Resolved in revision 0.2.* The `sensor` class needed: ports that read either pH or ORP; the calibration record as a state attribute; configuration attributes for a probe's nominal characteristics, its compensation method and coefficient, the factor for total dissolved solids, and the salinity used for dissolved oxygen; a `solution` for `calibratePoint`; a stale external compensation temperature; and the meanings of `isolated` and `smart-probe`. Device Classes revision 0.2 answers each with `port` and the `selectable` feature, `lastCalibration`, `probeNominal`, `compensationMethod`, `compensationCoefficient`, `tdsFactor`, `compensationSalinity`, `calibratePoint`'s `solution`, and the meanings asked for (its Section 11.1 and Appendix D, issues 22 and 25); its revision 0.3 gives `compensationCoefficient` the unit `%/degC` (its Appendix D, issue 30). This revision uses them, and keeps the provisional names only for reading devices of Device Classes revision 0.1 (Section 7.9).
8. **Data Model.** *Resolved in revision 0.2.* The Data Model needed structured calibration records, the reference electrode of an ORP reading, the reference temperature of specific gravity, and a probe's predicted end of life. Data Model revision 0.2 answers these with Calibration Records, a Method's `referenceElectrode` and `referenceTemperature`, and an Equipment's `endOfLife` (its Sections 8.3, 8.4, and 8.12), and its revision 0.3 adds the reference electrode `ag-agcl-3.5m`, so that one vocabulary of reference electrodes serves both specifications. A calibration record is now a Data Model Calibration Record, with only what belongs to probes in its extension (Section 14.9); ORP readings name their reference electrode (Section 8.5.3); and a predicted end of life is recorded on the probe's equipment (Section 14.10.2).
9. **Alarms and Notifications.** *Resolved in revision 0.2, with Alarms and Notifications revision 0.2.* `input-unavailable` for an input whose probe is being calibrated is expected, and its notifications held, as during a maintenance mode. Alarms and Notifications revision 0.2 says so, with the limits that issue 23 decided (its Sections 12.8.6 and 12.8.7, and Appendix D, issue 27), and Section 14.7.5 follows it.
10. **Automation.** *Resolved by Automation revision 0.2.* The calibration hold (Section 14.8) is a cause of an unavailable input that Automation inputs should name, so that a controller can show why a function stopped. Automation revision 0.2 names it (its Section 9.8.6, and Appendix D, issue 28).
11. **Reference firmware.** *Resolved in the reference firmware.* The breadboard firmware's pH calibration fitted three points as two segments, accepted slopes from 80 % to 125 % of the probe's factory slope, offsets up to 1.5 pH, and references 1 pH apart [Firmware]. It now computes pH from the electrode's potential as Section 8.4 says, and calibrates with the model, limits, and records of Sections 14 and 15.1, checked against the test vectors (Section 14.5.5).

Details of this Specification

12. **Numbers.** *Open: to be confirmed with the breadboard, the first probe module, and owners' experience.* Every value marked provisional, especially the input characteristics of Tables 5, 8, and 11, the ratings of Table 14, the protection levels of Section 13, the values of Table 23, and the limits and intervals of Table 19, needs confirming.

Decided by the Project Lead

23. **Alarms during a calibration hold.** *Resolved in revision 0.2.* The Project Lead decided on 15 October 2026 that the hold of Section 14.7.5 never holds critical alarms, and that it ends when the calibration ends (Alarms and Notifications Appendix D, issue 27). Section 14.7.5 now says so: a controller holds only the `input-unavailable` alarms of the probe's inputs, never a critical one, from `beginCalibration` until the

calibration ends, completed, failed, cancelled, or timed out, and then sounds those still active. The inputs stay unavailable until the calibration hold ends (Section 14.8), which issue 6 is about.

24. **Isolation of temperature ports.** *Resolved in revision 0.2.* The Project Lead decided on 15 October 2026 that a temperature port may rely on the probe insulation of Section 10.4.1 instead of galvanic isolation, and that Section 10.5.1 keeps its recommendation. Sections 10.4.1, 10.5.1, and 12.1 now say so, and Section 2.4 says that electrode inputs, for pH, ORP, and conductivity, are isolated.
25. **The name 1-Wire.** *Resolved in revision 0.2.* The Project Lead decided on 15 October 2026 that "1-Wire" may be named, as a protocol. Section 10.3.1, its check, and its test now describe the behavior a sensor needs: its ROM code, its commands, its scratchpad, its CRC, and its value at start-up, rather than a family code.
26. **Readings beyond the measuring range.** *Resolved in revision 0.2.* The Project Lead decided on 15 October 2026 that conductivity and temperature ports, which can tell a working probe from a missing one, report a reading beyond the measuring range as `good`, with a `qualifier`, so that range alarms and interlocks act on it (Automation Section 9.2.2; Alarms and Notifications Section 9.3.5), and that pH and ORP readings beyond the range are not `good`, because an unplugged electrode reads off scale. Section 7.3 now says so, and Sections 8.6.2, 9.5.3, 9.7.2, 10.2.5, 13.2.1, 13.4.2, and 17.1 follow it. Revision 0.2 treats dissolved oxygen and PAR readings, which also come from electrode ports, as pH and ORP readings, provisionally (issue 27); and it reports a short circuit across a conductivity cell, which reads more than any water conducts, as `sensor-disconnected` rather than as a reading (Section 9.7.2).

The following issues arose in revision 0.2:

27. **Dissolved oxygen and PAR beyond the range.** *Open: it waits for the bench tests.* Issue 26 decided how conductivity, temperature, pH, and ORP ports report readings beyond their range, but not dissolved oxygen and PAR. Revision 0.2 treats them as readings of an electrode port, which are not `good` beyond the range (Section 7.3.4), because an unplugged millivolt sensor reads 0 mV, or drifts. A galvanic oxygen probe or a PAR sensor in strong light can read above its range while working; treating such readings as conductivity readings would let range alarms act on them. The recommendation is to keep revision 0.2's rule until bench tests show whether a port can tell a missing sensor from a reading beyond its range.
28. **Holds after faults.** *Open: the settle time waits for the bench tests and owners' experience.* Section 14.8.6 now holds a probe's inputs, for the settle time, after any fault or loss of `good`, not only after `sensor-disconnected`, so that a probe that a fault interrupted is not trusted at once. The hold delays a function's return by at least 120 s after every glitch, such as a compensation temperature that went stale while the controller restarted. Bench tests and owners' experience should show whether a shorter settle time suffices after faults that did not involve the probe.
29. **A time in Data Model Calibration Records.** *Resolved in revision 0.4, with Data Model revision 0.4.* A Data Model Calibration Record took its time from its event, but `lastCalibration` and a probe record hold records without an event, so revisions 0.2 and 0.3 gave each record its time in its extension. Data Model revision 0.4 adds an optional `time` to Calibration Records, for records that no event holds [OAP-DM Section 8.12]. Revision 0.4 gives each record its time there, in place of the extension (Section 14.9.2), and a controller reads the time of an older record from its extension (Section 14.9.7).
30. **Short circuits on conductivity ports.** *Open: the threshold waits for the bench tests.* Section 9.7.2 reports a reading above 300 mS/cm as a short circuit, because no aquarium water, and not even saturated brine, conducts that much. A port with a cell of K = 0.1 or 1.0 cannot reach 300 mS/cm within its range; bench tests should show whether the threshold should depend on the cell constant.
31. **Calibrating without a valid clock.** *Resolved in revision 0.3, as the Project Lead decided on 17 October 2026.* A record needs its time (Section 14.9.2), so a port whose clock is not valid cannot make a valid one. Revision 0.3 has such a port refuse `beginCalibration` (Section 14.2.1).
32. **A restart during a calibration.** *Resolved in revision 0.3, as the Project Lead decided on 17 October 2026.* Revision 0.2 did not say what a port does when it restarts during a calibration, so a controller could hold alarms for a calibration that had already ended. Revision 0.3 ends it as cancelled, with the reason `other`, and has the port report its record (Section 14.2.13).
33. **Resetting after a failed calibration.** *Resolved in revision 0.3, as the Project Lead decided on 17 October 2026.* Revision 0.2 kept `calibration-failed` until a calibration was accepted, even after

`resetCalibration`, and did not say what a reset during a calibration does. Revision 0.3 clears the fault with the reset, and refuses a reset during a calibration (Section 14.2.11).

34. **The resolution of an electrode port.** *Resolved in revision 0.3, as the Project Lead decided on 17 October 2026.* Table 5 asked for 0.01 mV, about 0.0002 pH, far finer than an aquarium's pH needs and than common measuring circuits for electrodes report. Revision 0.3 asks for 0.1 mV, about 0.002 pH (provisional).

The following issue records the choices of revision 0.4:

35. **Choices of revision 0.4.** *Resolved in revision 0.4: the Project Lead accepted each choice on 18 October 2026.* Revision 0.4 made these choices where the decisions and findings it applies left them open:
    - a temperature probe that the controller asks for in the reference is held until a person confirms that it is back, as the calibrated probe is, with its alarms that are not critical held during the calibration, rather than released when its readings return to the system's range (Section 14.7.8);
    - a controller also treats a calibration as ended when no endpoint of the probe reports `calibrating` any more, so that a calibration that a port lost never keeps alarms held (Section 14.7.9);
    - the tests of readings beyond the range drive each port beyond its own range by a tenth of the range's width (Table 24);
    - a port of revision 0.4 gives a record's `time` only in the record itself, and a controller reads the time of an older record from its extension (Section 14.9.7);
    - a conductivity port's BNC jack stays provisional, because a connector for cells with temperature sensors and four-electrode cells is deferred (Section 9.2.1); and
    - a controller shows the readings of a probe that needs a calibration before use and has none, marked as not calibrated (Section 14.7.10).

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