Development of Instruments for Improved Safety Measure for LWRs

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The Fukushima Dai-ichi Nuclear Power Station (Fukushima NPS) accident has the following aspects: it was triggered by a natural disaster; it led to a severe accident with damage to nuclear fuel, reactor pressure vessels (RPVs) and primary containment vessels; and accidents involving multiple reactors arose at the same time. IAEA reported the 28 “lessons learned” in the June Mission Report. As countermeasures against severe accident in the 28 “lessons learned”, IAEA pointed out the enhancement of measures to prevent hydrogen explosions and enhancement of instrumentation for reactors and Primary Containment Vessels (PCVs).

The Japanese government referred to a lesson of necessity of instrumentation systems working under accident conditions and Nuclear and Industrial Safety Agency suggested preventing hydrogen explosion, securing the reliability of instrumentation systems under accidents, and strengthening supervision function of plant status, etc. so as not to seriously progress nuclear accidents. Therefore, developments of new instrumentations which work well even during station black out are demanded.
# Progress of Accident and Demand of Instrumentations

## Accident at TEPCO's Fukushima Nuclear Power Stations

<table>
<thead>
<tr>
<th>Accident progress</th>
<th>Earthquake (reactor scrum)</th>
<th>Tsunami (loss of power supply)</th>
<th>Fuel dry out</th>
<th>Core damage</th>
<th>RPV damage</th>
<th>PCV damage</th>
<th>Hydrogen explosion</th>
<th>Recovery of power supply</th>
</tr>
</thead>
</table>

### Measurement target

- **RPV:** Water level, Pressure, Temp.
- **PCV:** D/W press., Temp.
- **S/C:** Water level, press, Temp.

### Influence to instrumentation

- **Un-measurable due to loss of power supply, loss of records**
- **Loss of reliability of instrumentation due to severe condition over design demand**
- **Impossible to access to measurement panel**

RPV: Reactor Pressure Vessel, PCV: Primary Containment Vessel, D/W: Dry well, S/C: Pressure Suppression Chamber, R/B: Reactor building, SFP: Spent fuel pool

Ref: [http://www.enecho.meti.go.jp/info/event/120703event.htm](http://www.enecho.meti.go.jp/info/event/120703event.htm)

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## [June Mission Report]

‘Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety’ (June 2011)

**Lesson14** The necessity of instrumentation system working under accident conditions

## [NISA]

‘Technical information on the Accident at TEPCO’s Fukushima Nuclear Power Stations’ (March 2012)

**Measure 24** Prevent of Hydrogen explosion

**Measure 27** Secure the reliability of instrumentation system under accident

**Measure 28** Strengthen supervision function of plant status
Irradiation Techniques in JMTR

IASCC test of LWR core internals

Life time extension of LWR

Power ramping test of LWR fuels

Burn up extension

Saturation temp. Automatic constant temp. High temp.

Environmental control

Water chemistry, load

Special instrumentation

Displacement, crack propagation Re-instrumentation (temp., pressure)

Power ramping

Fuel power control by $^3$He gas

Neutron control

Spectrum adjustment Pulse irradiation

Re-irradiation

Assembling in hot cell

High accuracy temp. control

Research of radiation damage

High temp. irradiation

Development of HTTR

ITER operation, He production rate/dpa simulation

Development of fusion reactor

In these irradiation techniques, many instrumentations under neutron irradiation conditions have been developed in JMTR.
Development of instrumentations for hydrogen concentration, water level, temperature, and dose rate based on the fundamental irradiation technologies accumulated at JMTR.

**Environments during severe accidents**
- RPV: high pressure, temperature, humidity, radiation
- PCV: high pressure, temperature, humidity, radiation
- Reactor building: high radiation

**Measure 24** Prevention of hydrogen explosion
- Application of the technologies on gas sensor at JMTR
  ⇒ hydrogen concentration sensor with solid electrolysis

**Measure 27** Securement of instrumentation reliability during accidents
- Application of the technologies on temperature measurement at JMTR
  ⇒ multi-paired thermocouple, water level gauge

**Measure 28** Enhancement of reactor status monitoring
- Application of the technologies on radiation measurement at JMTR
  ⇒ self-powered neutron detector, gamma-ray detector
Development of Hydrogen Gas Sensor

Prevention of gas explosion by monitoring hydrogen concentration

Fukushima accident Buildings were damaged by hydrogen explosion.

Investigation of Gas analyzer for hydrogen content in reactor

<table>
<thead>
<tr>
<th>Items</th>
<th>Sensor Type</th>
<th>Thermal conductivity</th>
<th>Controlled potential electrolysis</th>
<th>Semiconductor</th>
<th>Solid electrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
<td>&lt; 65°C</td>
<td>&lt; 50°C</td>
<td>&lt; 50°C</td>
<td>600 °C</td>
</tr>
<tr>
<td>Humidity</td>
<td></td>
<td>&lt; 90%RH</td>
<td>&lt; 80%RH</td>
<td>&lt; 80%RH</td>
<td>~ 100%RH</td>
</tr>
<tr>
<td>Irradiation</td>
<td></td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>g-ray, Neutron</td>
</tr>
<tr>
<td>Sensitivity of H₂</td>
<td></td>
<td>100%</td>
<td>&lt; 0.1%</td>
<td>&lt; 1%</td>
<td>~ 20%</td>
</tr>
<tr>
<td>External power</td>
<td></td>
<td>necessary</td>
<td>necessary</td>
<td>necessary</td>
<td>necessary</td>
</tr>
<tr>
<td>Response</td>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td></td>
<td>○</td>
<td>○</td>
<td>○</td>
<td></td>
</tr>
</tbody>
</table>
Measurement techniques of hydrogen isotopes in sweep gas at fusion reactor blankets had been developed at JMTR.

**Principle and structure**

**Proton conductor**
- Difference in concentration of hydrogen
- Evolution of electric current due to movement of hydrogen ions

**Performance**

- Temperature at sensor: 700°C
- Electromotive force vs. time
  - Response to change of hydrogen concentration: less than 1 min
  - γ-ray resistance: $2.2 \times 10^6$ Gy

- High-temperature (700°C) and high-radiation (γ dose: $\sim 10^7$ Gy) resistance
- Operation using common batteries ($\sim 12$ V)
Development of Thermocouple for Multipoint Measurement

Increase of measurement points and its operation under unusual environments

**Structure**

- Thermocouple with sheath (K-type, N-type)
- Measurement point
- Dummy rod
- Protection tube

**Performance**

- Upper
- Middle
- Lower

Irradiation test specimen

- Thin radius
- Accuracy of measurement point with ±1mm
- Performance for 17,000 h under neutron irradiation

- High-temperature (700°C) and high-radiation (γ dose: ~10⁷ Gy) resistance
- Operation using common batteries (~12 V)
Development of Water Level Gauge in LWR

Constant water-level monitoring and its operation under unusual environments

Differential pressure Type water level gauge (Current method)

(Environment at accident)
- High temp.
- High dose
Water Level Indicator with Built-in Heater and Thermo-couple

It achieves continuous monitoring of water level in reactor vessel and monitoring under special conditions.

Structure

- MIcable
- [Unit: mm]
- Sensor unit
- Sheath (SUS316)
- K-type Thermocouple

Result

- Measureable at high accuracy in boiled water.
- Confirmed by the indicator with 100m MI cable
- Measurable in high temperature (700°C) and high dose condition (about 10⁷Gy)
- Durable for long term measurement and accuracy was improved by using plural Water level indicators.
# Development of γ-ray Detector

**Constant radiation monitoring and its operation under unusual environments**

- Fukushima accident ➔ Delay of recovery efforts due to failure of radiation measurement

## Research of γ-ray detectors

<table>
<thead>
<tr>
<th>Environment</th>
<th>Gamma thermometer</th>
<th>Ionization chamber type detector</th>
<th>SPGD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under water</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Temperature</td>
<td>&lt; 200°C</td>
<td>&lt; 200°C</td>
<td>600°C</td>
</tr>
<tr>
<td>Irradiation experience</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Measurement range (Gy/h)</td>
<td>&lt; 10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>&gt; 10&lt;sup&gt;3&lt;/sup&gt;</td>
<td>&gt; 10&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>External power supply</td>
<td>Unnecessary</td>
<td>Necessary</td>
<td>Unnecessary</td>
</tr>
<tr>
<td>Response</td>
<td>bad</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Accuracy</td>
<td>bad</td>
<td>good</td>
<td>good</td>
</tr>
</tbody>
</table>

* : Self-power Gamma Detector
Results of Development of γ-ray Detector

Performance

Principle and Structure

Measurement of current due to Compton electrons induced by γ-ray irradiation

- Small cross-section of neutron capture
- Large atomic number

Selection of Pb
(Cross-section of (n, γ): 0.15 b)

- Linearity between γ-ray intensity and SPGD output
- Neutron attributable fraction less than 10%
- High-temperature (700°C) and high-radiation (γ dose: ~10^7 Gy) resistance
- Improvement of measurement accuracy
Further Enhancement of Monitoring Function

● After hydrogen explosion during the Fukushima accident, the accurate situations inside the reactor buildings could not be assessed due to the high-radiation environments. This is because the accident responses were one step behind.

● Therefore, developments of radiation-proof and high-resolution monitoring cameras and placement of them at many positions are planned. In addition, monitoring systems which work without any large electric source are desirable.
Enhancement of monitoring function by visualization of reactor core information using Cherenkov light

Structure of System

- \( \gamma \)-ray intensity
- Wave length
- Image analysis
- CCD camera (Acquisition of core image)
- Water surface
- MI cable
- Optical fiber
- Pico-ammeter
- Spectroscope
- Controller
- Core analysis (Neutronic Characteristics)
- \( \gamma \)-ray detector (SPGD)

Performance

- Image analysis (Visualization)
- Visualization and quantification of reactor information (reactor power, \( \gamma \)-ray intensity, fuel burnup)
- Radiation-proof and high-resolution monitoring cameras prepared for severe accident

Visualization of Cherenkov light by analysis of image from CCD camera
Determination of fading rate of camera by wave length and luminance of Cherenkov light
Outline of Measuring System and Image Analysis System

**Calculation code**
- **Neutronic Evaluation**
  1. SRAC code (Burn up evaluation of fuel)
  2. MVP code (Spatial distribution of Neutron flux)
  3. ORIGEN code (Gamma ray evaluation)

**γ-ray intensity**
- Gamma ray measurement
  1. Self-powered Gamma Detector (SPGD) (γ-ray calibration test)

**Wave length**
- Measurement of wave length and illuminance
  1. Spectroscope (Measurement of wave length and illuminance)

**Image analysis**
- Image analysis
  1. CCD camera (Acquisition of reactor image)
  2. Image analysis (Visualization)

**Analysis of neutron flux distribution by MVP code**
- Establishment of reactor core analysis
- Establishment of Image analysis of Cherenkov light
- Quantification of in-core information (Reactor power, γ-ray intensity, and burn-up of fuels)
Conclusions

We are developing the instrumentation monitoring reactor situations for improved safety measure for LWRs based on the lessons from the Fukushima accident.

- Self-powered and low-voltage working type instrumentations were adopted considering station black out.

- The preliminary verification tests were successfully performed and their results suggested the possibility of the practical applications well.

...in future

The in-pile testing at the JMTR to evaluate the performance of these objects.