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Prototype Fast Breeder Reactor Monju
Sector of Fast Reactor Research and Development

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Japan Atomic Energy Agency
日本原子力研究開発機構

国立研究開発法人日本原子力研究開発機構 研究連携成果展開部 研究成果管理課
〒319-1195 茨城県那珂郡東海村大字白方 2 番地4
電話 029-282-6387, Fax 029-282-5920, E-mail:ird-support@jaea.go.jp

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Verification of Alternative Dew Point Hygrometer for CV-LRT in MONJU
—Short- and Long-term Verification of Capacitance-type Dew Point Hygrometer—
(Translated Document)

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Plant Maintenance Engineering Department
Prototype Fast Breeder Reactor Monju
Sector of Fast Reactor Research and Development
Japan Atomic Energy Agency
Tsuruga-shi, Fukui-ken

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To reduce the influence of maintenance of dew point hygrometers on the plant schedule at the prototype fast-breeder reactor MONJU, Japan Atomic Energy Agency examined a capacitance-type dew point hygrometer as an alternative to the lithium-chloride dew point hygrometer being used in the containment vessel leak rate test. As verifications, a capacitance-type dew point hygrometer was compared with a lithium-chloride dew point hygrometer under a containment vessel leak rate test condition. And the capacitance-type dew point hygrometer was compared with a high-precision-mirror-surface dew point hygrometer for long-term (2 years) in the containment vessel as an unprecedented try.

A comparison of a capacitance-type dew point hygrometer with a lithium-chloride dew point hygrometer in a containment vessel leak rate test (Atmosphere: nitrogen, Testing time: 24 h) revealed no significant difference between the capacitance-type dew point hygrometer and the lithium-chloride dew point hygrometer. A comparison of the capacitance-type dew point hygrometer with the high-precision-mirror-surface dew point hygrometer for long-term verification (Atmosphere: air, Testing time: 24 months) revealed that the capacitance-type dew point hygrometer satisfied the instrumental specification (synthesized precision of detector and converter: ±2.04°C) specified in the Leak Rate Test Regulations for Nuclear Reactor Containment Vessel.

It was confirmed that the capacitance-type dew point hygrometer can be used as a long-term alternative to the lithium-chloride dew point hygrometer without affecting the dew point hygrometer maintenance schedule of the MONJU plant.

Keywords: MONJU, CV-LRT, Dew Point Hygrometer, Capacitance, Lithium-chloride, High-precision-mirror-surface, Maintenance Periods

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*1 Mitsubishi Heavy Industries, Ltd.

*2 National Institute of Advanced Industrial Science and Technology

JAEA-Research 2017-001

もんじゅの原子炉格納容器全体漏えい率試験に対する代替露点検出器の実証試験
― 静電容量式露点検出器に対する短期間及び長期間の検証試験 ―
（翻訳資料）

日本原子力研究開発機構
高速研究開発部門　高速増殖原型炉もんじゅ　プラント保全部

市川　正一，千葉　悠介，大野　史靖，羽鳥　雅一，小林　孝典，上倉　亮一，
走利　信男[*1]，犬塚　泰輔[*1]，北野　寛[*2]，阿部　恒[*2]

（2017 年 1 月 26 日受理）

国立研究開発法人日本原子力研究開発機構は，現在，原子炉格納容器全体漏えい率試験で用いている塩化リチウム式露点検出器のメンテナンス等による高速増殖原型炉「もんじゅ」のプラント工程への影響を低減するため，塩化リチウム式露点検出器の代替品として，静電容量式露点検出器の検証試験を実施した。検証試験として，原子炉格納容器全体漏えい率試験における静電容量式露点検出器と既設の塩化リチウム式露点検出器との比較検証試験，また，他に類を見ない試みとして，原子炉格納容器内にて 2 年間にわたる長期間，静電容量式露点検出器の性能評価に資する長期検証試験が行われた。

原子炉格納容器全体漏えい率試験（試験条件：窒素雰囲気，24 時間）における静電容量式露点検出器の測定結果は，既設の塩化リチウム式検出器と比較して有意な差は無かった。また，長期検証試験（試験条件：空気雰囲気，2 年間）においては，静電容量式露点検出器は，高精度鏡面式露点検出器との比較の結果，「電気技術規程（原子力編）」の「原子炉格納容器の漏えい率試験規程」に基づく使用前検査時に要求される機器精度（検出器・変換器との合成精度：±2.04℃）を長期間にわたり有することを確認した。

以上のことから，静電容量式露点検出器は，既存の塩化リチウム式検出器の代替露点検出器として使用可能であり，かつ，メンテナンスによる高速増殖原型炉「もんじゅ」のプラント工程への影響がなく，また，長期間の運用が可能である露点検出器であることを確認した。

本レポートは JAEA-Research 2016-021 の翻訳版である。
高速増殖原型炉もんじゅ：〒919-1279　福井県敦賀市白木 2 丁目 1 番地
*1　三菱重工業株式会社
*2　国立研究開発法人　産業技術総合研究所

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The lithium-chloride dew point hygrometer has been used for containment vessel leak rate test (hereinafter called “CV-LRT”) in the prototype fast-breeder reactor MONJU (hereinafter called “MONJU”). Maintenance of the lithium-chloride dew point hygrometer has been carried out at intervals of 3–6 months (as recommended by the manufacturer) to apply lithium-chloride to a sensor. The CV-LRT schedule is affected seriously by this periodical application of lithium-chloride.

MONJU is a sodium-cooled fast-breeder reactor. The primary and the secondary cooling systems of MONJU used sodium. When sodium is filled in the primary cooling system, underfloor installed the primary cooling system in the nuclear reactor containment vessel (hereinafter called “CV”) is the nitrogen atmosphere. For this reason, during maintenance period, workers cannot work on the lithium-chloride hygrometers.

To shorten the MONJU plant schedule, there is a need to find an alternative to the lithium-chloride dew point hygrometer. The alternative dew point hygrometer would need to satisfy the following: it should meet the instrumental specifications required by the Containment Vessel Leak Rate Test Regulations[1][2] (hereinafter called “JEAC-4203-2008”) and can be calibrated according to the Japan Calibration Service System (hereinafter called by “JCSS”) based on the Measurement Act[3]. Capacitance-type dew point hygrometer was selected as the equipment that satisfied these conditions.

The capacitance-type dew point hygrometer was selected as the alternative to the lithium-chloride dew point hygrometer as follows. In order to verify the performance of the alternative dew point hygrometer under the CV-LRT condition, the capacitance-type dew point hygrometer was compared with the lithium-chloride dew point hygrometer during CV-LRT (examination time: 24 h). Furthermore, to verify stable performance over the long-term, the capacitance-type dew point hygrometer was measured continuously for 24 months under atmospheric condition, which placed a greater load on the dew point hygrometer sensor than the CV-LRT condition. Moreover, the capacitance-type dew point hygrometer was compared at fixed intervals with the high-precision mirror-surface dew point hygrometer as the reference device.

2. Outline of MONJU, CV-LRT and dew point hygrometer

2.1 Prototype fast breeder reactor MONJU

Figure1 shows the outline of MONJU. MONJU was constructed to establish domestic technology for fast-breeder reactors (hereinafter called "FBR") by the Japan Atomic Energy Agency (abbreviated name: JAEA). MONJU is a nuclear power plant consisting of a primary sodium cooling system, secondary sodium cooling system, and tertiary water cooling system. The outline of MONJU is as follows: Power generation: 280 MW; Fuel: mixed oxide (PuO_2, UO_2). Each cooling system has three independent loops (A loop, B loop, and C loop).

The 714 MW of heat generated in the reactor core is retrieved outside of the reactor vessel by the primary sodium cooling system (sodium flow per loop: 5,100 t/h). This heat is transmitted to the secondary nonradioactive sodium cooling system (sodium flow per loop: 3,700 t/h) via the heat exchanger. Therefore, the heat of the secondary nonradioactive sodium cooling system is transmitted to the tertiary water cooling system via a steam generator (helical coil flow-through separation type). This steam (temperature: 483°C, pressure: 12.5 MPa, total amount of steam through the three loops: ~1,100t/h) drives a steam turbine to generate power. The thermal energy generated in the nuclear reactor is converted into electrical energy (280 MW) at an efficiency of about 40%. The generated 280 MW of electrical energy is fed into a 275-kV transmission system.

- Location: Tsuruga, Fukui, Japan
- Construction began: May 10, 1986
- Reactor type: Fast breeder reactor (FBR)
- Power generation: 280 MW
- Coolant: Sodium
- Fuel: Mixed oxide (PuO_2, UO_2)

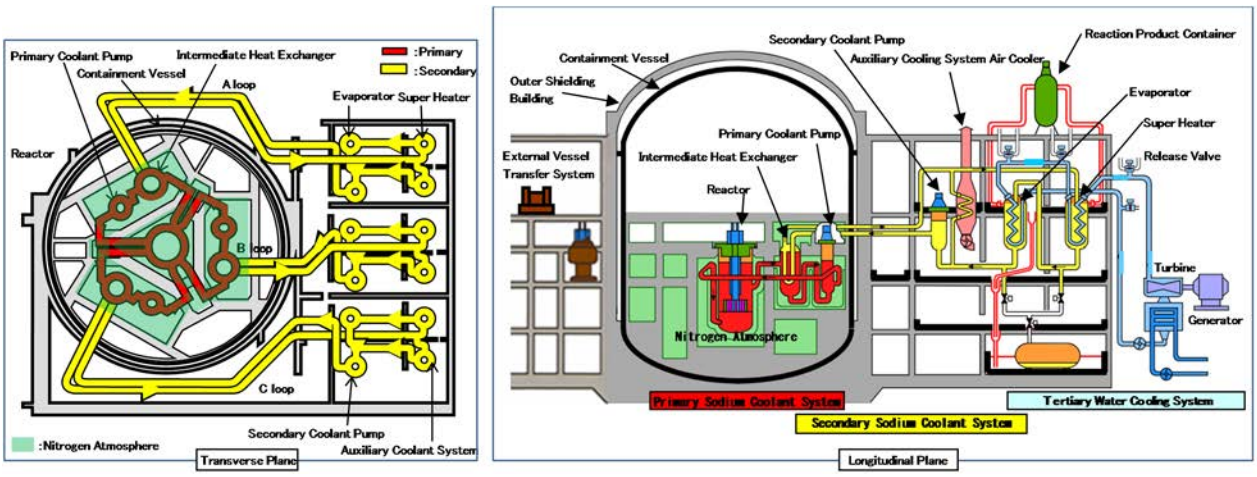

Fig.1 Outline of MONJU

2.2 CV-LRT

The CV requires high air-tightness to confine radioactive substances in the event of a severe accident. Therefore, it is necessary to confirm air-tightness of the CV before nuclear reactor start-up. Air-tightness is determined based on the leak rate over a given period. This method was developed under CV-LRT based on JEAC4203-2008.

Figure 2 shows an outline of CV-LRT. After all gas systems penetrating the CV are isolated, except for the system equipment used in CV-LRT, the CV is filled with nitrogen to a pressure of 50 kPa (54 kPa/maximum) and is held for 24 h. Leak rate (%/day) is the ratio of the weight of leaked nitrogen during the hold time and the weight of nitrogen at the outset. The weight of nitrogen is calculated based on pressure change during hold time in the CV. Nitrogen pressure is corrected by temperature and humidity.

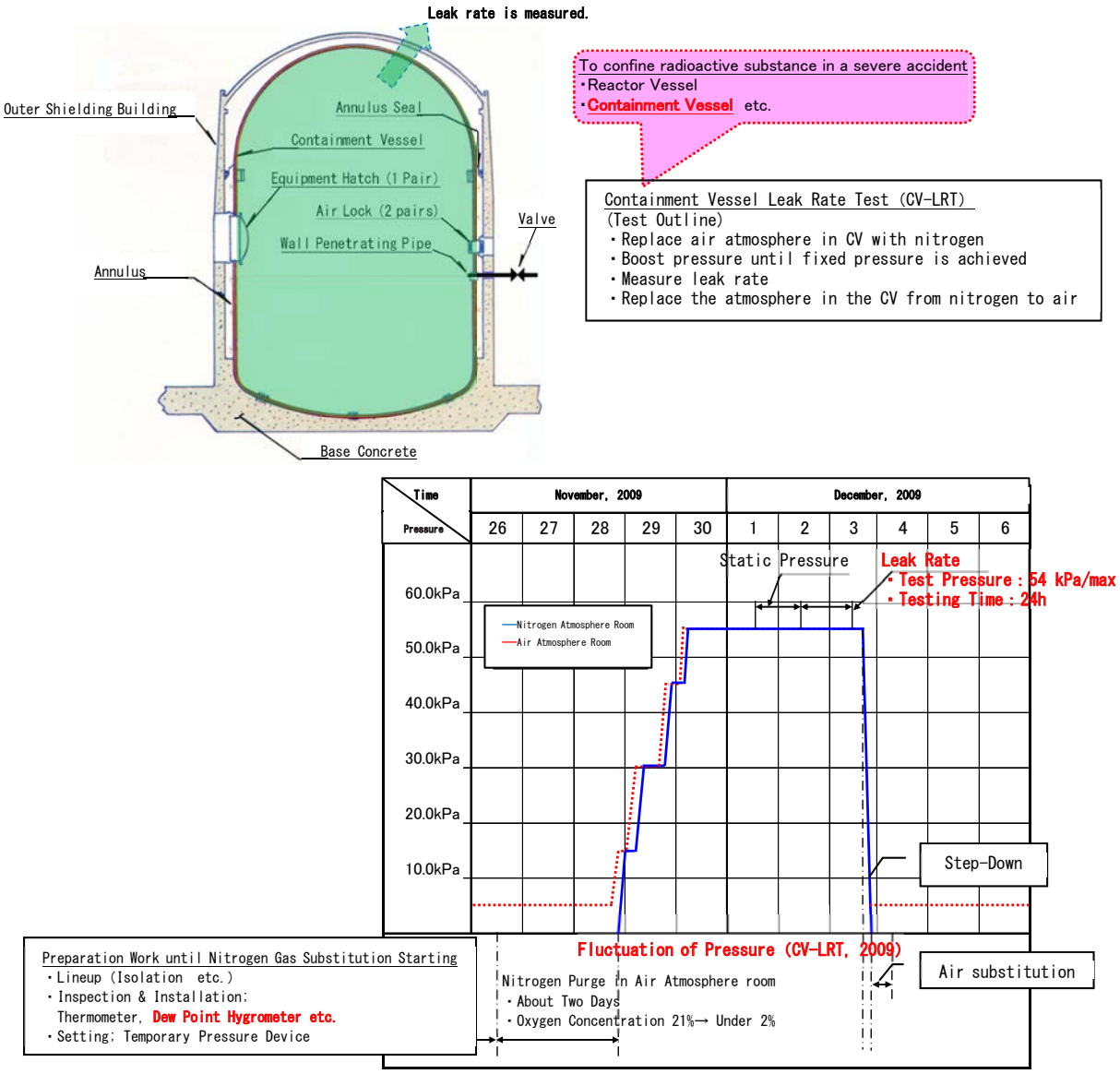

Fig. 2 Outline figure of CV-LRT at MONJU

2.3 Dew point hygrometer

Temperature in the CV changes continually with atmospheric temperature and due to the running of ventilation fans etc. during CV-LRT. This temperature change causes moisture in the CV to evaporate and changes pressure in the CV. Because volume of the CV is massive, the occurrence of hygroscopy in the CV cannot be ignored. Then, saturated vapor pressure is corrected by measuring dew point, and it is then possible to calculate average leak rate (%/day).

2.3.1 Lithium-chloride dew point hygrometer

Figure 3 shows the principle and the structure of the lithium-chloride dew point hygrometer (made by YOKOGAWA DENSHIKIKI Co., Ltd.) used in MONJU.

The resistance temperature sensor of the lithium-chloride type dew point hygrometer is covered by a sintered metal tube and glass wool, and is wrapped with a pair of wires for heating. Lithium-chloride solution is applied to the glass wool. Lithium-chloride is strongly hygroscopic, which means it absorbs a lot of water, so humidity is high under a constant temperature and the concentration of solution is weak. When AC voltage is applied to the heating wire, the temperature of the lithium-chloride solution increases and the water in the solution is vaporized. Because glass wool is in the dry state at a certain temperature, current does not almost flow. In this time, vapor pressure of the glass wool surface is equal to the atmospheric vapor pressure at a temperature. This temperature is measured by the resistance temperature sensor. Vapor pressure or dew point is measured based on the temperature of the lithium-chloride solution. Because lithium-chloride solution is highly corrosive, the heating wire generally is a gold wire or a gold-plated silver wire.

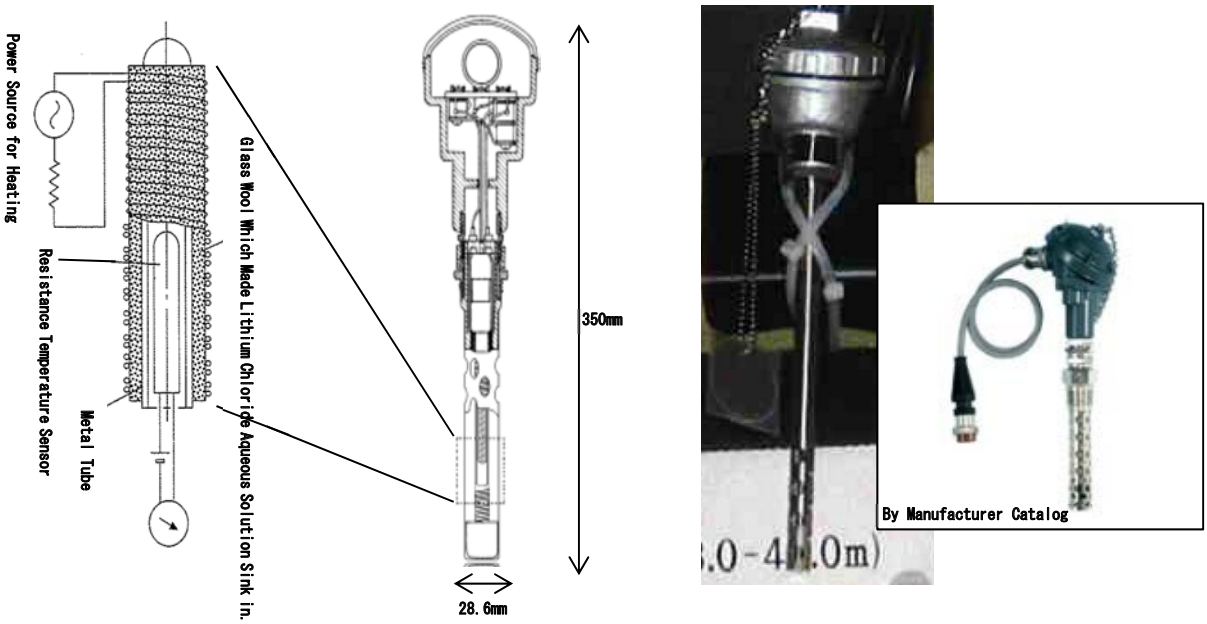

Fig.3 Principle and structure of lithium-chloride dew point hygrometer (Made by YOKOGAWA DENSHIKIKI Co., Ltd, E-771)

2.3.2 Limitations of lithium-chloride dew point hygrometer

The lithium-chloride dew point hygrometer has problems that influence MONJU plant schedule, for example, expiration date of applied lithium-chloride solution. Although it depends on the use environment, the hygrometer requires application of lithium-chloride solution at intervals of 3–6 months, as recommended by the manufacturer. In MONJU and pressurized water reactor plants (hereinafter called "PWR"), to be on the safe side, lithium-chloride solution is applied at intervals of 3 months.

Unlike light water reactor plants (hereinafter called "LWR"), and given the peculiar circumstances of MONJU, the primary and the secondary cooling systems of MONJU employ sodium. When sodium is filled in the primary cooling system, nitrogen atmosphere is maintained in the CV underfloor. Therefore, workers cannot enter the CV underfloor. To do so, they need to drain sodium from the primary cooling system and replace nitrogen in the CV underfloor with air, and this process requires a considerable amount of time.

3. Screening of alternative dew point hygrometer

3.1 Instrumental specification to measure dew point required by JEAC

The instrumental specifications (measurement range, accuracy etc.) of the dew point hygrometer are given in JEAC4203-2008. Table 1 shows the relevant extract from JEAC4203-2008. JEAC4203-2008 stipulates only instrumental specifications and does not limit the type of dew point hygrometer that can be used. At present, only lithium-chloride dew point hygrometers are used at MONJU and LWR. However, subject to satisfaction of the instrumental specifications given in JEAC4203-2008, it is possible to use other types of dew point hygrometers.

Dew point hygrometers based on different detection principles and manufactured by domestic and/or foreign manufacturers were investigated. These were compared with the instrumental specifications given in JEAC4203-2008. The results are shown in Table 2. Further, Survey result (JCSS calibration) in Table 2 is as a result of the time in May, 2012.

Domestic manufacturers produce only lithium-chloride dew point hygrometers. By contrast, several overseas manufacturers, including GE Sensing & Inspection Technologies, Inc. in the United States and VAISALA, Inc. in Finland, manufacture capacitance-type dew point hygrometers. We confirmed whether the instrumental specifications of these capacitance-type dew point hygrometers are compliant with JEAC4203-2008. Furthermore, the number of domestic JCSS registration enterprisers was 7 at the time of the main investigation (May, 2012), but as of October 2016, the number of domestic JCSS registration enterprisers is 13.

Table 1 Instrumental specifications required by JEAC4203-2008 for CV-LRT

Measurement Item	Instrument	Measurement Range	Measurement Accuracy
Atmospheric Pressure	Mercury Barometer	870-1100hPa[abs]	±0.05hPa
Pressure of CV	Mercury Manometer	0-3340hPa[gage]	±2.0hPa
	Pressure Indicator	0-500kPa[gage]	±0.2% of F.S
Absolute Pressure of CV	Quartz Manometer	0-6500hPa[abs]	±(0.01% of F.S + 1 digit)
Temperature of CV	Thermometer	0-50℃	±(0.15+0.002x|t|)℃ t: Temperature [℃]
Dew Point of CV	Dew Point Hygrometer	-30-50℃	±2.0℃
	Convertor	-30-50℃	±0.5% of F.S

Table 2 Comparison with instrumental specifications of JEAC4203-2008

	JEAC4203 Requirement	GE Sensing & Inspection Technologies, Inc. (USA)	VAISALA, Inc. (Finland)	GE Sensing & Inspection Technologies, Inc. (USA)	GE Sensing & Inspection Technologies, Inc. (USA)
Model Number	-	M Series Prove	DMT242B	DF750	D2
Type	-	Capacitance (Al_2O_3) Type	Capacitance (High Molecular) Type	Laser Type	Mirror-Surface Type
Range	-30-50℃	-110-20℃ (Option -60℃)	-60-60℃	-120--60℃	-35-25℃
Accuracy	±2.0℃	±2.0℃	±2.0℃	±3.0℃	±0.2℃
JCSS*1 Calibration	—	NG*3 (NIST*2:OK)	OK*3	NG*3	NG*3

*1: Japan Calibration Service System
*2: National Institute of Standards and Technology
*3: When the main investigation was performed in May, 2012

3.2 Calibration management for alternative dew point hygrometer

The dew point hygrometer used for CV-LRT must have traceability to facilitate instrumental calibration management during the official inspection before commercial operation. Additionally, because high-level calibration is carried out, it is necessary that the corrector is in the know about the technical structure of the dew point hygrometer and can calibrate the dew point hygrometer by themselves if any adjustment is required. Accordingly, we investigated whether it was possible to issue a calibration certificate under JCSS for the alternative dew point hygrometer.

As a result of the investigation, we confirmed that a calibration certificate under could be issued by JCSS to the dew point hygrometer made by VAISALA, Inc. Moreover, we confirmed that a calibration certificate could be issued by National Institute of Standards and Technology (NIST) to the dew point hygrometer made by GE Sensing & Inspection Technologies, Inc., but not by JCSS (as of May, 2012; refer to chapter 3.1).

3.3 Selection of alternative dew point hygrometer

Based on the results in chapters 3.1 and 3.2, capacitance-type dew point hygrometer was selected as the alternative dew point hygrometer.

Figure 4 shows the principle and the structure of the capacitance-type dew point hygrometer. The polymer thin film of the sensor is placed between the electrodes (upper electrode and lower electrode). This assembly is then placed on a glass plate.

The polymer thin film of the sensor absorbs or releases vapor based on changes in humidity in its surroundings. Changes in humidity around the sensor change the characteristic of the sensor's polymeric dielectric, specifically, its capacitance. The capacitance change indicates the humidity level. Because the

device combines a high molecular humidity sensor with a temperature sensor, dew point is calculated by the indicated values of humidity and temperature.

The measurement range of the capacitance-type dew point hygrometer is from −60°C to 60°C. The initial cost of the capacitance-type dew point hygrometer is lower than that of the lithium-chloride dew point hygrometer. However, there is no history of the use of this hygrometer in a CV-LRT in other LWRs.

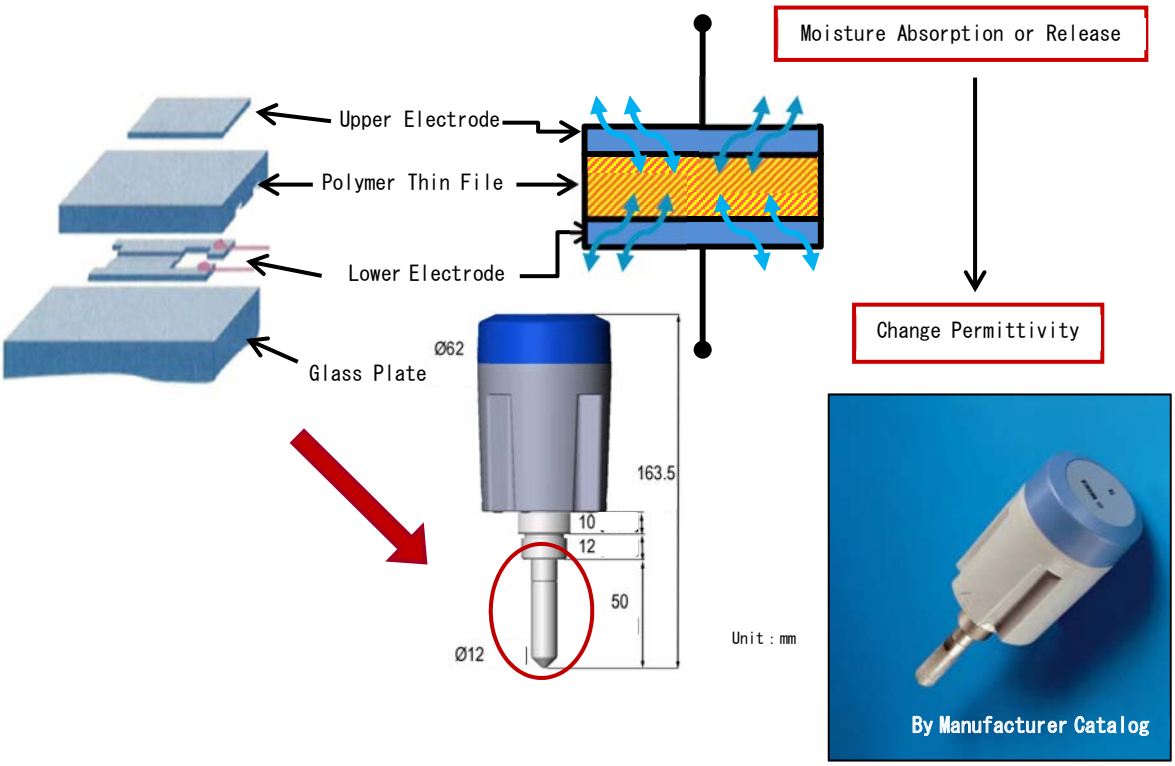

Fig. 4 Principle and structure of capacitance-type dew point hygrometer (Made by VAISALA, Inc., DMT242)

3.4 Use results of alternative dew point hygrometer in nuclear reactor facilities

The capacitance-type dew point hygrometer made by VAISALA, Inc., described in chapter 3.1, has not been used for CV-LRT in domestic and overseas LWRs thus far. However, a capacitance-type hygrometer made by VAISALA, Inc, which is similar to the capacitance-type dew point hygrometer made by VAISALA, Inc., has been used for moisture control in air-conditioning equipment in domestic and overseas nuclear facilities. The capacitance-type hygrometer has been used for moisture control on an experimental basis in the spent fuel storage of the kingdom of Sweden. Moreover, the capacitance-type hygrometer has been used at the fuel handling facility, computer room, and so on, in MONJU. These hygrometers, which have been not been maintained for 40 months each, as decided by the conservation planning of MONJU, did not need recalibration to be within the limits of error (±2.0%) at last inspection (2011). Before establishment of conservation planning, these hygrometers were calibrated after about ten years' at an

inspection in 2001. This inspection revealed that the error of these hygrometers was only from −0.08–1.2%. Table 3 shows the usage details of capacitance hygrometers made by VAISALA, Inc. in MONJU.

Table 3 Uses of capacitance hygrometers made by VAISALA, Inc. in MONJU

No.	Installation location	Instrument No.	Instrumental Errors (%RH)	Inspection Date (Previous Inspection Date)
1	Radiation Control Room	673-ME001	-0.08	2011/1/19 (2001/1/15)
2	Fuel Handling Facility Computer Room	687-ME011	0.4	2011/3/16 (2000/12/4)
3	Central Computer Room	687-ME021	1.2	2011/3/11 (2000/12/5)
4	Access Control Room	694-ME011	1.2	2011/3/4 (2000/12/11)

4. Experimental procedure

4.1 Verification examination under CV-LRT condition

To confirm the difference between the capacitance-type dew point hygrometer and the lithium-chloride dew point hygrometer under the CV-LRT condition, the capacitance-type dew point hygrometers (2 cars) and the lithium-chloride dew point hygrometers were offered to the verification examination. These capacitance-type dew point hygrometers were put on the floor (Elevation level (hereinafter called "EL"): about 43 m) of the CV. Figure 5 shows the unit plot plan of CV-LRT in the year 2009. Twenty lithium-chloride dew point hygrometers were arranged in the location in accordance with the arrangement of the thermometer based on JEAC 4203-2008. Two capacitance-type dew point hygrometers were arranged near the lithium-chloride dew point hygrometers on the EL (location was D20, as in Figure 5). Measurements were recorded at intervals of one hour, 25 times in total over 24 h (From December 2 12:00 to December 3 12:00, 2009).

These capacitance-type dew point hygrometers were calibrated before and after this examination, and satisfactory levels of precision were confirmed (synthesized precision of detector and converter: ±2.04°C*) according to JEAC4203-2008. The devices were calibrated at the manufacturing plant.

*: The synthesized precision of the detector and the converter was calculated as follows:

$$\pm\sqrt{(2.0)^2+(0.4)^2}=\pm 2.04℃$$

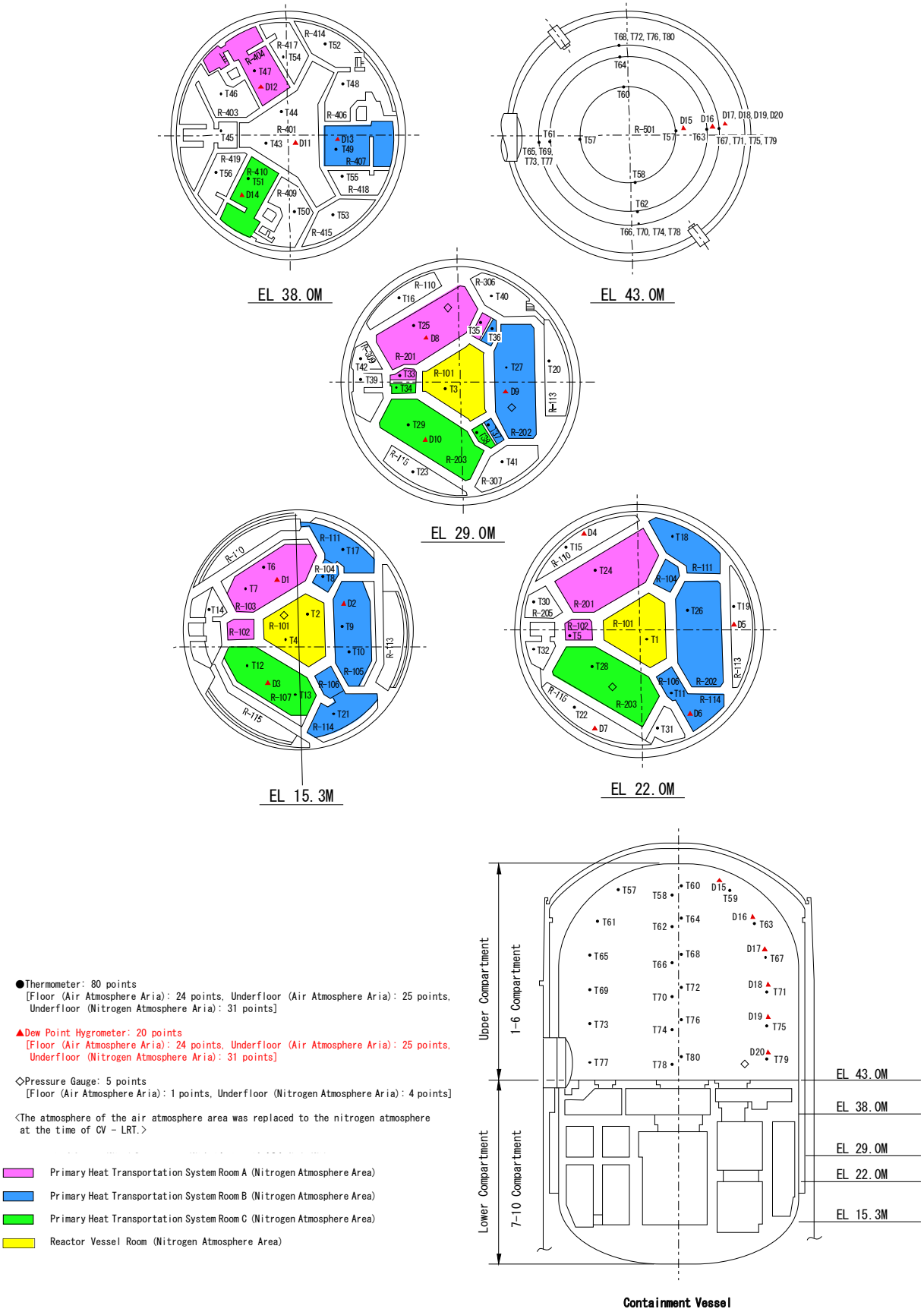

Fig.5 Equipment layout at CV-LRT

(1) Examination condition

Table 4 shows the examination condition. After the capacitance-type dew point hygrometers were installed on the CV floor, the atmosphere on the floor was replaced from air to nitrogen and was linked to the underfloor (nitrogen atmosphere). The atmosphere in the CV was pressurized to 50 kPa (54 kPa maximum) and was held for 24 h. The outline and procedure of the CV-LRT are given and shown in chapter 2.2 and Figure 2, respectively.

Temperature and humidity of the atmosphere in the CV were controlled by the ventilation air-conditioning facility. Moisture, salinity, dust, and temperature fluctuation (about 20–25 °C) in the CV were kept lower than those of the outside environment to mitigate the degrading effects of those factors on the dew point hygrometer sensors in the CV.

(2) Instrumental specifications

Table 4 shows the specifications of the instruments and the recording device. The equipment used for this examination is as follows:

1) Capacitance-type dew point hygrometer (VAISALA, Inc.; DMT242B; Measurement range: −60–60 °C; System accuracy: ±2.0°C; Car: 2 (detector A, detector B); EL: about 43 m) as the alternative dew point hygrometer.
2) The existing lithium-chloride type dew point hygrometer (YOKOGAWA DENSHIKIKI Co., Ltd.; Type: E-773; System configuration: detector and signal converter; Measurement range: −40–60°C; Accuracy of detector system: ±0.5°C; Accuracy of signal converter system: ±0.5%; Car: 20; EL: 45–47 m) was employed as the comparison dew point hygrometer (dew point hygrometer used in basic design).
3) A data logger (GRAPHTEC Corporation; Type: GL800; Sampling interval: 100 ms minimum; Measurement accuracy: ±0.1 % of F.S. (voltage)) was used as the recording device.

(3) Calibration

The capacitance-type dew point hygrometers, before and after examination, were calibrated using the dew point calibration systems made by VAISALA, Inc. This following procedure was employed.

Calibration period: 1 year; Standard: Surface-acoustic-wave-type dew point hygrometer (Traceable to national standard); Public authorized body: JCSS; Calibration method: Comparison with surface-acoustic-wave type dew point hygrometer for a standard reference gas in a thermostatic chamber.

Table 4 Examination condition, instrumental specifications, and calibration for verification under CV-LRT

Examination Condition		
Atmosphere	N_2	
Pressure	+54kPa/maximum	
Temperature	20-25℃	
Test Period	24h	
Comparative Measurement Interval	1h	
Instrumental Specification		
Dew Point Hygrometer Type	Capacitance-Type	Lithium-Chloride
Type	DMT242B	E-773
The number of Instrument	2 (A, B)	20
Manufacturer	VAISALA, Inc.	YOKOGAWA DENSHIKIKI Co., Ltd.
Measurement Range	-60-60℃	-40-60℃
Accuracy of Detector	±2.0℃	±0.5℃
Accuracy of Convertor	—	±0.5% of F.S.(-30-50℃)
Data Logger Specification		
Type	GL800	Same as on the left side
Manufacturer	GRAPHTEC Corporation	Same as on the left side
Sampling Interval	100ms/minimum	Same as on the left side
Accuracy	±0.1% of F.S. (voltage)	Same as on the left side
Calibration		
Calibration period	1 year	—
Standard	Surface-Acoustic-Wave Type Dew Point Hygrometer (Traceable to national standard) (Manufacturer: VAISALA, Inc.)	—
Public Authorized Body	JCSS	—
Location	VAISALA, Inc. (Japan)	—
Calibration Method	Comparison with Surface-acoustic-wave-type dew point hygrometer for standard reference gas in a thermostatic chamber	—

4.2 Long-term verification examination under usual condition

To confirm the long-term operation performance of the capacitance-type dew point hygrometers as the alternative dew point hygrometer, they (3 cars) were measured continuously (term: 24 months) on the floor (atmosphere: air) of the CV. The lithium-chloride dew point hygrometer (1 car) of the basic design was used for obtaining reference data. To confirm the measurement data, the results obtained with the capacitance-type dew point hygrometers were compared with those obtained using the high-precision-mirror-surface dew point hygrometer (1 car) as the reference device in measurement months 0, 3, 6, 12, 14, 16, 20, and 24. It was verified that the difference between the measurement data of the capacitance-type dew point hygrometer and that of the high-precision-mirror-surface dew point hygrometer was within the instrumental requirements (synthesized precision of detector and converter: ±2.04°C) specified in JEAC4203-2008. Figure 6 shows the unit plot plan of the CV. The high-precision-mirror-surface dew point hygrometer was prepared for each of the measurement months and was calibrated according to the verification standards, with precision higher by one digit than the instrumental requirements (synthesized precision of detector and converter: ±2.04°C) specified in JEAC4203-2008, before and after the examination. Figure 7 shows the system configuration of the high-precision-mirror-surface dew point hygrometer. Figure 8 shows the location of each dew point hygrometer.

Furthermore, the intake hose length may have an effect on the output of the high-precision-mirror-surface dew point hygrometer; we evaluated the dependence of the high-precision-mirror-surface dew point hygrometer on hose length. After the prescribed measurement ended, the intake hose of the high-precision-mirror-surface dew point hygrometer was removed. Each dew point hygrometer was used to perform measurements continuously for several hours. We could verify the difference between the measurement data of the capacitance-type dew point hygrometer and that of the high-precision-mirror-surface dew point hygrometer.

It was considered that the environment (atmosphere: air) of floor was more severe than the environment (atmosphere: nitrogen) in CV-LRT, leading to a reduction in the efficiency of the dew point hygrometer. Five degradation factors (dew point, temperature, humidity, dust, and salt) were identified based on humidity-measurement methods[4] (hereinafter called “JIS Z 8806”). These degradation factors were compared with the data of the floor (atmosphere: air) and underfloor (atmosphere: nitrogen) in the CV. Observatory data from the Meteorological Agency and historical CV-LRT data were used for this purpose.

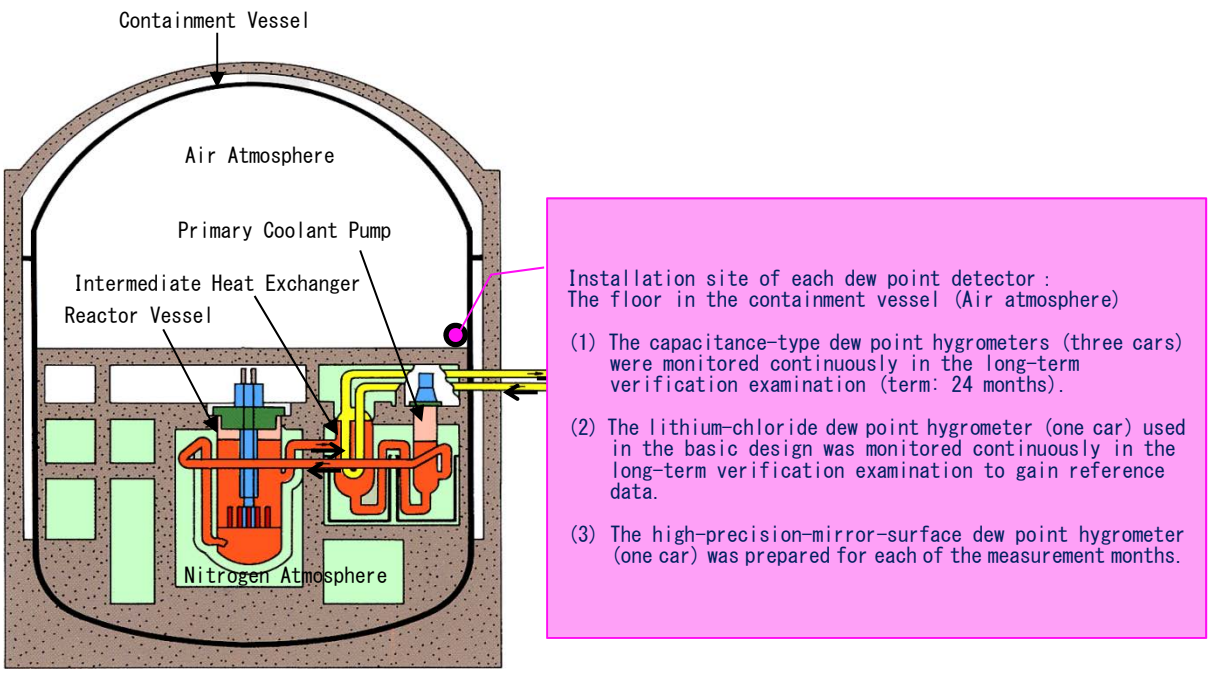

Fig.6 Unit plot plan of CV

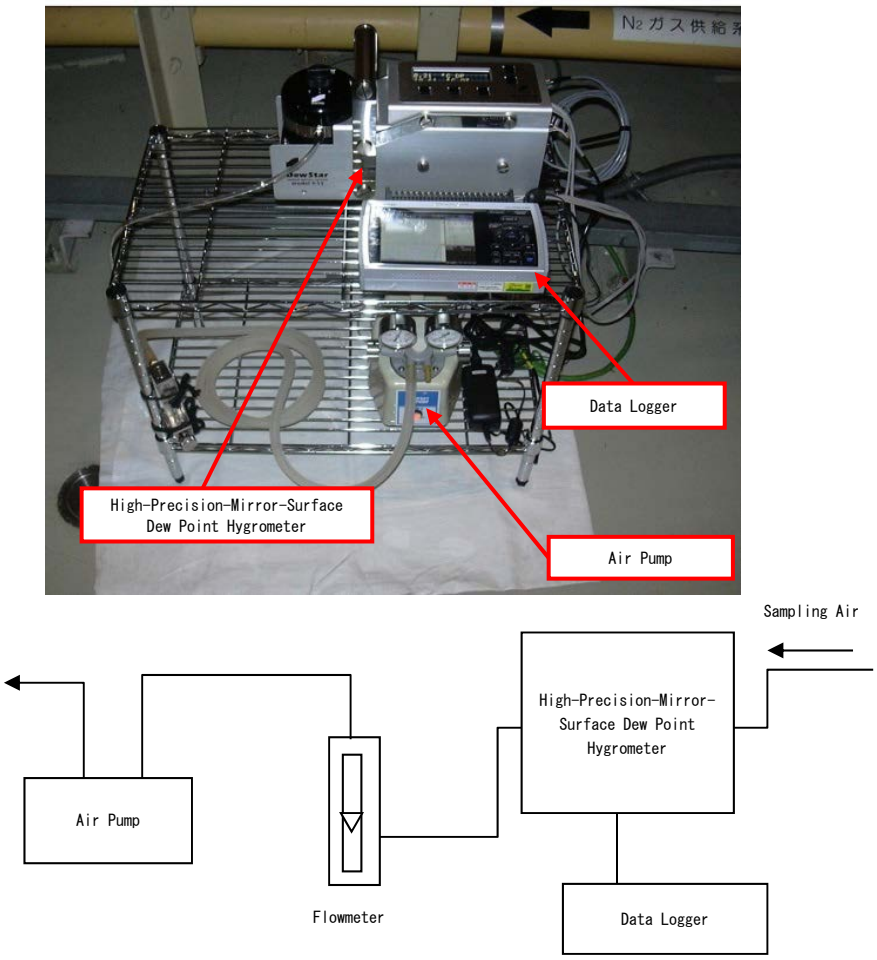

Fig.7 System configuration of high-precision-mirror-surface dew point hygrometer

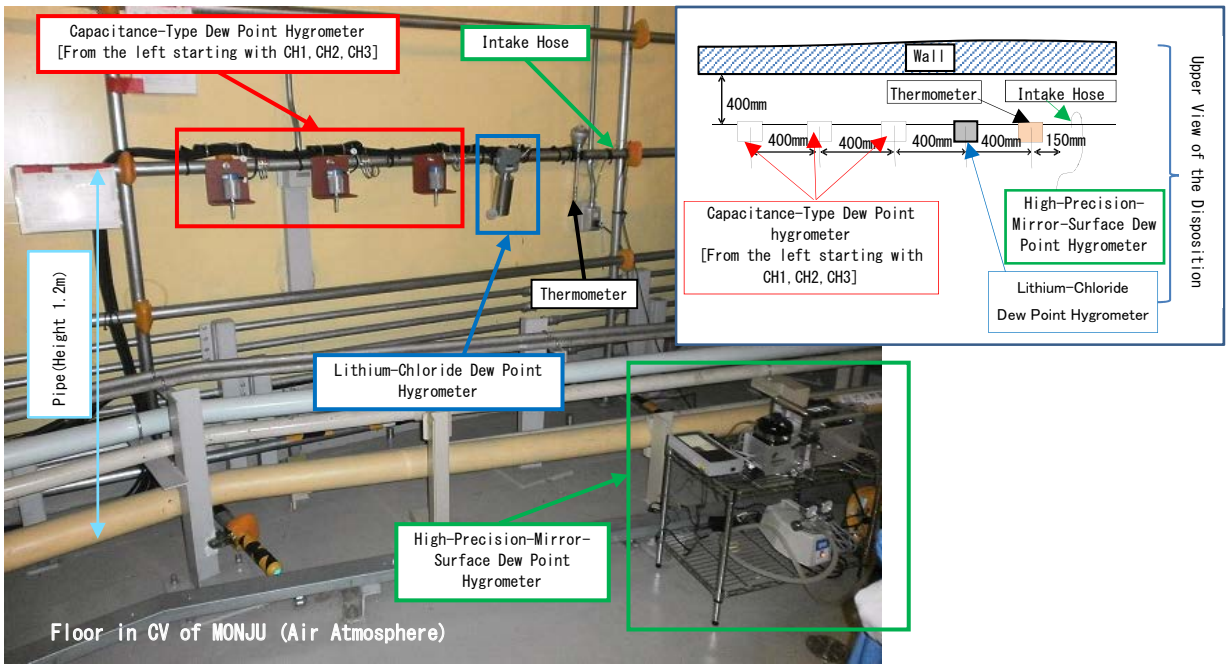

Fig. 8 Schematic layout of instruments

(1) Examination condition

Table 5 shows the examination condition. JAEA installed the capacitance-type dew point hygrometers on the floor of the CV and performed examinations under air atmosphere. The agency did not examine the CV underfloor by replacing air atmosphere with a nitrogen one and draining sodium from the main system during the examination to maintain the MONJU plant schedule.

The environment in the CV influences the dew point hygrometer sensor in the manner described in the second paragraph of chapter 4.1 (1).

(2) Instrumental specifications

Table 5 shows the specifications of the instruments and the recording device. The equipment used for this examination is as follows:

1) The capacitance-type dew point hygrometer (VAISALA, Inc.; Type: DMT242B; Measurement range: −60–60°C; Accuracy of system: ±2.0°C; Car: 3 (CH1, CH2, and CH3); EL: about 43 m) as the alternative dew point hygrometer.
2) The existing lithium-chloride dew point hygrometer (YOKOGAWA DENSHIKIKI Co., Ltd.; Type: E-773; System configuration: detector and signal converter; Measurement range: −40–60°C; Accuracy of detector system: ±0.5°C; Accuracy of signal converter system: ±0.5%; Car: 1; EL: about 43 m) was used for comparison.
3) The high-precision-mirror-surface dew point hygrometer (SHINYEI Technology Co., LTD.; Type: DewStar S-1; Measurement range: −35–50°C; Accuracy of system: ±0.2°C; Sampling rate: 0.5–2.5 L/min; Car: 1; EL: about 43 m) was used as the reference device.
4) A data logger (HIOKI E.E. Corporation; Type: MEMORY HiLOGGER8430; Sampling interval: 10 ms minimum; Measurement accuracy: ±0.1% of F.S. (voltage)) was used as the recording device for the capacitance-type dew point hygrometer and the lithium-chloride dew point hygrometer.
5) A data logger (GRAPHTEC Corporation; Type: GL820; Sampling interval: 10 ms minimum; Measurement accuracy: ±0.1% of F.S. (voltage)) was used as the recording device for the high-precision-mirror-surface dew point hygrometer.

(3) Calibration

After the final examination month (month 24), the capacitance-type dew point hygrometers were calibrated using the dew point calibration systems made by VAISALA, Inc. The dew point calibration particulars are as follows:

Calibration period: 1 year; Standard: Surface-acoustic-wave type dew point hygrometer (Traceable to national standard); Public authorized body: JCSS; Calibration method: Comparison with the output of the surface-acoustic-wave type dew point hygrometer for a standard reference gas in a thermostatic chamber.

A high-precision-miller-surface type dew point hygrometer, which was used as the reference device for long-term verification, was calibrated using the dew point calibration system made by SHINYEI

Technology Co., LTD. before and after each examination. The particulars of dew point calibration are as follows:

Calibration period: 6 month; Standard: Miller -surface type dew point hygrometer (traceable to national standard); Public authorized body: JCSS; Calibration method: sample air produced by a divided flow humidity generator is introduced into the dew point hygrometer under calibration. The dew point hygrometer was compared with the standard dew point hygrometer.

Table 5 Examination condition, instrumental specification, and calibration for long-term verification

Examination Condition			
Atmosphere	Air		
Pressure	Atmospheric Pressure		
Temperature	20-25℃		
Test Period	2 years (24 months)		
Measurement Time / Measurement Month	Throughout 24h / 0, 3, 6, 12, 14, 20, 24 month		
Instrumental Specification			
Dew Point Hygrometer Type	Capacitance-Type	Lithium-Chloride	High-Precision-Mirror-Surface Dew Point Hygrometer
Type	DMT242B	E-773	DewStar S-1
Number of Instruments	3(CH1, CH2, CH3)	1	1
Manufacturer	VAISALA, Inc.	YOKOGAWA DENSHIKIKI Co., Ltd.	SHINYEI Technology Co., LTD.
Measurement Range	-60-60℃	-40-60℃	-35-50℃
Accuracy of Detector	±2.0℃	±0.5℃	±0.2℃
Accuracy of Convertor	—	±0.5% of F.S.(-30-50℃)	—
Data logger specification			
Type	MEMORY HiLOGGER 8430	Same as on the left side	GL820
Manufacturer	HIOKI E.E. Corporation	Same as on the left side	GRAPHTEC Corporation
Sampling Interval	10ms/minimum	Same as on the left side	10ms/minimum
Accuracy	±0.1% of F.S. (voltage)	Same as on the left side	±0.1% of F.S. (voltage)
Calibration			
Calibration Period	1 year	—	6 month
Standard	Surface-Acoustic-Wave-Type Dew Point Hygrometer (Traceable to national standard) (Manufacturer: VAISALA, Inc.)	—	Miller-surface-Type Dew Point Hygrometer (Traceable to national standard) (Manufacturer: GE Sensing & Inspection Technologies, Inc.)
Public Authorized Body	JCSS	—	JCSS
Location	VAISALA, Inc. (Japan)	—	SHINYEI Technology Co., LTD.
Calibration Method	Comparison with Surface-acoustic-wave-type dew point hygrometer for standard reference gas in a thermostatic chamber	—	Sample air produced by a divided flow humidity generator is introduced into a dew point hygrometer under calibration. The dew point hygrometer is compared with the standard dew point hygrometer.

5. Results

5.1 Verification examination results under CV-LRT condition

Figure 9 shows the behavior of the dew point of the capacitance-type dew point hygrometer (detectors A, B) and the lithium-chloride dew point hygrometer (the mean value of 20 cars, detector ME-20) in CV-LRT. The detector ME-20 was installed at position D20, as shown in Figure 5.

The mean value of 20 cars, that is, measurement of detector ME-20 of the lithium-chloride dew point hygrometer, increased with time. The value measured by detector ME-20 increased slightly more than the mean value of 20 cars with time.

The values measured by detectors A and B of the capacitance-type dew point hygrometer, same as the lithium-chloride type dew point hygrometer, increased with time. There were no significant differences between the measurements of detectors A and B. The measurement of detectors A and B were a little lower than the measurement of detector ME-20 installed at the same place. However, the maximum difference was 0.5°C[5].

The calibration result of the capacitance-type dew point hygrometer obtained by the manufacturer is summarized in Table 6. The maximum error of the capacitance-type dew point hygrometer is 0.5°C before and after CV-LRT. The capacitance-type dew point hygrometer maintained high precision, as predicted by the manufacturers (±2°C) 1/4.

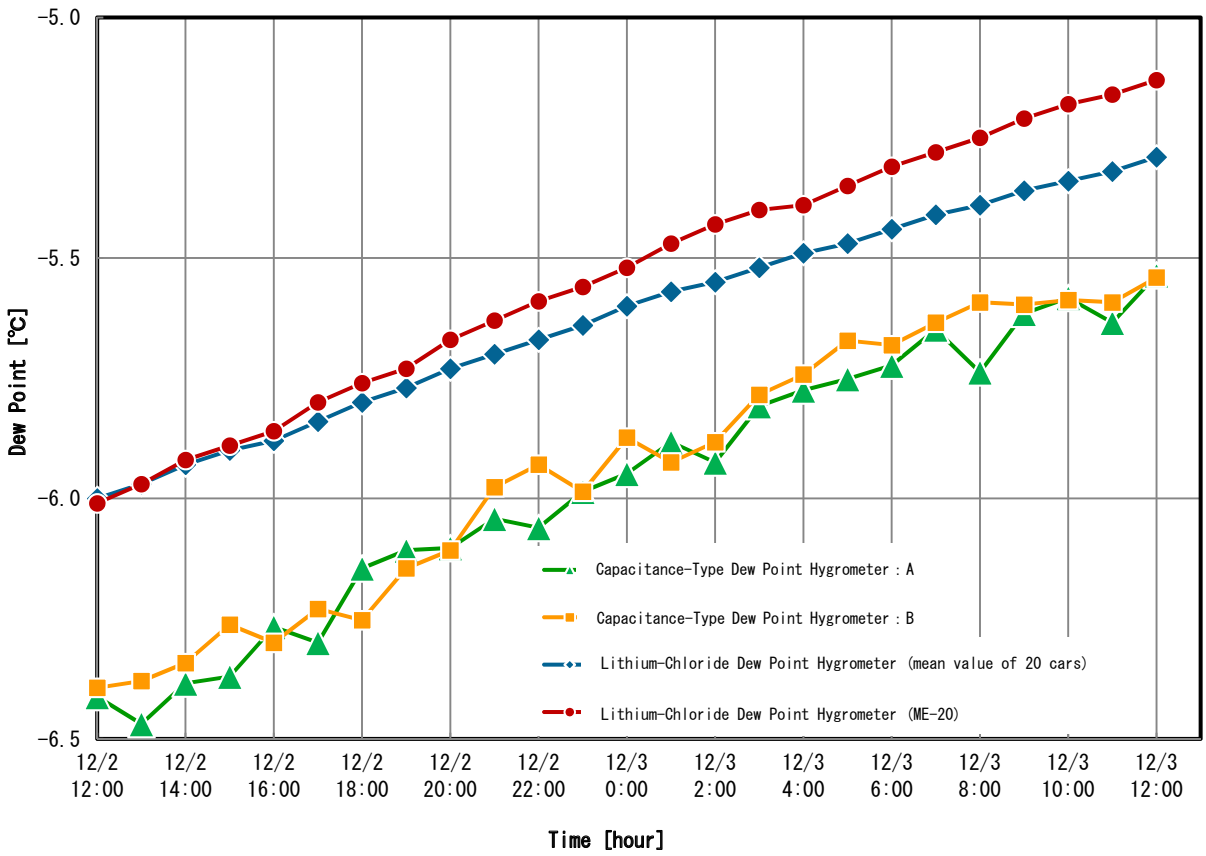

Fig. 9 Verification results under CV-LRT condition

Table 6 Calibration result of capacitance-type dew point hygrometer

Standard Dew Point [℃]	Before CV-LRT (2009.11.13)		Standard Dew Point [℃]	After CV-LRT (2009.1.27)	
	Capacitance-Type A [℃]	Capacitance-Type B [℃]		Capacitance-Type A [℃]	Capacitance-Type B [℃]
−10	−10	−10	−11.8	−11.8	−11.9
−6.4	−6.5	−6.5	−7	−7	−7.3
0	−0.1	−0.2	0.9	0.8	0.4

5.2 Long-term verification examination results under usual condition

(1) Comparison of value measured by each dew point hygrometer

For the capacitance-type dew point hygrometer (3 cars: CH1, CH2, CH3), lithium-chloride dew point hygrometer (1 car for gaining reference data), and high-precision-mirror-surface dew point hygrometer (1 car for confirming measurement data), Table 7 and Figure10 show the mean value of each measurement (0, 3, 6, 12, 14, 16, 20, and 24 month) and Figures. 11–17 show the measurements themselves. Table 8 shows the deviation of the mean value of the capacitance-type dew point hygrometer and the lithium-chloride dew point hygrometer from the mean value of the high-precision-mirror-surface dew point hygrometer for each measurement (0, 3, 6, 12, 14, 16, 20 and 24 month), and Figures 18–21 show the deviations across the typical measurement months (0, 6, 12, 14, and 16 month). The deviation of the maximum measurement of the capacitance-type dew point hygrometer and the lithium-chloride dew point hygrometer from the maximum measurement without disturbance of the indicated value (for example at 3 month measurement) are given in Table 8. The lithium-chloride dew point hygrometer used for recording reference data was provided from 3 month measurement by the reason of supply delay of the instrument. Because the measurement with the lithium-chloride dew point hygrometer was started within the expiration date of the lithium-chloride solution, there was no significant difference between the measurement performed in month 0 and that performed in month 3.

The mean values of CH1 and CH2 of the lithium-chloride type dew point hygrometer were almost the same as the mean value of the high-precision-mirror-surface dew point hygrometer, as listed in Table 7 and shown in Figure 10. The deviation of the mean value of the capacitance-type dew point hygrometer from that of the high-precision-mirror-surface dew point hygrometer was within ±0.4°C, which is very small. The measurement recorded with each of the dew point hygrometers showed the same qualitative trend in each measurement month[5].

On the other hand, the mean value of CH3 was lower than those of other dew point hygrometers, as in Table 7 and Figure 10. The maximum deviation of the mean value of CH3 from the mean value of the high-precision-mirror-surface dew point hygrometer was −1.23°C and was larger than the deviation of the mean values of CH1 and CH2 from the mean value of the high-precision-miller-surface dew point hygrometer[5]. The measurement of each of the dew point hygrometers showed the same qualitative trend in each measurement month, as shown in Figures 11–17. However, there were abrupt and significant

stoppages and decreases in the indicated value of CH3, which increased its deviation in Figures 11, 13, 18–21 (especially in Figure 11, 13, 18, and 19 (measurement months: 0 and 6)).

Table 7 Measurement result of each dew point hygrometer (mean value)

Time (Year/Month)	Mean Value of each Measurement Month [℃]				
	High-Precision-Mirror-Surface	Capacitance-Type: CH1	Capacitance-Type: CH2	Capacitance-Type: CH3	Lithium-Chloride
0 Month (2012/5)	10.78	11.16	10.89	9.76	—*
3 Month (2012/8)	9.97	10.07	9.92	9.11	9.61
6 Month (2012/11)	4.12	4.36	4.12	3.15	4.19
12 Month (2013/5)	12.02	12.13	11.82	10.77	12.37
14 Month (2013/7)	13.23	13.49	13.21	12.12	13.40
16 Month (2013/9)	9.88	10.15	9.84	8.80	10.10
20 Month (2014/1)	−1.02	−0.92	−1.13	−1.87	−0.76
24 Month (2014/5)	12.98	13.07	12.80	11.75	13.49

*: Lithium-chloride dew point hygrometer was provided from 3 month measurement by the reason of supply delay of the instrument.

Table 8 Deviation of capacitance-type dew point hygrometer and lithium-chloride dew point hygrometer from high-precision-mirror-surface dew point hygrometer (mean value)

Time (Year/Month)	Deviation of the Mean Value for the High-Precision-Mirror-Surface [℃] [“()” is the absolute value*1 of the deviation by the maximum measurement.]			
	Capacitance-Type: CH1	Capacitance-Type: CH2	Capacitance-Type: CH3	Lithium-Chloride
0 Month (2012/5)	0.38 (0.78)	0.11 (0.54)	−1.02 (1.40)	—*2
3 Month (2012/8)	0.10 (0.84)	−0.05 (1.02)	−0.86 (1.51)	−0.36 (0.70)
6 Month (2012/11)	0.24 (0.62)	0.00 (0.44)	−0.97 (1.25)	0.07 (0.21)
12 Month (2013/5)	0.11 (0.28)	−0.20 (0.44)	−1.25 (1.51)	0.35 (0.50)
14 Month (2013/7)	0.26 (0.71)	−0.02 (0.33)	−1.11 (1.46)	0.17 (0.37)
16 Month (2013/9)	0.27 (0.95)	−0.04 (0.60)	−1.08 (1.62)	0.22 (0.67)
20 Month (2014/1)	0.10 (0.35)	−0.11 (0.38)	−0.85 (1.06)	0.26 (0.41)
24 Month (2014/5)	0.09 (0.36)	−0.18 (0.32)	−1.23 (1.41)	0.51 (0.59)

*1: Capacitance-Type or Lithium-Chloride − High-Precision-Mirror-Surface [℃]

*2: Lithium-chloride dew point hygrometer was provided from 3 month measurement by the reason of supply delay of the instrument.

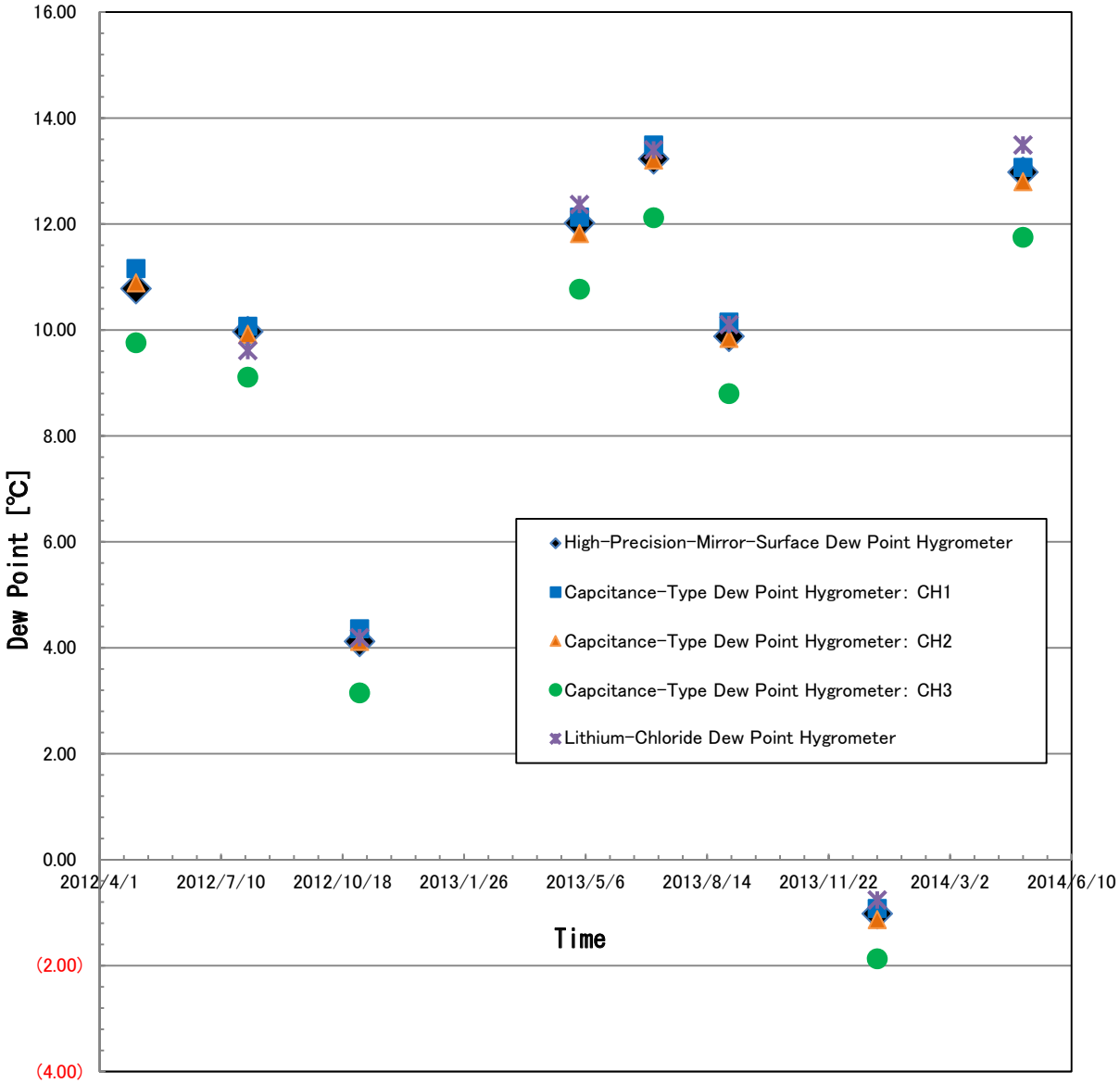

Fig. 10 Measurement result of each dew point hygrometer (mean value)

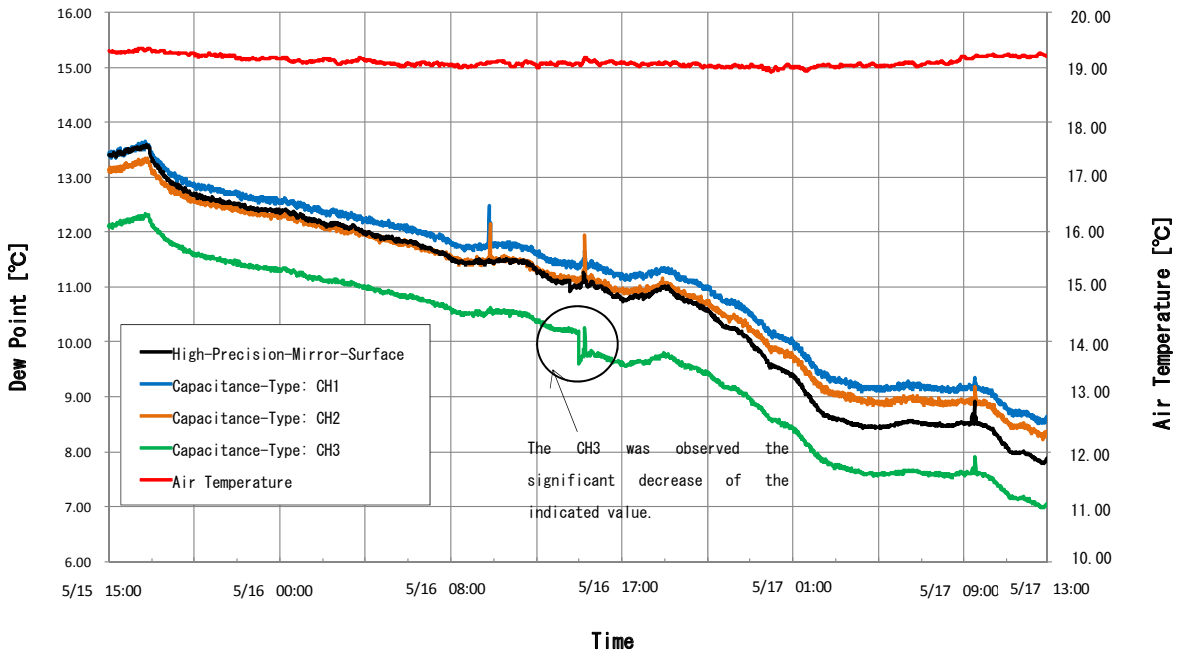

Fig. 11 Measurement result of each dew point hygrometer (2012.5.15-16)

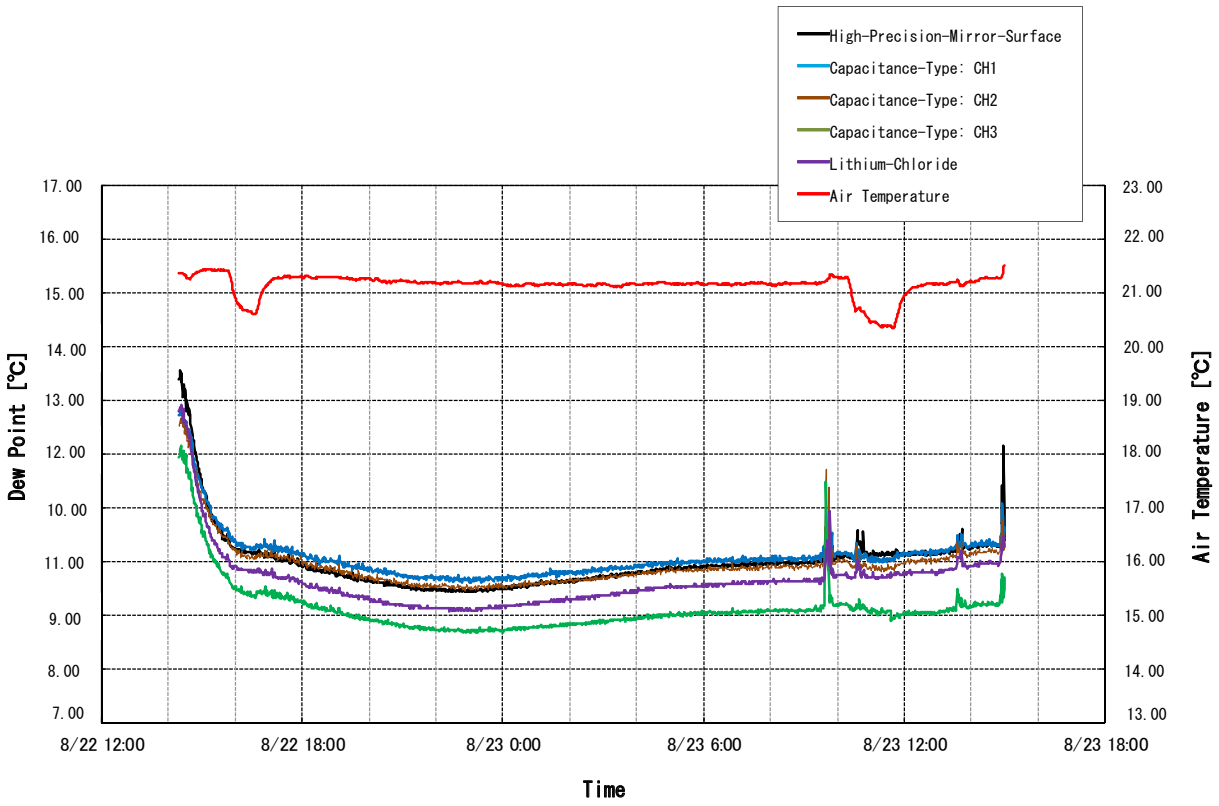

Fig. 12 Measurement result of each dew point hygrometer (2012.8.22-23)

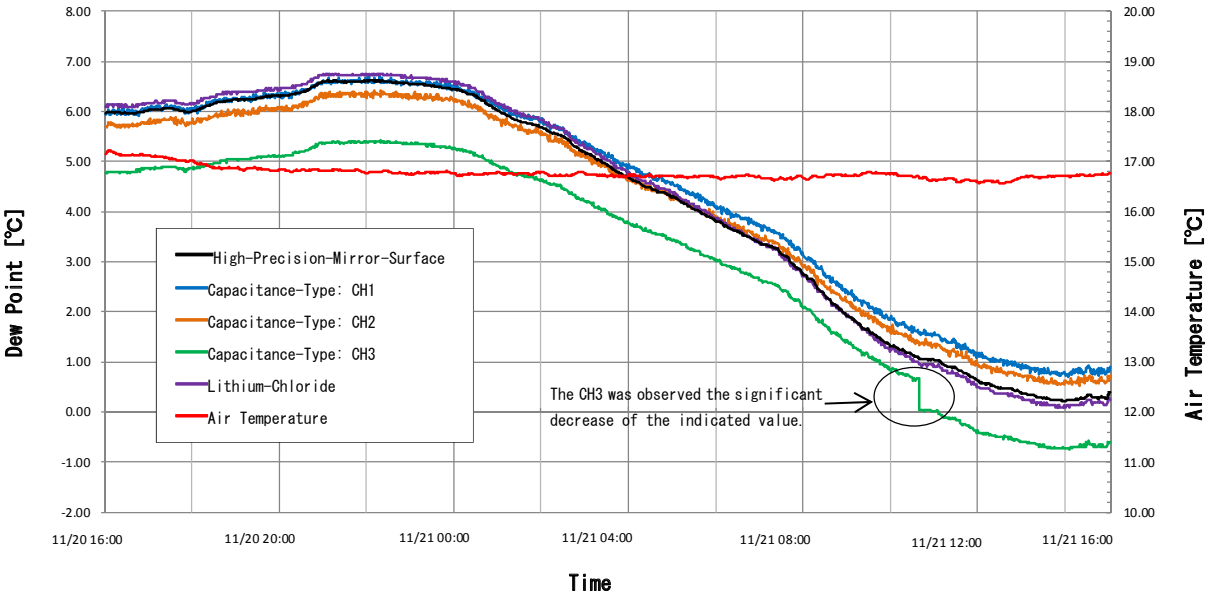

Fig. 13 Measurement result of each dew point hygrometer (2012. 11. 20-21)

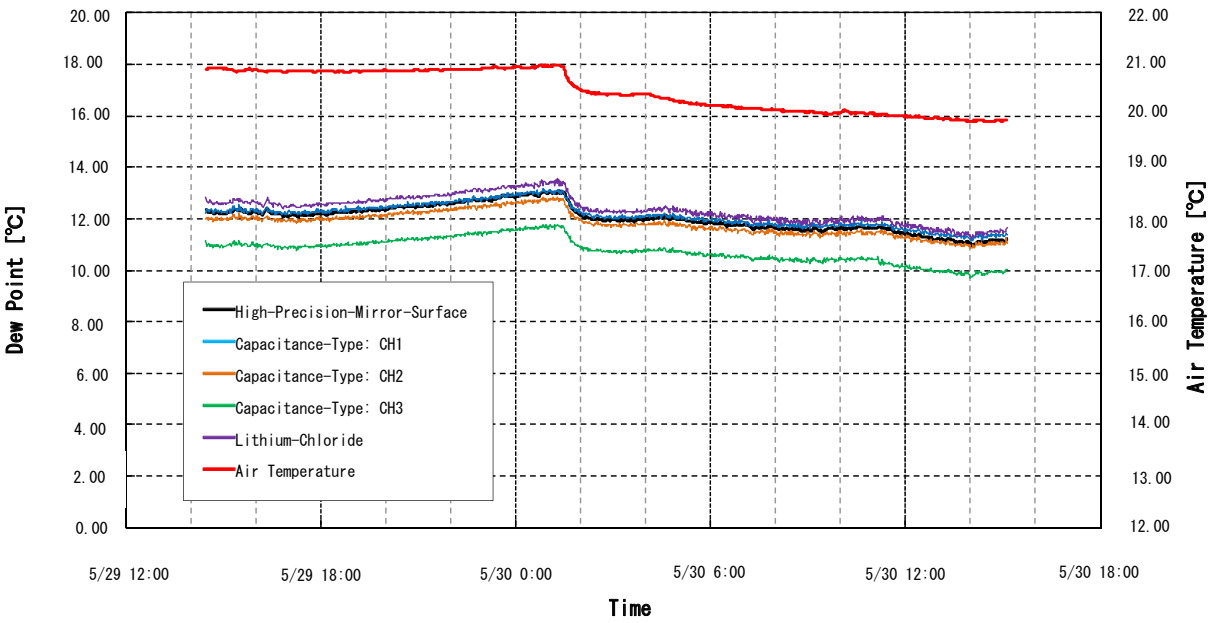

Fig. 14 Measurement result of each dew point hygrometer (2013. 5. 29-30)

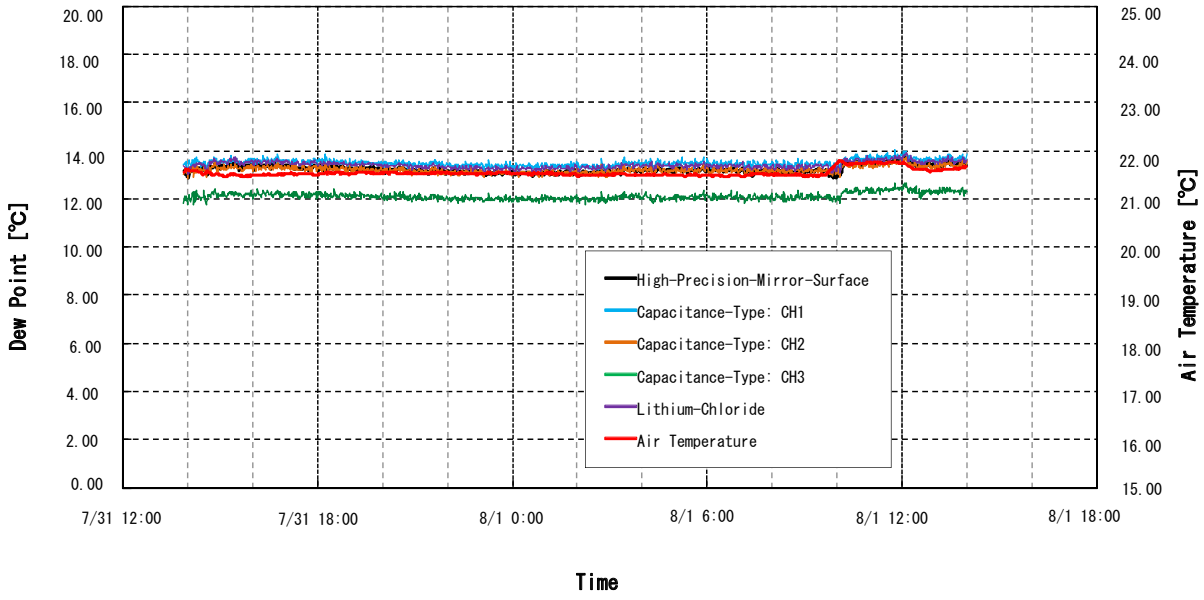

Fig.15 Measurement result of each dew point hygrometer (2013.7.31-8.1)

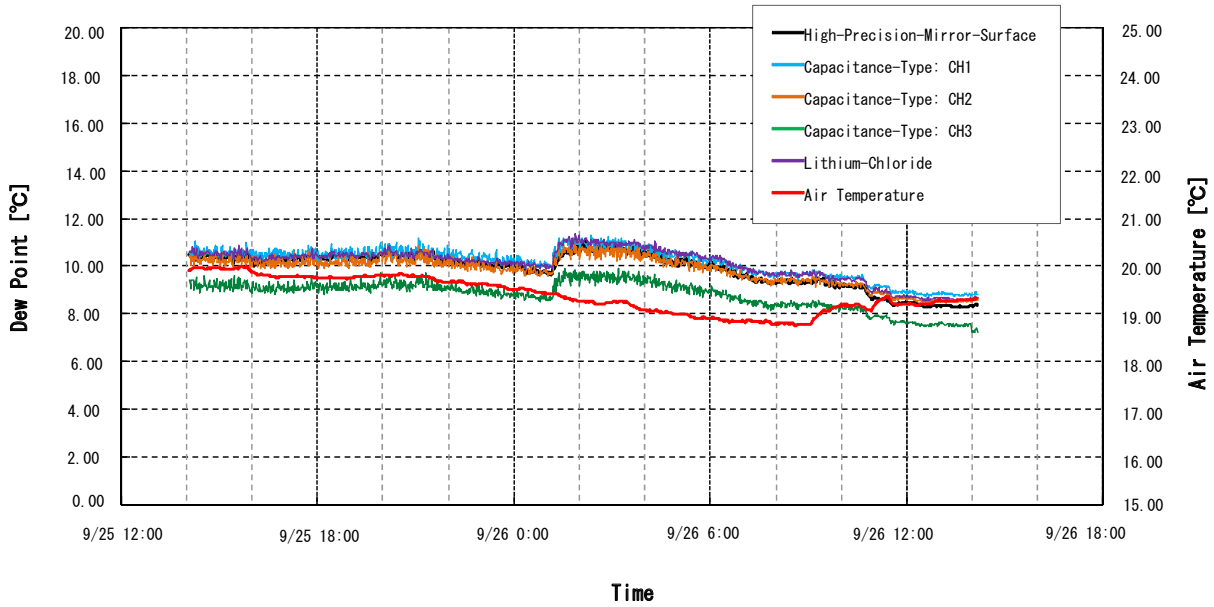

Fig.16 Measurement result of each dew point hygrometer (2013.9.25-26)

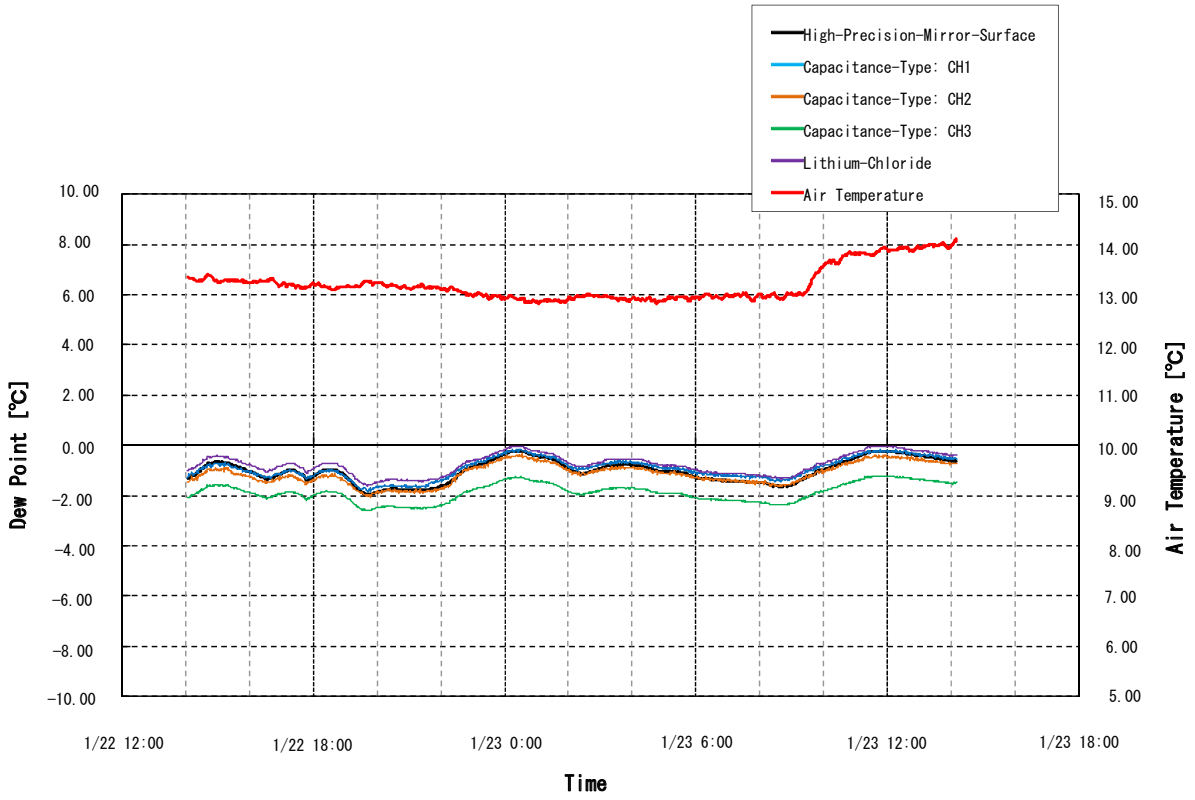

Fig.17 Measurement result of each dew point hygrometer (2014.1.22-23)

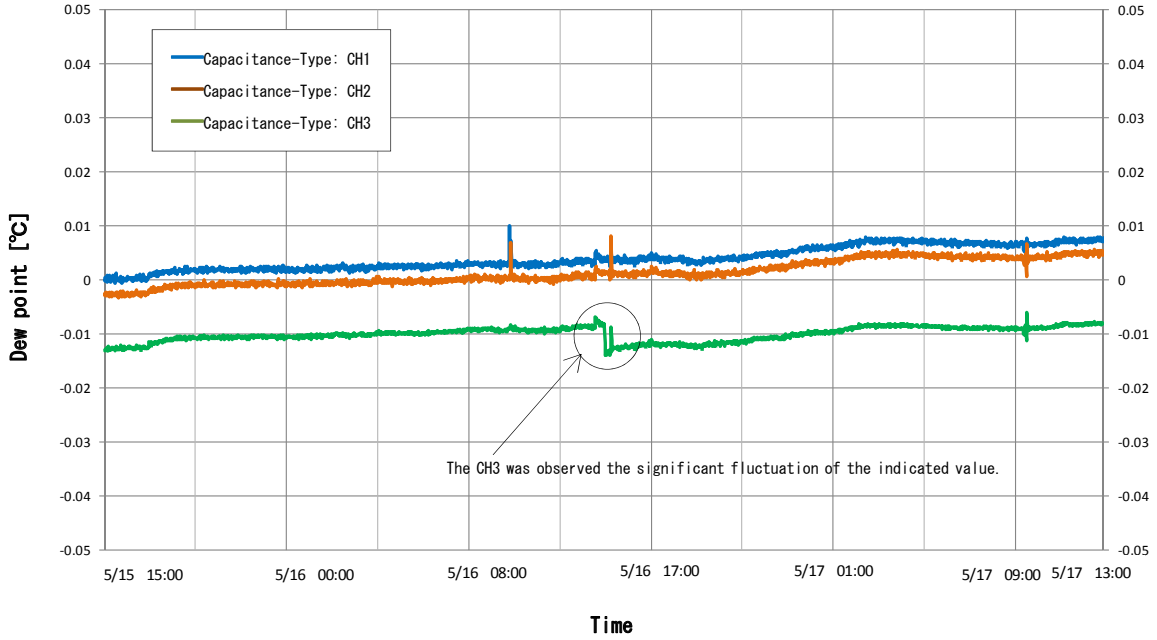

Fig. 18 Deviation of capacitance-type dew point hygrometer from high-precision-mirror-surface dew point hygrometer (2012.5.15-16)

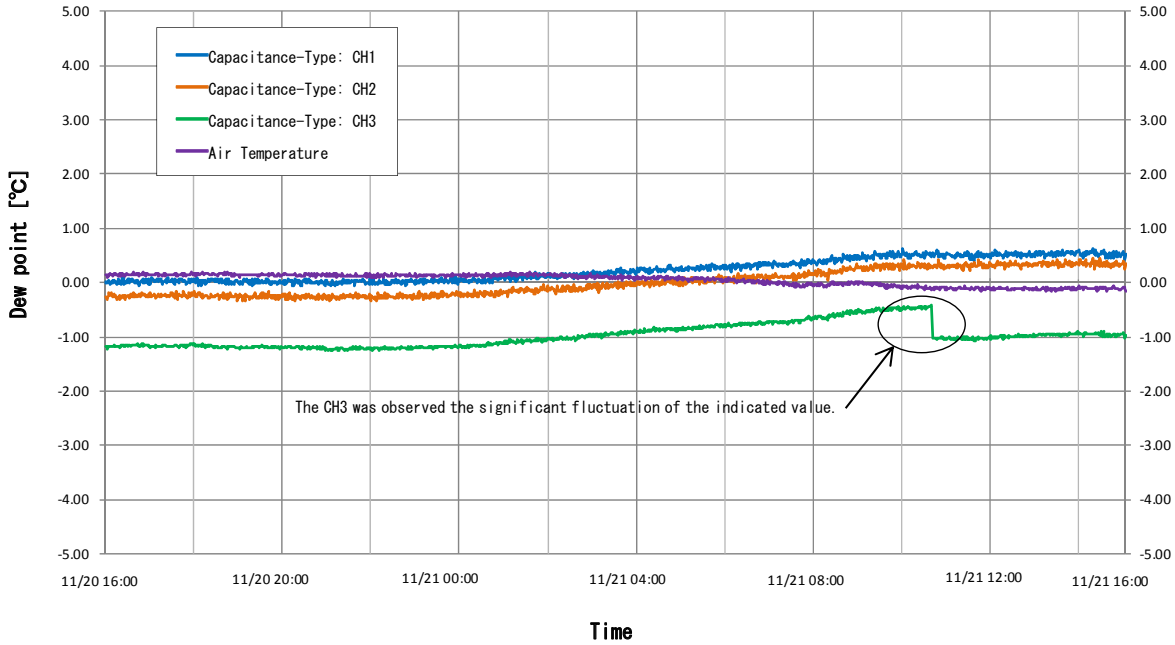

Fig. 19 Deviation of capacitance-type dew point hygrometer from high-precision-mirror-surface dew point hygrometer (2012.11.20-21)

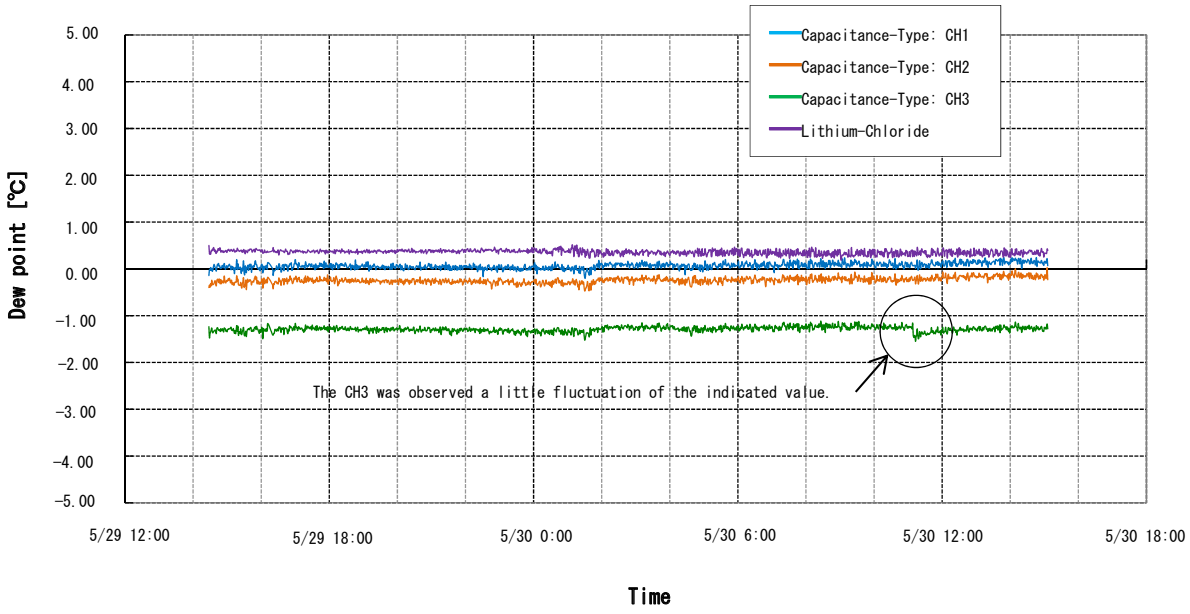

Fig.20 Deviation of capacitance-type dew point hygrometer from high-precision-mirror-surface dew point hygrometer (2013.5.29-30)

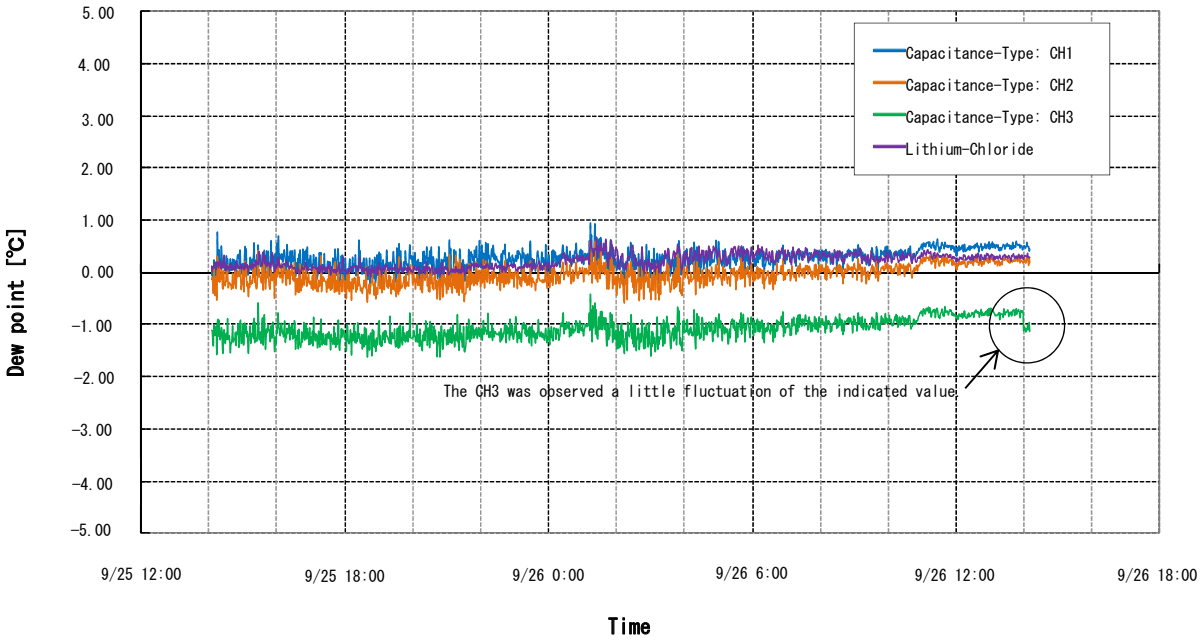

Fig.21 Deviation of capacitance-type dew point hygrometer from high-precision-mirror-surface dew point hygrometer (2013.9.25-26)

(2) Influence of intake hose length on each dew point hygrometer

Because the intake hose length may influence the output of the high-precision-mirror-surface dew point hygrometer, we evaluated the dependence of the high-precision-mirror-surface dew point hygrometer on hose length. After the prescribed measurement ended, the intake hose of the high-precision-mirror-surface dew point hygrometer was removed. Figure 22 shows the values measured by each of the dew point hygrometers before and after removal of the intake hose of the high-precision-mirror-surface dew point hygrometer. There was no significant difference in the measurements before and after removal of the intake hose of the high-precision-mirror-surface dew point hygrometer. Table 9 shows deviation of the measurement of the capacitance-type dew point hygrometer (CH1, CH2) and the lithium-chloride dew point hygrometer from the measurement of the high-precision-mirror-surface dew point hygrometer. The deviation of the measurement of the capacitance-type dew point hygrometer (CH1, CH2) from the measurement of the high-precision-mirror-surface type dew point hygrometer was about 0.06°C. The deviation of the measurement of the lithium-chloride type dew point hygrometer from the measurement of the high-precision-mirror-surface dew point hygrometer was about 0.03°C. There was no significant difference in these results.

Table 9 Deviation of capacitance-type dew point hygrometer and lithium-chloride dew point hygrometer from high-precision-mirror-surface dew point hygrometer before and after removing intake hose

Dew Point Hygrometer	Deviation from High-Precision-Mirror-Surface [℃]		Absolute Value [℃]
	Before Removing Hose	After Removing Hose	
Capacitance-Type: CH1	−0.22	−0.28	0.06
Capacitance-Type: CH2	0.04	−0.00	0.04
Lithium-Chloride	−0.50	−0.47	0.03

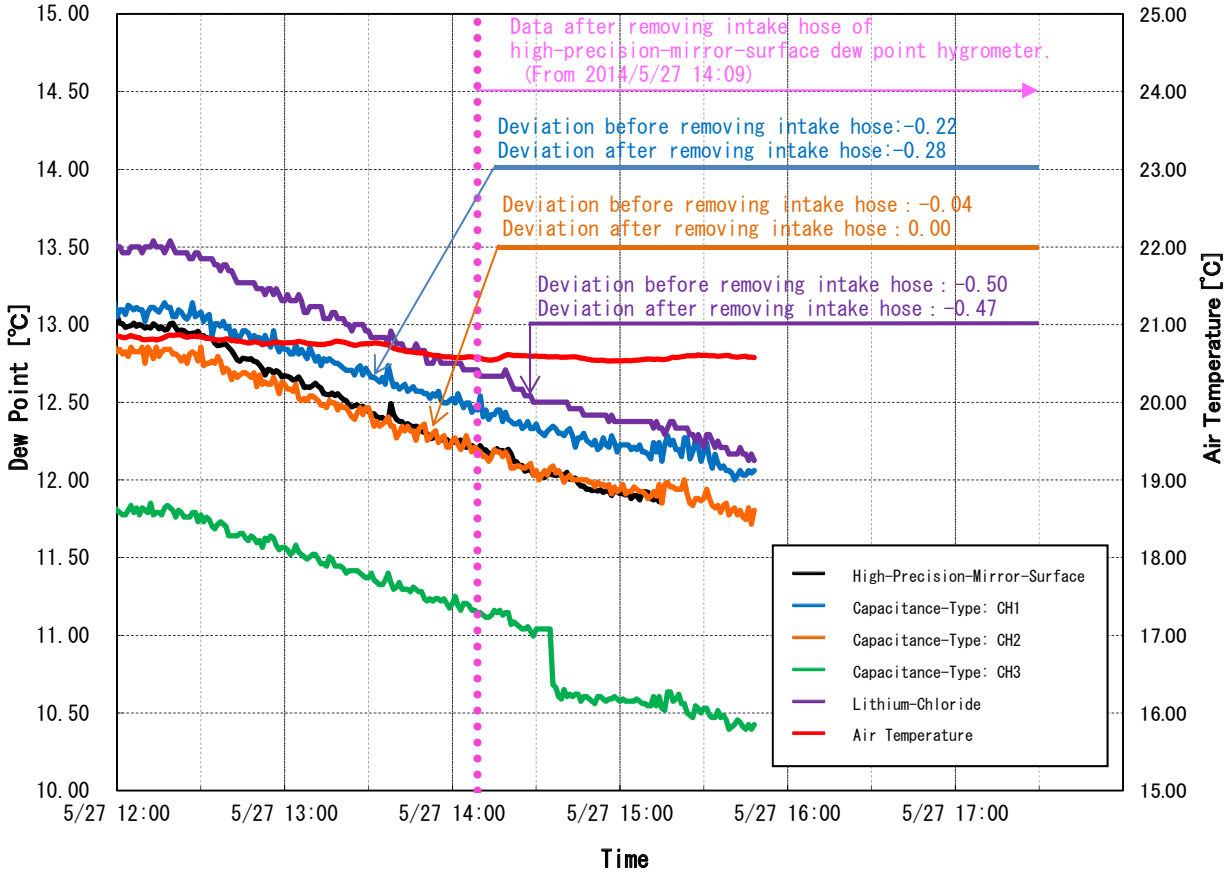

Fig.22 Measured value of each dew point hygrometer before and after removing intake hose

(3) Comparison of environment data at each MONJU location

Table 10 shows the environmental data (dew point (including partial water vapor pressure), temperature, humidity, salinity, dust condition) at each location (floor (air atmosphere), underfloor (nitrogen atmosphere), and warehouse) of MONJU.

The dew point and the temperature of the underfloor were measured in the CV-LRT carried out in 2009. The dew point was measured by a lithium-chloride dew point hygrometer. The humidity was calculated from the dew point and the temperature in the CV-LRT.

The dew point of the floor was measured by the lithium-chloride dew point hygrometer used in the long-term verification examination (6, 8 months). The humidity was calculated from the dew point and the temperature.

The temperature and the humidity of the warehouse in MONJU were obtained from data (temperature, humidity) published by the Meteorological Agency. The dew point was calculated from these data. The environment of the warehouse corresponded to the environment of the instrument shelter used for meteorological observation.

As a result of the comparison at each location, because the dew point, temperature, salinity, and dust levels on the floor (air atmosphere) were higher than those on the underfloor (nitrogen atmosphere), it was

confirmed that the environment of the floor significantly influenced the sensor than the environment of the underfloor.

Table 10 Comparison of environmental data at each location in MONJU

	Warehouse in MONJU (No Ventilating and Air Conditioning Facility)	Floor in CV (Air Atmosphere) (Examination Room)	Underfloor in CV (Nitrogen Atmosphere)
Dew Point [℃] 【】 shows partial water vapor pressure calculated from dew point	約 20.6 ℃ ※1 【2429Pa】	Max. 10.21 ℃※3 【1246Pa】	Max. -3.84 ℃ ※5 【460Pa】
	約 23.3 ℃ ※2 【2864Pa】	Max. 16.26 ℃※4 【1850Pa】	
Environmental Temperature [℃] Humidity [%]	24.9 ℃※6, 77%※6	21.5 ℃ , 46%※8	20.9 ℃ ※10 19%※8
	29.5 ℃※7, 69%※7	25.5 ℃ , 50%※9	
Salinity [mg/m^2]	約 90～470mg/m^2	3mg/m^2※11	<3mg/m^2※12
Dust Condition	Because a fresh air is taken with the ventilation fan and flow in at the time of the opening and shutting of the shutter, there are many dusts.	Because a filter is installed in the aeration side of the ventilation air conditioner, dusts are few.	Because the underfloor is supplied nitrogen and is confined (cell structure), dusts are fewer than floor.

※1 Converted from temperature (24.9 ℃) in June, 77% humidity.
※2 Converted from temperature (29.5 ℃) in August, 69% humidity.
※3 Data from six months after (June, 2010, 9.55 ℃ minimum, <1192Pa>)
※4 Data from eight months after (14.38 ℃ at the least in August, 2010, <1640Pa>)
※5 Dew point in CV-LRT carried out in December, 2009 (minimum: -8.39 ℃, <325Pa>)
※6 Mean temperature and mean humidity according to Meteorological Agency data (at the time of the June data collection, in Tsuruga-shi)
※7 Mean temperature and mean humidity according to Meteorological Agency data (at the time of the August data collection, in Tsuruga-shi)
※8 Data collected six months after. There was no dew condensation because it was managed with an air conditioner; humidity in the MONJU warehouse was lower than that in the atmosphere. The humidity was calculated from environmental temperature and dew point.
※9 Data collected eight months after. There was no dew condensation because it was managed with an air conditioner; humidity in the MONJU warehouse was lower than that in the atmosphere.
※10 Average temperature during CV-LRT carried out in December, 2009. There is no dew condensation. On the underfloor with nitrogen atmosphere, humidity was lower than that on the floor with air atmosphere.

(4) Calibration result

Table 11 shows the calibration result of the capacitance-type dew point hygrometer (CH1, CH2, CH3) obtained by the manufacturer after final examination (24 measurement months). The deviation of measurement of the capacitance-type dew point hygrometer from the standard measurement was within the accuracy (±2.0°C) specified by the manufacturer, with the exception of one point in the low temperature range (standard dew point for CH3: −56.6°C); it was within ±1.0°C across most of the temperature range.

The high-precision-miller-surface dew point hygrometer, which was used as the reference device for long-term verification, was calibrated against the standard before and after the examination in each measurement month. The accuracy of the standard was an order of magnitude higher than that specified in JEAC4203-2008 (synthesized precision of detector and converter: ±2.04°C). It was confirmed that the accuracy of the high-precision-mirror-surface type dew point hygrometer was within ±0.2°C. As an example, Table 12 shows the calibration result before and after the final examination (24 measurement months).

Table 11 Calibration result of capacitance-type dew point hygrometer after final examination

Standard Dew Point [℃]	Capacitance-Type: CH1		Standard Dew Point [℃]	Capacitance-Type: CH2		Standard Dew Point [℃]	Capacitance-Type: CH3	
	Dew Point [℃]	Deviation [℃]		Dew Point [℃]	Deviation [℃]		Dew Point [℃]	Deviation [℃]
−10.0	−9.8	+0.2	−10.0	−9.9	+0.1	−10.0	−10.4	−0.4
−40.0	−39.3	+0.7	−40.0	−39.4	+0.6	−40.0	−39.4	+0.6
−56.6	−56.0	+0.6	−56.8	−57.2	−0.4	−56.6	−50.0	+6.6
−10.4	−10.0	+0.4	−10.4	−10.3	+0.1	−10.1	−10.6	−0.5
−5.5	−5.2	+0.3	−5.5	−5.5	0.0	−5.0	−6.0	−1.0
0.6	0.3	−0.3	0.6	−0.1	−0.7	1.0	−0.5	−1.5

Table 12 Calibration result of high-precision-mirror-surface dew point hygrometer before and after final examination

Standard Dew Point [℃]	High-Precision-Mirror-Surface Dew Point Hygrometer			
	Before 24 Measurement Months (2014/5/14)		After 24 Measurement Months (2014/6/17)	
	Dew Point [℃]	Deviation [℃]	Dew Point [℃]	Deviation [℃]
−10.00	−9.89	0.11	−9.88	0.12
0.00	0.09	0.09	0.09	0.09
10.00	10.05	0.05	10.05	0.05
20.00	20.00	0.00	20.00	0.00
23.00	22.97	−0.03	22.98	−0.02

6. Discussion

6.1 Discussion of verification examination under CV-LRT condition

The indicated value of each dew point hygrometer, namely, capacitance-type dew point hygrometer (2 cars: detector A and detector B) and lithium-chloride dew point hygrometer (mean value of 20 cars, and detector ME-20 (installed at D20 in Figure 5)), increased with time, as shown in Figure 9. Because there was no significant difference between the measurements of detectors A and B, and the measurement of these capacitance-type dew point hygrometers were similar to the measurement of the lithium-chloride dew point hygrometer used in the basic design, it is conceivable that the responsiveness of the capacitance-type dew point hygrometer conformed to the CV-LRT condition. The details of the increase in the indicated value will be discussed later.

The measurements of detectors A and B were a slightly lower (maximum of 0.5°C) than the measurement of ME-20 installed in the same place. It is considered that the difference was caused by the difference in the accuracy of the two types of instruments (capacitance-type dew point hygrometer: ±2.0°C, lithium-chloride type dew point hygrometer: ±0.5°C). However, because the difference was within the JEAC4203-2008 (synthesized precision of detector and converter: ±2.04°C) specification, and there were no individual differences between the two capacitance-type dew point hygrometer, conceivably, the accuracy of the capacitance-type dew point hygrometer during the CV-LRT is within the value specified in JEAC4203-2008.

Because the error of the capacitance-type dew point hygrometer did not require calibration after the examination, it is conceivable that the CV-LRT condition does not affect the capacitance-type dew point hygrometer.

From the discussion, it is conceivable that the capacitance-type dew point hygrometer can be used for CV-LRT in MONJU.

Even in the measurement of the lithium-chloride dew point hygrometer, there were differences between the mean values of 20 cars and detector ME-20. It is conceivable that these differences were caused by a rise in the partial water vapor pressure on the CV floor during CV-LRT. Figure 23 shows the measurements recorded by the thermometers installed at 80 locations in the CV (refer to Figure 5). There were no significant fluctuations of temperature across the thermometer locations on the floor with the air atmosphere, underfloor with air atmosphere, and underfloor with nitrogen atmosphere in usual time. From this phenomenon, it is considered that there is no contribution to increase of a dew point of the difference of ventilation air-conditioning system at each places.* By contrast, the partial water vapor pressure values measured by the lithium-chloride dew point hygrometer at 20 places in the CV showed significant difference across the floor, underfloor with air atmosphere, and underfloor with nitrogen atmosphere in usual time. There were no significant differences in the partial water vapor pressure on the underfloor with nitrogen atmosphere in usual time. By contrast, the partial water vapor pressure on the floor and the underfloor in usual time increased with time, as shown in Figure 24. The phenomenon was observed in another CV-LRT of the fast experimental reactor Joyo (hereinafter called "JOYO")[6][,7]. This reason was ascribed to the following reasons:

Because the equipment hatch in JOYO was open before the CV-LRT, humidity from air was introduced to the CV and was absorbed into the concrete structure and the heat insulating material of the pipe, and so on. This humidity was released to the CV during CV-LRT. As a result, the partial water vapor pressure increased.

It is conceivable that same phenomenon occurred in the CV of MONJU. Because the underfloor with nitrogen atmosphere in usual time was isolated and nitrogen was passed in cycles through each the room of the underfloor under controlled conditions, it is conceivable that the partial water vapor pressure on the underfloor with nitrogen atmosphere did not increase. From the discussion, it is conceivable that the value measured by the dew point hygrometer of detector ME-20 was higher than the mean value of the lithium-chloride dew point hygrometer (20 cars) because the mean value of the lithium-chloride dew point hygrometer (20 cars) contained the data of the underfloor with nitrogen atmosphere in usual time.

*: The ventilation air-conditioning system for the floor and the underfloor with air atmosphere in usual time is the common unit for each room, and it circulates the air that is taken from outside and cooled. This ventilation air-conditioning system stops to take in outside air and stops the part of circulation cooling function during CV-LRT. On other hand, the ventilation air-conditioning systems for the underfloor with nitrogen atmosphere are independent for each loop, and they cool and circulate nitrogen.

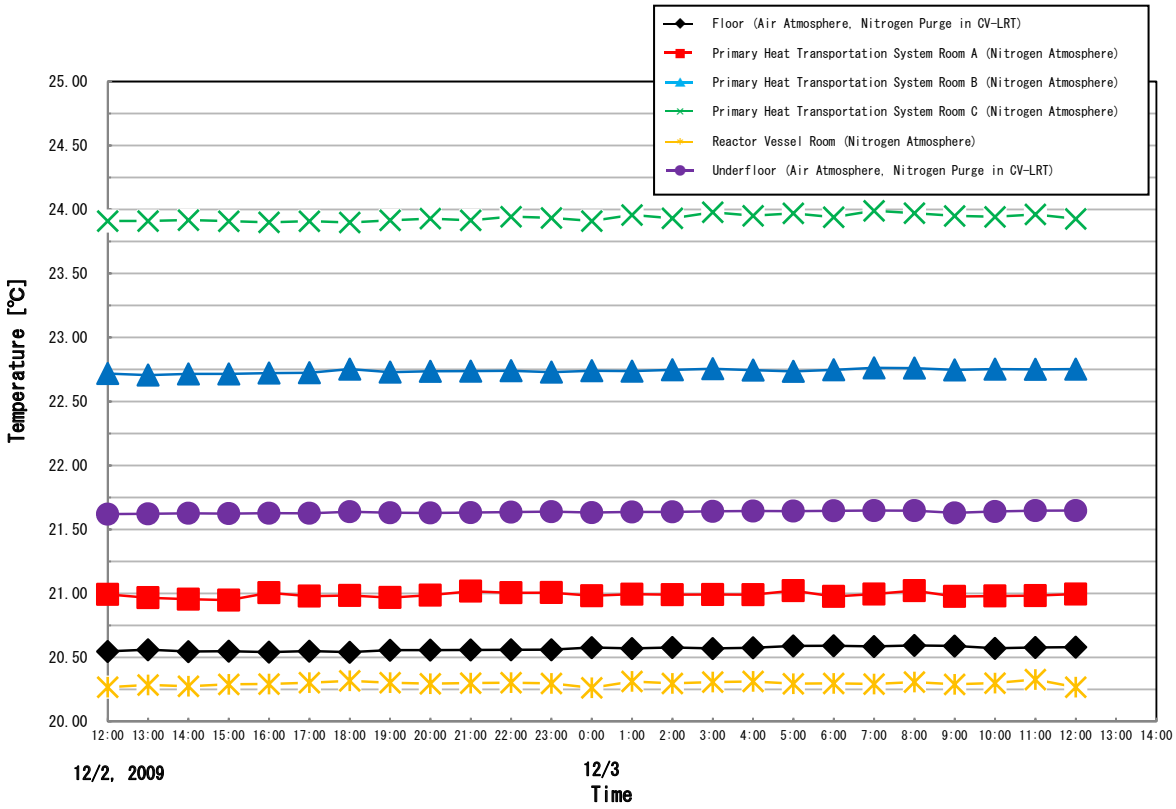

Fig.23 Temperature change in CV during CV-LRT of MONJU

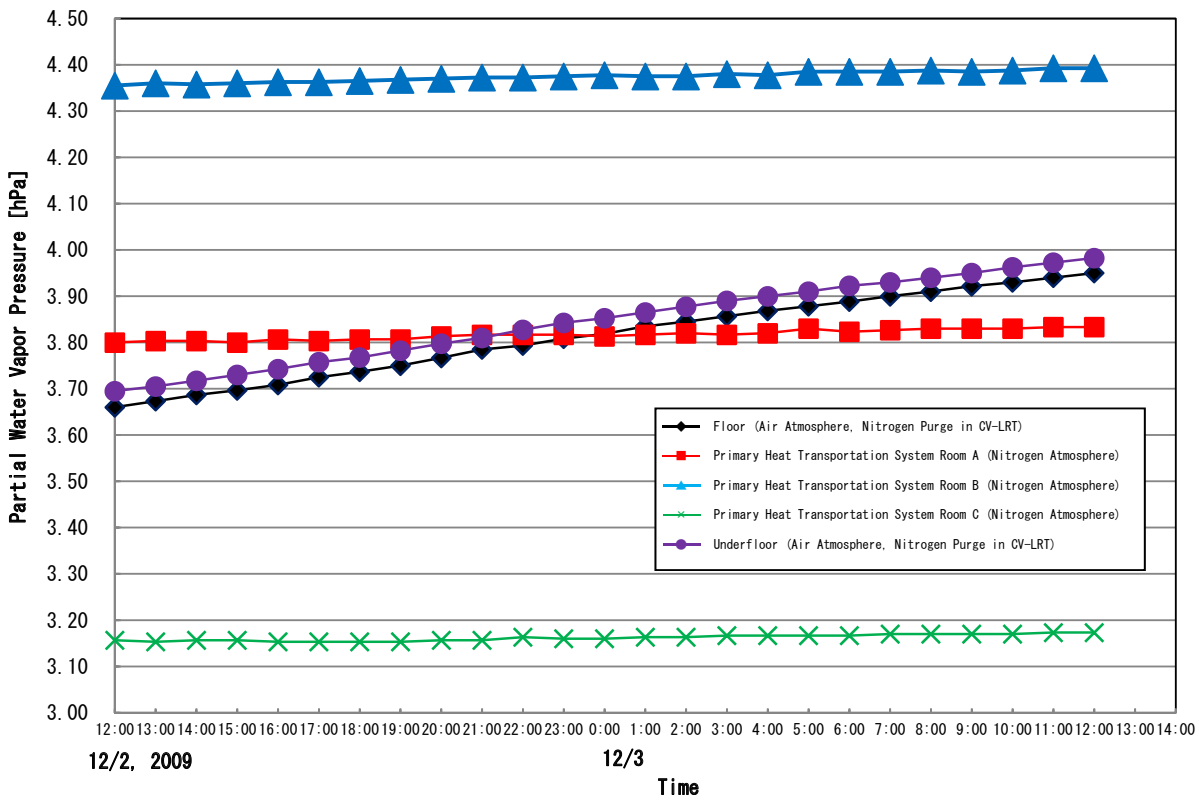

Fig.24 Partial water vapor pressure change in CV during CV-LRT of MONJU

6.2 Discussion of long-term verification examination under usual condition

As a result of the comparison of the floor (atmosphere: air) with the underfloor (atmosphere: nitrogen), as summarized in Table 10, dew point, humidity, salinity, and dust on the floor were found to be higher than that on the underfloor. The floor environment influenced the sensor of the dew point hygrometer to a greater extent than the underfloor environment. Because long-term verification was carried out on the floor, the environment of which had a higher load than the underfloor environment, the measurement of the long-term verification was influenced by the CV-LRT condition with the nitrogen atmosphere.

In the above environment, because the indicated values of the capacitance-type dew point hygrometer (detector CH1 and detector CH2) showed same behavior as that of the high-precision-mirror-surface dew point hygrometer, which was the reference, and the lithium-chloride dew point hygrometer, as shown in the comparisons in Figures 11–17, it is conceivable that the responsiveness of the capacitance-type dew point hygrometer does not matter. Because the mean deviation of the measurements of detectors CH1 and CH2 from the measurement of the high-precision-mirror-surface type dew point hygrometer was 0.38°C (1.02°C was the maximum value), as in Table 8, and was within JEAC4203-2008 specification (synthesized precision of detector and converter: ±2.04°C), it is conceivable that the capacitance-type dew point hygrometer can measure continuously for at least 24 months in an environment identical to the floor without performance degradation over time. However, if the capacitance-type dew point hygrometer is to be used in other locations, it is necessary to confirm that dust concentration in the location is lower than that on the floor in advance.

The indicated value of detector CH3 was the same as the indicated value of detector CH1 and detector CH2 (refer to Figures 11–17). The deviation of the measurement of detector CH3 from the high-precision-mirror-surface type dew point hygrometer, which was used as the reference, was larger than that of detectors CH1 and detector CH2, as in Table 8, and the indicated value fluctuated in measurement months 0, 6, 12, and 16 (refer to Figures 18–21). Specifically, in measurement months 0 and 6 (refer to Figures 18, 19), the indicated value of the CH3 stopped temporarily (hold state) and decreased to a low value after it was restarted (hereinafter called “step change”). It is conceivable that the sensor purge function of the capacitance-type dew point hygrometer influences the indicated value.

The sensor purge function removes chemical ingredients and impurities on the sensor by heating the sensor. The measurement is kept on hold for about 5 min until the sensor is cooled, and it is then recalculated. However, because the sensor purge function is developed for environments characterized by low dew point (relative humidity: under 10%RH), it is possible that running the sensor purge function in intermediate and high dew point regions negatively influences the sensor owing to differences in humidity.

According to Table 10, the humidity on the CV floor in MONJU, where the long-term verification examination was carried out, is about 50% RH, which corresponds to an environment of intermediate-to-high dew point. The frequency of sensor purge is different for detectors CH1, CH2, and CH3 (detector CH1, CH2: 1 time/10 days; detector CH3: 1 time/1 day). The larger deviation of CH3 from the high-precision-mirror-surface dew point hygrometer compared to those of the other two detectors can

be ascribed to the influence of the detectors' different sensor purge frequencies (detectors CH1, CH2: about 73 times/24 months; detector CH3: about 730 times/24 months) in intermediate-to-high dew point regions.

The step change of detector CH3, especially in measurement months 0 and 6 can be ascribed to sensor purge in the CV environment. There is a possibility that the indicated value after the running sensor purge is lower than that before sensor purge owing to rejection ratio of impurities.

The moisture in the sensor was likely removed by sensor purge. However, because the impurities in the moisture were not removed completely, the measured dew point decreased. To apply the sensor purge function to detectors CH1, CH2, and CH3, these detectors was in the state that the step change was easy to occur during the long-term verification examination which was the environment of the intermediate-to-high dew point regions. Because the frequency of sensor purge in detector CH3 was higher than those in the other detectors, detector CH3 tended to experience step change during the long-term verification examination. Furthermore, the humidity and dust levels in measurement months 0 and 6 were higher than those in the other measurement months, which influences the rejection ratio of impurities by sensor purge, leading to significant step changes in detector CH3. For the sake of information, the floor environment during the long-term verification examination was different from that during CV-LRT because it was not isolated, with people, articles, machineries, and materials moving in and out of the CV. The floor environment during the long-term verification examination was not different every measurement month.

However, the deviation of detector CH3 was within the JEAC4203-2008 specification (synthesized precision of detector and converter: ±2.04°C) for long-term verification examination (24 months). The deviation of detector CH3 was in the reach of the individual differences which was allowed as products. It is possible that the individual differences were corrected at the time of shipment. Therefore, it was assumed that there were no problems in using the capacitance-type dew point hygrometer. Furthermore, the sensor purge function is effective at low dew points. Therefore, there is no necessity to use the sensor purge function in MONJU, which has an environment with intermediate dew point (about 0–15°C; relative humidity: 20–60% RH).

Before and after removing the intake hose of the high-precision-mirror-surface dew point hygrometer, there were no significant differences in the indicated values of each of the dew point hygrometers. It was found from the results that there was no influence of the hose on the high-precision-mirror-surface dew point hygrometer.

7. Conclusions

We tested the capacitance-type dew point hygrometer as an alternative to the lithium-chloride dew point hygrometer, and we carried out an efficiency examination by comparing the capacitance-type dew point hygrometer and the lithium-chloride dew point hygrometer under the CV-LRT condition (atmosphere: nitrogen, examination time: 24 h). Furthermore, we compared efficiencies of the capacitance-type dew point hygrometer and the high-precision-mirror-surface dew point hygrometer under the usual long-term condition (atmosphere: air, examination time: 24 months).

As results of these examinations, we confirmed that the capacitance-type dew point hygrometer satisfied the instrumental specifications (synthesized precision of detector and converter: ±2.04°C) required by JEAC-4203-2008 for the CV-LRT condition and the long-term condition.

From the discussion, we confirmed that the capacitance-type dew point hygrometer can be used as a long-term alternative to the lithium-chloride dew point hygrometer without affecting the hygrometer maintenance schedule at the MONJU plant.

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国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度[a]，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率[b]	（数字の）　1	1
比透磁率[b]	（数字の）　1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[b]	rad	1 [b]	m/m
立体角	ステラジアン[b]	sr[c]	1 [b]	m^2/m^2
周波数	ヘルツ[d]	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度[e]	℃		K
光束	ルーメン	lm	cd sr[c]	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能[f]	ベクレル[d]	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト[g]	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ s\ A$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（X 線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ s\ A$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	μ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	1 ha=1 $hm^2=10^4m^2$
リットル	L, l	1 L=1 l=1 $dm^3=10^3cm^3=10^{-3}m^3$
トン	t	1 t=10^3 kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1 eV=1.602 176 53(14)×10^{-19}J
ダルトン	Da	1 Da=1.660 538 86(28)×10^{-27}kg
統一原子質量単位	u	1 u=1 Da
天文単位	ua	1 ua=1.495 978 706 91(6)×10^{11}m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100 kPa=10^5Pa
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100fm^2=$(10^{-12}cm)^2$=$10^{-28}m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =$1cm^2\ s^{-1}$=$10^{-4}m^2\ s^{-1}$
スチルブ	sb	1 sb =1cd cm^{-2}=10^4cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} =10^4lx
ガル	Gal	1 Gal =1cm s^{-2}=$10^{-2}ms^{-2}$
マクスウエル	Mx	1 Mx = 1G cm^2=10^{-8}Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド[a]	Oe	1 Oe ≙ $(10^3/4\pi)$A m^{-1}

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1 γ=1 nT=10^{-9}T
フェルミ		1 フェルミ=1 fm=10^{-15}m
メートル系カラット		1 メートル系カラット= 0.2 g = 2×10^{-4}kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	μ	1 μ =1μm=10^{-6}m

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