# Test Analysis About Hydrogen Detection Equipment Under Severe Accident in Nuclear Power Plant

Dan Xu[1], Zhou Xiao[1], Ya-Jie Tian[1], and Xiao-Ming Qian[2](✉)

[1] State Key Laboratory of Nuclear Power Safety Monitoring Technology and Equipment, China Nuclear Power Engineering Co., Ltd., Shenzhen 518172, China
xudan@cgnpc.com.cn

[2] Nuclear and Radiation Safety Center, MEE, Beijing 100082, China

**Abstract.** Fukushima accident has caused serious damages to public health and environment. Licensees of nuclear power plants in China are required to take measures to prevent severe accident happening. Control and detection hydrogen in containment under severe accident is one of the improvement actions. This article has analyzed the requirements for hydrogen detection system and related tests requirements for this detection system. A comparison of IEC 61298 and IEC 61779 is made to find tests should be carried on a new developing detection system/equipment. Nuclear qualification tests also have been considered. One testing system frame has been put forward.

**Keywords:** Severe accident · Hydrogen detection · Testing system

## 1 Introduction

Explosions happened in Fukushima accident has reminded nuclear authorities in different countries of big damages caused by flammable and explosive gas in containment under severe accident. China National Nuclear Safety Administration (NNSA) has set up the General Requirements for Nuclear Plant Safety Improvement Actions after Fukushima Accident [1]. The hydrogen detection in containment under severe accident is one of these actions.

Due to the radioactive environment in the containment, ordinary hydrogen detection equipment isn't applicable. After the hydrogen detection improvement requirement being published, several instrument manufactures start to develop sensors which can meet the needs of nuclear plants.

There are quite a lot of hydrogen detection principles [2]. Hydrogen sensitive alloy is one of them. Hydrogen sensitive alloy can catch hydrogen atom and form a structure showing electrical feature which reflects the hydrogen concentration in the environment. Another one or more elements added in the alloy could ameliorate the fragile problem due to high hydrogen concentration and improve its detection performance. The detection equipment made of this principle can have small size and little hydrogen consumption merits. Here after this kind of sensor is named as Alloy-film sensor [3].


Y. Xu et al. (Eds.): SICPNPP 2020, LNEE 779, pp. 177–185, 2021.
https://doi.org/10.1007/978-981-16-3456-7_19

This article is to analyze the tests should be carried on a new developing hydrogen detection system/equipment which is based on the Alloy-film sensor.

## 2 Hydrogen Detection Requirement Analysis

### 2.1 Requirements on System Level

The General Requirements for Nuclear Plant Safety Improvement actions after Fukushima accident published by NNSA is a high level input for hydrogen detection system design and equipment development [1]. Considering the hydrogen control system, the hydrogen concentration in containment should be controlled under 10%.

The classification and performance requirements of the hydrogen detection system/equipment are specified by the plants. Quality managements, qualifications or tests are applied to corresponding level of standards. Detailed analysis for the applicable standards is discussed in article [4].

The operation environment for hydrogen detection equipment is related with the design of detection system. There are two main types of the hydrogen detection system which are distinguished by hydrogen sensor location, inside or outside of the containment [5]. The type of sensor locating inside of the containment is chosen as precondition for the test analysis in this article.

### 2.2 Requirements on Equipment Level

The hydrogen detection system discussed in this article mainly contains hydrogen sensor, signal transformation cabinet, environment parameter compensation components, connectors and protection enclosure. These components can be divided into two groups, self-developed components and market purchase components.

Test of self-developed components should focus on the re-productivity and stability of the sensor.

For the standard commercial components which can be purchased from market, it's important to inspect documentations or records which can support the usage of one component. These include user manual, performance features, operation feedback and potential risk judgment. Adequate analysis should be made before making choice. These components shouldn't introduce danger or risk for the safety operation of the system.

Normal operation of the hydrogen detection system under defined situations should be guaranteed by the equipment.

## 3 Design of the Testing System

### 3.1 Testing Requirement Analysis

As one kind of instrument, the hydrogen detection equipment should consider the tests mentioned in IEC 61298, and those in IEC 61779 which is a standard for hydrogen [6, 7]. Qualification tests following nuclear power standards also need to be analyzed.

Standard IEC 61298 and IEC 61779 are compared to sort out general testing requirements for system/equipment performance under normal ambient conditions [6, 7]. Qualification test is performed after the hydrogen detection performance tests under normal ambient condition. Some performance tests are used to judge if the system/equipment has pass the challenge of the qualification tests.

## 3.2 Testing Requirement Under Normal Ambient Condition

**Test Sample and Test Sequence**

IEC 61298 has no requirement for sample quantity and testing sequence [6].

IEC 61779 gives requirements on sample and test sequence of type test in its Chapter 4.2; it allows changing test sample due to different test items [7]. Long-term stability test and environmental test (dust, poisons and high gas concentration) are carried on one sample which is different from the one used for other tests.

For the situation discussed in this article, poisons which may impact function of the Alloy-film sensor don't exist in containment and storage places of nuclear power plant. So poisons test isn't applicable. Dust test can be covered by IP class test of equipment.

**Test on Accuracy**

IEC 61298 suggests carrying three or five cycles for type test [6]. Every cycle includes up and down directions, eleven test points and location at every 10% of the input span. Tests are to confirm the inaccuracy, maximum measured error, non-linearity and non-repeatability.

IEC 61779 demands the calibration to be performed three times consecutively at the points of four volume ratios evenly distributed over the measuring range [7]. For the response characteristics test, a minimum of three points spreading evenly between 20% and 100% of the measuring range needs to be checked.

Five cycles for type testing is suggested for the new developing detection system. Meanwhile, despite the check points required by standards, points to trigger alarms as defined in plant project requirement specification should be considered.

**Stability Test**

IEC 61298 sets requirements for start-up drift and long-term drift [6]. Testing time for the former is eight hours and for latter is thirty days.

IEC 61779 cares about short-term stability and long-term stability [7]. Short-term stability test is to check sensor indication value under the condition that the sensor has operated one hour in clean air and then changed to operate in hydrogen after ten minutes intervals. Long-term stability test is to check the indication value of the sensor after the detection system has continued working three months. Testing frequency of long-term stability test are different between IEC 61298 and IEC 61779 [6, 7].

**Variable Effects Test**

IEC 61298 takes several variables into consideration [6], like power, environment temperature, process fluid temperature and flow, static line pressure, atmospheric temperature, humidity, vibration, etc.

IEC 61779 covers most of variables listed in IEC 61298 [6, 7]. For a special part, IEC 61779 considers the requirement for poisoning and other gases disturbing tests [7].

EMC effects are mentioned in both standards. This will be discussed in following qualification part.

The Alloy-film sensor and its supporting components need to consider testing the influence of power changes, environment temperature and pressure, humidity and vibration. For high temperature vapor and vibration effects test, they will be discussed in following qualification part.

**Dynamic Test**

IEC 61298 checks the step response characteristic of sensor [6]. The output span changes from 10% to 90% and then reversely to 10% by triggering 10% changes of output span from a series of points.

IEC 61779 requires a step change from clean air to standard test gas, corresponding response time t(50) and t(90) to be measured in each direction [7].

How to facilitate the realization of step change is a key point for a testing system. IEC 61779 has introduced a few of methods to carry [7].

The dynamic test for the new developing hydrogen detection system will consider t(90) as the judging criteria of response time.

**Over-Range Test**

IEC 61298 requires the over-range test to be performed by using the 50% value of the maximum and minimum span as input, and to check the changes of output for the minimum span [6].

IEC 61779 requires sensor to be subjected to a step change from clean air to 50% volume fraction of gas for three minutes, and then be changed to clean air for twenty minutes [7]. After that, check residual effect tests under standard test gas.

Over range of the span usually needs to trigger alarm in the nuclear power plant operation, so 100% of maximum span is to be tested for the new developing hydrogen detection system.

**Others**

IEC 61779 sets requirements for safety degree of testing devices and preparation of standard gases [7]. It suggests methods for mixing standard gases by quoting ISO 6142/6145/6147.

A Summary of these two standards comparison is shown in Table 1.

**Table 1.** Summary of standard comparison

| Test Standard | Sample quantity | Response Test | Accuracy | Repeatability |
|---|---|---|---|---|
| IEC 61298 [6] | X | √ | - inaccuracy<br>- maximum measured error<br>- non-linearity | non-repeatability |
| IEC 61779 [7] | √ | √ | accuracy | X |
| **Test Standard** | **Long-term stability** | **Alarm** | **Variables** | **Orientation** |
| IEC 61298 [6] | √ | X | √ | √ |
| IEC 61779 [7] | √ | √ | √ | √ |
| **Test Standard** | **Selectivity** | **Poisons test** | **Over-range test** | **Power change test** |
| IEC 61298 [6] | X | X | √ | √ |
| IEC 61779 [7] | X | √ | √ | √ |
| **Test** | **EMC** | **Calibration kit** | **Drop** | **Others** |
| **Test Standard** | **Sample quantity** | **Response Test** | **Accuracy** | **Repeatability** |
| IEC 61298 [6] | √ | X | √ | X |
| IEC 61779 [7] | √ | √ | NA | - standard gas<br>- safety |

## 3.3 Qualification Tests for Nuclear Power Plant

Qualification is to confirm the equipment performance reliability under defined working environment. There are different qualification tests according to equipment's safety importance and installation environment. The commonly used standards for hardware qualification include RCC-E, IEC 60780, IEEE 323 and KTA 3503 [8–11].

Considering the possible situation of the hydrogen detection system/equipment, following qualification tests are to be carried out:

- aging tests
- EMC tests
- Seismic tests
- Radiation tests
- Thermal environment tests
- Aerosol tests
- Explosion proof tests
- Software V&V analysis and test

The qualification sequence depends on the qualification standard to be used.

### 3.4 Testing System Design

Considering all the testing requirements, a testing system can fulfill tests under normal ambient conditions and thermal environment test is built. This system can be used to check main performance features of the hydrogen detection system/equipment after some qualification tests, like aging tests and EMC tests.

**Test Chamber**

Hydrogen accumulates in the upper space of the containment under severe accident, in the way of natural diffusion. Gas flow and velocity are thought to be zero. A test chamber should provide adequate space to simulate real environment and install sensor in it. 30 L is suggested by ISO 26142 [12]. Steam producing system and thermal insulation system need to be added to support the thermal environment test.

**Response Test**

The hydrogen concentration in the test chamber can't be stabilized immediately. This influences the defining of start moment for response test.

The required response time for the hydrogen detection equipment is counted by minutes. If the claimed response time of the manufacture is obviously shorter than the required time, the hydrogen concentration stabilizing time won't influence the judgement of the test result. Because of this, the starting point of the response test can be set at the moment to begin injecting gas into the chamber. If the time difference isn't huge, the method introduced in ISO 62142 [12] (Fig. 1) can be used, that is to open small box containing sensor to let the sensor touch the gas suddenly.

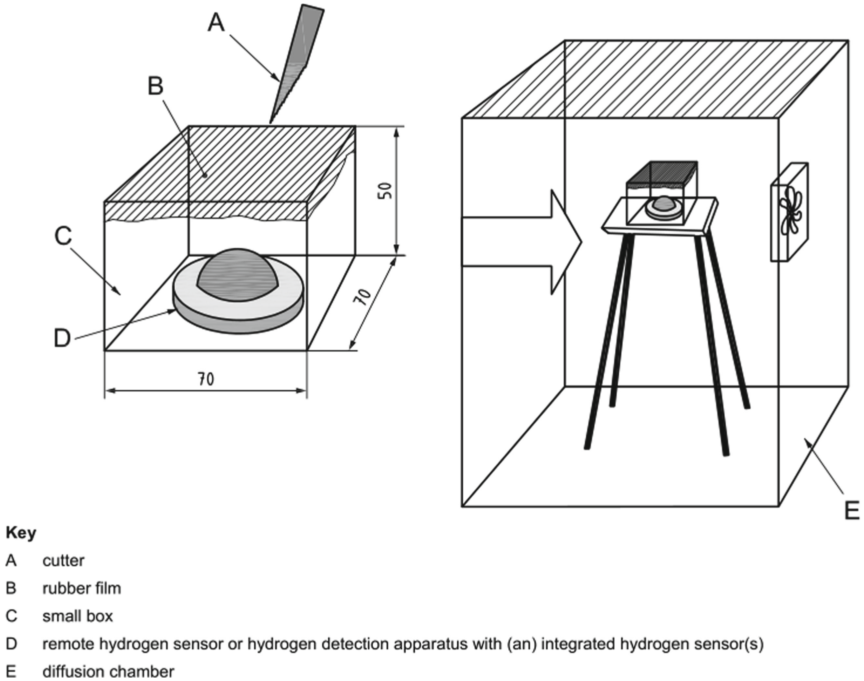


**Fig. 1.** Small box used for response time

**Control System of Test Gas Concentration**

The purpose of the test gas concentration control system is to provide the testing needed hydrogen volume concentration in test chamber by controlling the flow of different gases. Based on ideal gas equation of state, calculation of gas mass quantity is shown in Eq. (1). Compressibility factor for gas real state should be considered in tests.

$$pV = nRT$$

$$V = \sum v_i$$

then

$$n_i = \frac{p_i v_i}{RT} \tag{1}$$

The design of the test gas concentration control system has considered the control method (b) introduced in article [13]. The chamber and pipes are to be purged with gas of known composition, and then the test chamber is vacuumed by device to a preset degree. The open position of inlet valves and mass flow value are acquired by controller. Valves are to be closed when the predefined value is reached. Schematic diagram is shown in Fig. 2.

Reference sensor is set at the exhaust line of test chamber by using a diverse hydrogen detection principle, this is to validate if the test gas concentration is the value as planned.

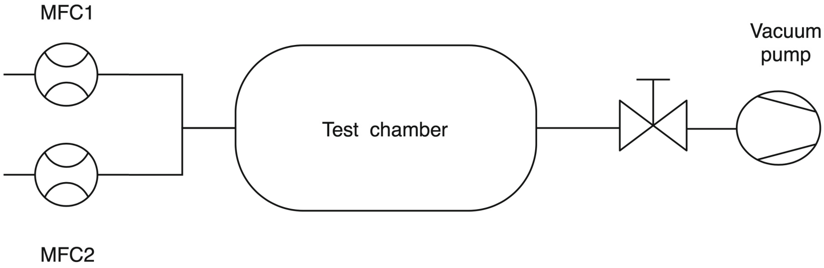


**Fig. 2.** Gas control schematic diagram

### 3.5 Testing Environment

Testing room should be broad enough to prevent explosion risk caused by hydrogen leakage. Install leakage detectors at potential areas to help confirm the environment safety and trigger alarms in time when leakage happens. Testing area, monitoring area and exhaustion area need to have adequate physical isolation. Hydrogen in exhaustion area should be diluted adequately by ventilation.

Figure 3 shows a schematic diagram combined with above analysis.

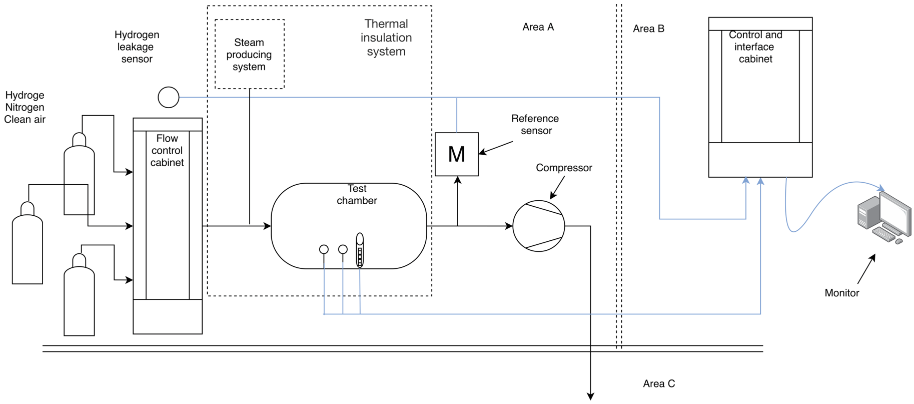


**Fig. 3.** Testing system schematic diagram

## 4 Testing System Application

The testing system discussed in this article is used in the development of one new hydrogen detection system which is based on Alloy-film sensor. This detection system aims at being used in second and third generation of pressurized water reactor nuclear power plant.

Along with the development, the testing system isn't fixed and non-changeable. With the help of several findings happened during large quantities of tests, some adjustments on the testing system are made. For example, chamber with larger volume is used for thermodynamic test than the one for normal condition tests; manufacturing materials with higher level for some components of the testing platform are applied in order to prolong their life; some suggestions mentioned in ISO 26142 are considered for the resting realization, like acceptance criteria for testing on low part of the detection range.

## 5 Summary

For the hydrogen detection equipment to be used in containment of nuclear power plant, tests following normal industry and nuclear industry standards should be implemented. Due to the hydrogen characteristics, special attention should be paid to the safety during these tests. The testing system designed in this article has covered those tests requirements and conditions applicable for pressurized water reactor nuclear power plant. But the realization of the testing system isn't so perfect, findings occurred during the testing process help make improvement for the testing system. To modularize the steam producing subsystem to quickly create thermodynamic environment can greatly improve the testing efficiency, this is the improvement target for the testing system discussed in this article.

## References


1. China National Nuclear Safety Administration: General Requirements for Nuclear Plant Safety Improvement Actions after Fukushima Accident (2012)
2. Buttner, W.J., Post, M.B., Burgess, R., Rivkin, C.: An overview of hydrogen safety sensors and requirements. Int. J. Hydrogen Energy **36**(3), 2462–2470 (2011)
3. Feng, Y.: Studies of Palladium-Silver Thin Film for Hydrogen Sensing. Master dissertation of Zhejiang University, March 2006
4. Xiao, Z., Liu, Z.-Y., Xu, D.: Analysis of the design standards for severe accident related instrument systems. Process Autom. Instrum. **36**, 18–21 (2015)
5. Xiao, Z., Jiang, X.-Y.: Discussion on the design of containment hydrogen concentration monitoring system under severe accident. Chin. J. Nucl. Sci. Eng. **31**(2), 35–40 (2011)
6. International Electrotechnical Commission: IEC 61298: Process measurement and control devices - General methods and procedures for evaluating performance (2008)
7. International Electrotechnical Commission: IEC 61779: Electrical apparatus for the detection and measurement of flammable gases (1998)
8. AFCEN: RCC-E: Design and construction rules for electrical equipment of PWR nuclear islands (2012)
9. International Electrotechnical Commission: IEC 60780: Nuclear power plants - Electrical equipment of the safety system - Qualification (2016)
10. Institute of Electrical and Electronics Engineers: IEEE 323: IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations (2003)
11. The Nuclear Safety Standards Commission (Kerntechnischer Ausschuss): KTA 3503: Specific acceptability test of electrical subassemblies of the reactor protection system (2015)
12. ISO 26142: Hydrogen detection apparatus- Stationary applications. International Standard (2010)
13. Salyk, O., Castello, P., Harskamp, F.: A facility for characterization and testing of hydrogen sensors. Meas. Sci. Technol. **17**, 3033–3041 (2006)