Fundamental Research Program for Removal of Fuel Debris

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Better understanding on the characterization of damaged fuel debris is important for the restoration work of Fukushima Daiichi NPS (1F). Especially for the following:

- Debris Sampling / Removing Works
- Criticality Safety for the Debris Handling
- Material Accounting
- Evaluation of Accident Progression
- Screening of the Debris Treatment
  (which provide technical information to “judgment” of Debris Treatment)

Previous knowledge of TMI-2 and severe accident (SA) research works at around the world are very valuable, and we should create countermeasures with international cooperation.

This work would devote to the accident management and nuclear safety in the future.
2. R&D Schedule for Fuel Debris

<table>
<thead>
<tr>
<th>Item/Year</th>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Manufacture of simulated debris</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Estimation of actual fuel debris characteristics with simulated debris</td>
<td></td>
<td></td>
</tr>
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<td>3. Comparison with TMI-2 debris</td>
<td></td>
<td></td>
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<tr>
<td>4. Analysis of actual debris properties</td>
<td></td>
<td></td>
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<tr>
<td>5. Development of debris processing technologies</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **tool design**
- **Debris sampling**
- **Debris Sample**
- **Debris Removing**
- **Feasibility Study**
- **Technical Evaluation**
- **Engineering Applicability**
- **Evaluation on Long Term Storage or Disposal**

Discussion start for the debris treatment
3. Estimation of Fuel Debris Conditions in Fukushima Daiichi NPS

Weeping Cherry Blossom “Miharu-Taki-Sakura”
(Miharu-cho, Fukushima pref.)
3.1 Estimation of Damaged Reactor Core in Fukushima Daiichi NPS

**Damaged reactor core in Fukushima is quite different from TMI-2**

- Reactor type (BWR) and structures (materials and configuration)
- Accident progression (and various situations in each unit)
- Alternative coolant effect (sea water effect)

Ref. TEPCO Home Page (2012.2.21)
http://www.tepco.co.jp/nu/fukushima-np/series/index-j.html

Damaged fuel core in TMI-2 reactor

Fukushima Daiichi NPP
3.2 Estimation Scheme for the Damaged Fuel Debris

1. Damaged core conditions will be estimated by SA code.
2. Material phase information of the debris will be obtained by using thermodynamics analyzing.

Severe Accident Analyzing

- Plant Operation Data
- Reactor Core Information
- Analyzing of degraded core conditions by MELCOR etc.
- Thermodynamics Analyzing

Information to fabricate simulated fuel debris

Simulated fuel debris

TMI-2

Estimate cooling water level by neutron monitor

TMI-2

cladding tube

### 3.3 Results of reactor core analysis of TMI-2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Rod</td>
<td>393-982 °C</td>
</tr>
<tr>
<td>Upper support pillar</td>
<td>510-732 °C</td>
</tr>
<tr>
<td>Internal component</td>
<td>1227-1477 °C (stainless steel, inconel)</td>
</tr>
<tr>
<td><strong>Upper Debris Layer</strong></td>
<td>&gt; 2537°C ( : (\text{U,Zr})\text{O}_2 )</td>
</tr>
<tr>
<td></td>
<td>(Av. &lt; 1727°C)</td>
</tr>
<tr>
<td></td>
<td>(2827°C: Partially melted)</td>
</tr>
<tr>
<td>[ Upper Crust ]</td>
<td>&gt; 2537°C: Melted ( \text{U,Zr}\text{O}_2 )</td>
</tr>
<tr>
<td>[ Remelted Layer ]</td>
<td>&gt; 2537°C: Melted ( \text{U,Zr}\text{O}_2 )</td>
</tr>
<tr>
<td>[ Lower Crust ]</td>
<td>1127-1727 °C: Melted Structural Material and Control Rod</td>
</tr>
<tr>
<td>[ Stubbed Fuel ]</td>
<td>&lt; 647°C: No Crystallization of Cladding Material</td>
</tr>
<tr>
<td>Lower Debris Layer</td>
<td>&gt; 2537°C: Melted ( \text{U,Zr}\text{O}_2 )</td>
</tr>
<tr>
<td></td>
<td>(2827°C: Partially change of \text{UO}_2)</td>
</tr>
</tbody>
</table>
### 3.4 Possible impacts on the debris characteristics based on the comparison with TMI-2

<table>
<thead>
<tr>
<th>Items</th>
<th>TMI-2</th>
<th>1F</th>
<th>Departure of 1F debris from TMI-2</th>
<th>Impacts on the core debris</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Composition</td>
</tr>
<tr>
<td>Fuel Assembly</td>
<td></td>
<td></td>
<td></td>
<td>O</td>
</tr>
<tr>
<td>Structure</td>
<td>Spacer grid</td>
<td>Channel box</td>
<td>Larger amount of zirconium.</td>
<td>O</td>
</tr>
<tr>
<td>Control rod</td>
<td>Ag-In-Cd/SS</td>
<td>B4C/SS</td>
<td>Eutectic interaction between boron and iron. Distribution of FPs through metals.</td>
<td>O</td>
</tr>
<tr>
<td>Fuel</td>
<td>UO₂</td>
<td>UO₂ MOX</td>
<td>Change of the debris characteristics due to the difference between the O/M ratio of PuO₂ and UO₂.</td>
<td>O</td>
</tr>
<tr>
<td>Burn-up</td>
<td>3 months from commercial operation</td>
<td>High burn-up</td>
<td>Larger mass of FPs.</td>
<td>O</td>
</tr>
<tr>
<td>In-vessel structure</td>
<td>Lower part of RPV</td>
<td>Guide tube only.</td>
<td>Larger mass inclusions of noble metal FPs in the lower head debris possibly due to larger mass of iron.</td>
<td>O</td>
</tr>
<tr>
<td>Accident scheme</td>
<td>Melting period</td>
<td>1-2 h</td>
<td>Possibly, larger amount of molten corium formed and larger amount of FPs was volatilized. Then, highly compacted debris formed.</td>
<td>O</td>
</tr>
<tr>
<td></td>
<td>In-vessel pressure</td>
<td>&gt;5MPa</td>
<td>0.1-1MPa</td>
<td>Pressure is expected to have little impact on the corium metallurgy.</td>
</tr>
<tr>
<td></td>
<td>Cooling by sea water</td>
<td>-</td>
<td>After the melt down</td>
<td>The effect of sea water is still unknown. (e.g. Leaching behavior of FPs through the mid to long term storage.)</td>
</tr>
</tbody>
</table>
3.5 Arrangement and deliberation of plant information (e.g. Core Temperature, Amount of Material)

<Example of deliberation>
Presumption of debris creation process from the trend chart of core temperature (analytical result)

- **Actual time**
  - Around 2000°C: dissolution of UO2 by metallic melting material (Zr, Fe, B)
    - In core part, generation of (U, Zr, Fe) oxide and alloy, boride, carbide.
    - Moving of the melting materials to core bottom part.
    - Stratification of oxide layer and metallic layer.
  - Core temperature rising rate: < 0.5 K/s
    - In vapor rich condition, Zry oxidize to ZrO2 below the melting temperature.
  - Around 1200°C: Surpassing reaction of SUS/B4C, Zry/SUS around control rod.
    - Zr-Fe metallic compound, Fe-B compound fluidified around 1200°C, melting material moved core bottom and filled void.

- **Actual state**
  - Analogical inference of the composition of the fuel assembly from dimension data of public information such as construction permit application.
  - e.g.
    - UO2 : Zry : SUS : B4C = 61 : 32 : 6 : 0.8 wt%

The material composition data of each core part is needed since the properties of the plant materials affect the composition of generated debris.

### Basic specification of Fukushima Daiichi nuclear power station (construction permit application abr)
- IC stopped,
- PCV leak (assumption),
- W/W vent open,
- W/W vent close,
- Injection of seawater,
- Expanding PCV leak (assumption)