Research Needs for Thermal-Hydraulics

October 26, 2016

Koji Nishida

Hitachi-GE Nuclear Energy, Ltd.
1. Introduction
2. Thermal Hydraulic Design
3. Challenge to Critical Power Prediction
4. Detailed Two-phase Flow analysis
5. Developed Measurement Techniques
6. Proposal Test Rig in UK
7. Conclusion
Introduction

- Thermal hydraulic performance of fuel bundle has been mainly examined by mock-up fuel bundle tests.

- Hitachi has been developing an analytical method called subchannel analysis to predict critical power, which can reduce development costs and times.

- Detailed two-phase flow analysis codes are expected to apply to improve sub models in the subchannel analysis and design new fuel bundles directly.

- Detailed two-phase measurement tests are needed to make and verify models in the detailed two-phase flow codes.

- The Subchannel analysis and detailed two-phase flow codes are expected to use instead of mock-up tests in the future.
1. Introduction

2. Thermal Hydraulic Design

3. Challenge to Critical Power Prediction

4. Detailed Two-phase Flow analysis

5. Developed Measurement Techniques

6. Proposal Test Rig in UK

7. Conclusion
Development of High Economy Fuel

- Improvement of fuel economy by optimizing of arrangement of fuel and Water Rods
- Back-fit application of advanced fuel by using same fuel lattice size

![Diagram of Fuel Bundle]

- Upper Tie Plate
- Water Rod
- Spacer
- Fuel Rod (Full Length)
- Fuel Rod (Partial Length)
- Lower Tie Plate

![Graph of Fuel Enrichment vs Bundle Average Discharge Exposure]

- Full Length Rod
- Part Length Rod
- Water Rod

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Safety criteria: To prevent boiling transition caused by liquid film dryout

**Flow Pattern**
- Liquid single-phase flow
- Bubbly flow
- Churn flow
- Annular dispersed flow
- Dispersed flow

**Heat Transfer**
- No boiling
- Nucleate boiling
- Forced convection vaporization
- Post-dryout
- Dryout

**Fuel Rod**
- Dryout
- Liquid film

**Internals of RPV**
- Core
- Internal pump
- Separator
- Dryer
- Pressure vessel (RPV)

**Fuel Bundle**
- 4.5m

**Reactor**
- Liquid single-phase flow
- Bubbly flow
- Churn flow
- Annular dispersed flow
- Dispersed flow

**Flow Pattern**
- No boiling
- Nucleate boiling
- Forced convection vaporization
- Post-dryout
- Dryout

**Heat Transfer**
- Liquid film
- Dryout

**Fuel Rod**
- Dryout
- Liquid film

**Internals of RPV**
- Core
- Internal pump
- Separator
- Dryer
- Pressure vessel (RPV)
**Process of Thermal Hydraulic Design**

**Parametric Test**
- Parametric test by partial-sized or/and full-seized mock-up bundle (Example: HICOF[Hitachi])
  - Fuel rod number and size,
  - Spacer number and configuration, etc.

**Critical Power at Dryout**
- Flow Rate
  - Improve

**Pressure Drop**
- Flow Rate
  - Improve

**Nuclear Calculation**
- Fuel rod number and size,
- Water rod number and size, etc.

**Infinite Multiplication Factor**
- Burnup

**Design of Reactor Core and Fuel Bundle**

**Final Test**
- Final test by full-sized mock-up bundle (Example: Stern[Stern Lab., Canada])

**Development of Critical Power and Pressure Drop Correlations**

**Evaluation of Reactor Core and Fuel Bundle Performance**

**Licensing Process**
HICOF Test Rig

- Max. Heater Power : 4 MW
- Operating Pressure: 7 MPa
- Max. Pressure: 9 MPa
- Max. Water Flow Rate: 50 t/h
- Test Section

1/4-sized mock-up bundle for critical power test
Full-sized mock-up bundle for pressure drop test

HICOFF Test Rig

HICOF: Hitachi Core and Fuel Them-hydraulic Test Loop

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Stern Laboratory Test Rig

- Max. Heater Power: 16 MW

- Test Section
  BWR: Full-sized mock-up bundle
  PWR: Partial-sized mock-up core
  (5x5 bundle array)

http://sternlab.com/
Critical Power Test and Correlation

- Critical power data obtained by fill-sized mock-up fuel Bundle
- High accuracy correlation covered the operational condition range

Critical Power Correlation:
GEXL (General Electric Critical Quality ($x_c$)) - Boiling Length ($L_B$) Correlation

$$x_c = f(L_B, D_q, G, L, p, R)$$

Critical quality: the ratio of vapor flow rate to total vapor-water mixture flow rate at dryout

Boiling Length: the length from boiling inception to dryout

- $x_c$: Critical quality (-)
- $L_B$: Boiling length (m)
- $D_q$: Thermal Equilibrium Diameter (m)
- $G$: Mass flux (kg/m$^2$s)
- $L$: Heated Length (m)
- $p$: Pressure (MPa)
- $R$: Factor related to radial power distribution (-)

Thermal hydraulic parameters such as flow rate, pressure, fuel rods power distribution are varied to cover the operational condition range.
Operating limit: To prevent boiling transition under any transient conditions

- MCPR = Minimum Critical Power Ratio =
  
  \[
  \frac{\text{Fuel bundle power at which BT would occur}}{\text{Actual fuel bundle power}}
  \]

- MCPR through operation cycle

- Operational limit (OLMCPR, example value: 1.22)

- Decrease of MCPR during anticipated operational occurrences (ΔMCPR)

- Safety limit (SLMCPR, example value: 1.07)

- Uncertainties of GEXL correlation and monitoring system

- Boiling transition due to dryout (1.0)

- Beginning of cycle \[\Rightarrow\] End of cycle
1. Introduction

2. Thermal Hydraulic Design

3. **Challenge to Critical Power Prediction**

4. Detailed Two-phase Flow analysis

5. Developed Measurement Techniques

6. Proposal Test Rig in UK

7. Conclusion
Evaluation of critical power is an important subject in designing new nuclear fuel bundles. Critical power is examined by tests with partial-seized or/and full-sized mock-up fuel bundles.

Critical power correlations such as the GEXL have been obtained by tests with full-sized mock-up bundles under BWR condition.

Hitachi has been developing a subchannel analysis code based on a film flow model to reduce development costs and times.
Mechanistic Analytical Method

Subchannel analysis code based on film flow model, SILFEED

Outline of SILFEED
SILFEED: Simulation of Liquid Film Evaporation, Entrainment and Deposition

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Transverse mass flow rate composed of turbulent mixing, flow diversion and void drift

Transverse Mass Balance

\[ W'_{ij} = \left[ W'_{MIX} + W'_{CF} + W'_{VD} \right] \]

- \( W'_{MIX} \): Turbulent mixing due to pressure and flow fluctuations
- \( W'_{CF} \): Flow diversion due to transverse pressure gradient
- \( W'_{VD} \): “Void drift” due to strong tendency of two-phase system to approach an equilibrium phase distribution

**Mechanisms of Transverse Cross Flow**

(a) Turbulent mixing

(b) Flow diversion

(c) Void drift
Film Flow Analysis

Mechanistic dryout model in annular dispersed flow

Liquid film flow rate: $W_f$

$$\frac{dW_f}{dz} = Pe(D - E - B)$$

Deposition ante entrainment rates

$$D = kC$$
$$E = kC_{eq}$$

- $W_f$: Liquid film flow rate (kg/s)
- $z$: Axial distance (m)
- $Pe$: Wetted perimeter (m)
- $D$: Deposition rate (kg/m²s)
- $E$: Entrainment rate (kg/m²s)
- $B$: Evaporation rate (kg/m²s)
- $k$: Deposition coefficient (m/s)
- $C$: Droplet concentration rate in vapor (kg/m³)
- $C_{eq}$: Equilibrium concentration rate (kg/m³)
Critical Power strongly depends on spacer configuration and number of spacers. Critical Power increases with increasing the number of spacer.

Dryout can be observed in just front of spacer. So some researchers studied dry-patch formation due to obstacle simulating a part of spacer

Spacer effect on film flow was examined by mock-up fuel bundle with air and water at atmospheric pressure and room temperature.
Film Thickness Measurement Test

Mock-up Fuel Bundle

- Spacer
- Mock-up Fuel Bundle
- Porous Tube
- Air
- Water
- Channel Box
- Mock-up Fuel Rod
- Mock-up Water Rod

- Circular Electrode (Stainless Steel)
- Porous Tube

Film Thickness vs. Voltage Drop

Film Thickness Measurement Test

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Film Thickness Measurement Result

- Film thickness decreases just behind the spacer at side and center rods
- Film thickness increases in downstream region

Film Thickness decrease
Air velocity increases due to space ⇒ Enhancement of droplet entrainment

Film Thickness increase
Air turbulent intensity increases due to space ⇒ Enhancement of droplet deposition

Droplet concentration rate in vapor at BWR condition is larger than that at air-water condition, so we implemented deposition enhancement effect into film flow analysis.
Spacer effect is modeled by taking account of droplet deposition enhancement due to turbulent enhancement in downstream region.

Liquid film flow rate: \( W_f \)

\[
\frac{dW_f}{dz} = Pe(D - E - B)
= Pe(kC - kC_{eq} - B)
\]

Downstream deposition rate of spacer

\[
k_{SP} = \frac{v_{SP}}{v_B} k_B = \frac{\varepsilon_{SP}}{\varepsilon_B} k_B
\]

Spacer downstream eddy enhancement model

[Lahey et al., 1972]

\( v \): Fluctuation velocity (m/s)  \( \varepsilon \): Eddy diffusivity (m²/s)

[Subscripts]

\( SP \): Downstream value of spacer  \( B \): Background value
Boiling transitions are detected thermocouples in upstream region

Test Section for Verification

(a) Axial Power Distribution

Heater rod (Ø10.7mm)

(b) Radial Power Distribution

Channel Box

(c) Thermocouple Location
Verification of SILFEED

Predicted critical power is good agreement with measured one

- Pressure: 7MPa
- Mass flux: 600-2000 (kg/m²s)
- Inlet subcooling: 21-168 (kJ/kg)
Spacer Effect Analysis on Film Thickness

Spacer model taking account of deposition enhancement in the downstream can predict dryout in front of 7th spacers. Film thickness increases due to number of spacers.

### Analyzed Spacer Locations

(a) Analyzed Spacer Locations

### Calculated Film Thickness Changes

(b) Calculated Film Thickness Changes

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundle (Spacer type)</td>
<td>4X4 (Ferrule type)</td>
</tr>
<tr>
<td>Axial power distribution</td>
<td>Chopped cosine (Peak: 1.4)</td>
</tr>
<tr>
<td>Radial Power distribution</td>
<td>Uniform</td>
</tr>
<tr>
<td>Mass flux</td>
<td>1300 kg/m²s</td>
</tr>
<tr>
<td>Inlet subcooling</td>
<td>46 kJ/kg</td>
</tr>
</tbody>
</table>

It is important to measure film thickness and flow rate to clear dryout phenomena.
Hitachi has been extending the film flow analysis to predict transient and post-BT phenomena.

- Fuel bundle power has been limited to prevent boiling transition under any transient conditions.
- If "Post-BT period" is short enough and "peak clad temperature" is maintained the critical value, fuel rod damage is prevented. In BWR, high force convective heat transfer rate from rod surface to vapor can be obtained due to high speed vapor velocity (>10m/s).
Assumption of Rewet condition: Deposition rate $>$ Evaporation rate on heated rod

Mass conservation equation for liquid film

\[
\frac{\partial}{\partial t} \alpha_f \rho_f A + \frac{\partial}{\partial z} W_f = Pe (D - E - B)
\]

\[
D - E = k(C - C_{eq})
\]

Dryout condition: \( W_f = 0 \)

Rewet condition: \( D > \frac{q}{h_{lg}} \)

Heat transfer Coefficient for Post BT

Dougall-Rohsenow’s Equation*

\* MIT Report No. 9079-26 (1963)

\[
D \quad \text{Deposition rate (kg/m}^2\text{s})
\]

\[
E \quad \text{Entrainment rate (kg/m}^2\text{s})
\]

\[
k \quad \text{Deposition coefficient (m/s)}
\]

\[
C \quad \text{Droplet concentration (kg/m}^3\text{)}
\]

\[
C_{eq} \quad \text{Equilibrium droplet concentration (kg/m}^3\text{)}
\]

\[
\alpha_f \quad \text{Film volumetric fraction (-)}
\]

\[
\rho_f \quad \text{Film density (kg/m}^3\text{)}
\]

\[
A \quad \text{Flow area (m}^2\text{)}
\]

\[
P e \quad \text{Wetted perimeter (m)}
\]

\[
q \quad \text{Heat flux (kW/m}^2\text{)}
\]

\[
h_{lg} \quad \text{Latent heat (kJ/kg)}
\]
HICOF Transient BT Test to simulate Load Rejection at Low Initial Critical Power Ratio

<table>
<thead>
<tr>
<th>Item</th>
<th>HICOF (4X4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial critical power ratio</td>
<td>1.25</td>
</tr>
<tr>
<td>Number of spacer</td>
<td>7</td>
</tr>
<tr>
<td>Axial power distribution</td>
<td>Chopped cosine (Peaking: 1.4)</td>
</tr>
</tbody>
</table>

Heater rod (Ø10.7 mm)

Radial Power Distribution

Bundle power increases rapidly until it reaches about 170% of the initial power at 1.5s, and it decreases until 33% of the initial power. Pressure increases and mass flux decreases gradually.

Inlet subcooling: 50kJ/kg
Confirmaion of Film Flow Model to Post BT Phenomena

- The assumption of rewet condition (Deposition rate > Evaporation rate on heated rod) can apply to low temperature region.
- Leidenfrost effect has to be considered to predict rewet for high temperature region.
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CFD codes such as PHOENICS, Star CCM+, etc. have been developed and used in many technical fields.

Hitachi had tried to apply a gas-sold flow analysis code to clear droplet behavior around spacer.
Predicted fluctuation part of velocity is good agreement with measured one

Analytical model
- Gas flow: k-ε model for low Reynolds number

Analytical condition
- Coordinate: 2 dimensional coordinates
- Channel size: 10mmX40mm
- Mesh number of channel: 2400(40X60)
- Pressure: Atmospheric pressure
- Temperature: Room temp.
**Droplet Deposition Behavior under BWR Condition**

**Droplet Deposition is caused by turbulence around ferrule**

Ferrule (O.D. φ16mm, Thickness 0.6mm)

Fuel Rod (φ12mm)

Flow

30mm 30mm 100mm 5mm

**Droplet deposition coefficient, \( k \) (m/s)**

\[
k = \frac{D}{C}
\]

- \( D \): Deposition rate (kg/m²s)
- \( C \): Droplet concentration in vapor (kg/m³)

**Analysis**

- **Gas flow**: k-\( \varepsilon \) model for low Reynolds number
- **Droplet transfer**: Lagrangian method in consideration of drag force

**Analytical condition**

- **Coordinate**: 2 dimensional cylindrical coordinates
- **Mesh number**: 2160(27X90)
- **Pressure**: 7MPa
- **Temperature**: 285°C
- **Droplet Size**: \( \gamma \) distribution (10-400 \( \mu \)m)

**Graphs**

- **Droplet deposition coefficient, \( K \) (m/s)**
- **Distance along fuel rod, \( z \) (mm)**

- **Average vapor velocity**: 24.8m/s
- **Droplet mass flux**: 750kg/m²s
- **Droplet size**: 10-400\( \mu \)m

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Comparison of Uni-sized Droplet Deposition Behavior

Droplet deposition rate and location differ with droplet size

- **Spacer region**
- **Ave. vapor velocity:** 24.8 m/s
- **Droplet mass flux:** 750 kg/m²s
- **Droplet size:** 10μm

- **Distance along Fuel Rod, z (mm)**

- **Droplet size:** 50μm

- **Droplet size:** 100μm

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Finding from Analysis

- We used a gas-solid flow analysis code to examine droplet deposition behavior. According to the analysis results, the turbulent enhancement due to the spacer causes the droplet deposition enhancement in the downstream of the spacer.

- The droplet deposition rate and location depends on not only vapor velocity, but also droplet size.

- CFD codes such as PHOENICS, Star CCM+, etc. have been developed and they are used in many technical fields. Their turbulent models may apply to dispersed flow. However, we think that their turbulent model cannot apply directly to annular dispersed flow.

- We should develop a droplet turbulent intensity model for annular dispersed flow.
<table>
<thead>
<tr>
<th>No</th>
<th>item</th>
<th>Technique</th>
<th>Applied Condition</th>
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<tbody>
<tr>
<td>1</td>
<td>3-D void fraction distribution</td>
<td>Computed tomography system with X-ray</td>
<td>Vapor-water at BWR condition</td>
</tr>
<tr>
<td>2</td>
<td>Liquid film thickness</td>
<td>Impedance liquid film sensor</td>
<td>Air-water at atmospheric pressure and room temperature</td>
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<tr>
<td>3</td>
<td></td>
<td>Ultrasonic sensor</td>
<td>Vapor-water at BWR condition</td>
</tr>
<tr>
<td>4</td>
<td>Droplet size and two dimensional velocities</td>
<td>PDPA(Phase Doppler Particle Analyzer)</td>
<td>Air-water at atmospheric pressure and room temperature</td>
</tr>
<tr>
<td>5</td>
<td>Two dimensional velocities</td>
<td>PIV(Particle Image Velocimetry)</td>
<td>water at atmospheric pressure and room temperature</td>
</tr>
</tbody>
</table>
Measurement technique for 3-D void fraction distributions

Test Condition
7MPa, 290℃

Mock-Up Fuel Rod (φ10mm)

Channel Box (Width: 68mm)

Computed Tomography System with X-ray

3-D Void Fraction Distribution

Void Fraction

Vapor Mass Velocity: 5kg/m²/s

1.0

0

80mm

15kg/m²/s
Liquid Film Measurement Techniques (1)

**Ultrasonic sensor for film thickness measurement**

**Test Condition**
7MPa, 285°C

**Measurement Location**

**Test Section**

**Test Loop**

HUSTLE

Water

Steam

Two-Phase Flow

P T F

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Liquid film thickness at BWR condition
⇒ Utilization for film flow model to predict dryout

Liquid Film Thickness = \( \frac{1}{2} \times \text{Sound Speed} \times \text{Time Difference (t)} \)

- [1] Measured Voltage (Water [Single Phase])


- Voltage
- Time [\( \mu s \)]
- Amplitude [-]

Superficial Water Velocity = 0.25 m/s
Superficial Vapor Velocity = 7.0 m/s

Measured Results

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## Expectation on Measurement Techniques

Detailed test data obtained using the latest measurement techniques will accelerate the development of more reliable models for two-phase flow analysis.

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<td>PIV(Particle Image Velocimetry)</td>
<td>Water at atmospheric pressure and room temperature</td>
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These laser measurement techniques are expected to apply for vapor/water at high temperature and high pressure conditions.
### Progress of Detailed Two-phase Flow Analysis (1)

<table>
<thead>
<tr>
<th>Flow Pattern</th>
<th>Turbulent Model</th>
<th>Expected development Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersed flow</td>
<td>Turbulent models for a single phase flow are applied. We have to confirm that these models are suitable for BWR condition.</td>
<td>&lt; 5 years</td>
</tr>
<tr>
<td>Annular dispersed flow</td>
<td>There is no turbulent model. We have to establish turbulent model taking account of the existence of liquid film.</td>
<td>About 15 years</td>
</tr>
<tr>
<td>Chun flow</td>
<td>Large pressure fluctuation is caused by large bubbles. Turbulent model is not expected in this flow pattern. Cross flow between subchannels are mainly caused in this flow pattern. So mechanistic cross flow model is needed to advance subchannel code.</td>
<td>&lt; 5 years</td>
</tr>
<tr>
<td>Bubbly flow</td>
<td>Some researchers propose turbulent models based on experiments with air-water condition. We have to confirm these models are suitable for BWR condition.</td>
<td>About 10 years</td>
</tr>
</tbody>
</table>

**Flow Pattern**
- Dispersed Flow
- Annular Dispersed Flow
- Churn Flow
- Bubbly Flow
- Liquid single-phase flow
Progress of Detailed Two-phase Flow Analysis (2)

- **Continuous Phase**: To establish turbulent model in two-phase flow
- **Dispersed Phase**: To calculate directly the effect of bubble or droplet diameter distribution

### Modeling levels of Two-phase flow

#### Bubbly Flow
- **Next Gen. Multi-Field Model**
  - Dispersed & Continuous Phase with Scale Distribution
- **Multi-Field Model**
  - Dispersed & Continuous Phase (Bubble, Droplet, Liquid Film...)
- **Multi-Fluid Model**
  - Gas & Liquid (Slip Model)
- **Homogeneous Model**
  - One-Fluid (Two-Phase Mixture Model)

#### Annular Dispersed Flow
- **Bubbles or Droplets w/ Diameter Distribution**
- **Bubbles or Droplets w/o Diameter Distribution**
- **Liquid Film on a Wall**
- **Gas-Droplet Mixture**
- **Liquid-Bubble Mixture**
- **Gas-Liquid Mixture**

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**Progress of Subchannel Analysis**

Detailed two-phase analysis can be applied to film flow part in subchannel analysis method

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross flow</td>
<td>Vapor/Liquid</td>
<td>Turbulent mixing Flow diversion Void drift</td>
<td>All Mechanistic models (no void drift model)</td>
</tr>
<tr>
<td>Film flow</td>
<td>Vapor</td>
<td>1 dimension flow</td>
<td>1-3 dimensions Turbulent flow</td>
</tr>
<tr>
<td></td>
<td>Liquid film</td>
<td>-Film disappearance</td>
<td>Droplet entrainment at film-vapor interface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Droplet entrainment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Droplet</td>
<td>Deposition (taking droplet concentration rate in vapor)</td>
<td>Deposition (taking droplet diameter distribution)</td>
</tr>
<tr>
<td></td>
<td>Spacer effect</td>
<td>Empirical deposition enhancement</td>
<td>Mechanistic (taking account of turbulent and flow direction change)</td>
</tr>
<tr>
<td></td>
<td>Leidenfrost Temp. effect</td>
<td>Not including</td>
<td>Including</td>
</tr>
</tbody>
</table>
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Progress of Critical Power Prediction Method

2016
- Detail two-phase flow analysis
- Subchannel analysis
- Partial-sized mock-up fuel bundle test
- Full-sized mock-up fuel bundle test

Around 2030
- Detail two-phase flow analysis
- Subchannel analysis
- Detail two-phase measurement test
- Partial-sized mock-up fuel bundle test

Around 2040
- Detail two-phase flow analysis
- Subchannel analysis
- Detail two-phase measurement test
- Partial-sized mock-up fuel bundle test
- Partial-sized mock-up fuel bundle test

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- Large test section: partial BWR fuel bundle for BT test with computed tomography system with X-ray, Ultrasonic liquid film sensor, etc..
- Small test section: single channel with PDPA, PIV, etc..
Estimated Dimensions of Facility Building

- Required building size: 22mW X 26mD X 28mH
- Larger building size is preferable for flexible test plan.
## Pressure Vessel and Heater Power

**Hitachi recommends #2 Plan**

<table>
<thead>
<tr>
<th>#</th>
<th>Max. test condition</th>
<th>Pressure vessel I.D and height</th>
<th>Heater power</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| 1. | 1 - 7MPa up to 290°C | 0.12m I.D. 8m height | 4MW | ● ¼ partial BWR fuel bundle BT test is possible.  
● Flexibility for component tests is low. |
| 2. | 1 - 7MPa up to 290°C | 0.18m I.D. 13m height | 4MW | ● ¼ partial BWR fuel bundle BT test is possible.  
● Most of component tests can be conducted. |
| 3. | 1 - 7MPa up to 290°C | 0.24m I.D. 13m height | 16MW | ● Full BWR fuel bundle BT test is possible. |
Example Test Items Using Small Test Section

Adiabatic and Diabatic single channel tests with detailed two-phase flow measurement system such as PDPA, PIV, etc..
- BT data for mechanistic BT prediction model development.
  (BT: dryout for BWR, departure of nucleate boiling for PWR)
- Validation data for two-phase CFDs and/or their sub models.

**BT at low heat flux**
- Due to Liquid film disappearance on a heated surface; typical BT mechanism of BWR fuels
- Detailed measuring items
  - Film flow rate, thickness and/or velocity in a flow direction
  - Droplet size, velocity, concentration distribution across a cross section, etc.

**BT at high heat flux**
- Due to bubble layer formation close to a heated surface, typical BT mechanism of PWR fuels
- Detailed measuring items
  - Steam volume fraction, length and thickness of bubble layers
  - Bubble size and velocity around boiling and BT point
  - Temperature and velocity distribution of water, etc.
1. Introduction

2. Thermal Hydraulic Design

3. Challenge to Critical Power Prediction

4. Detailed Two-phase Flow analysis

5. Developed Measurement Techniques

6. Proposal Test Rig in UK

7. Conclusion
Conclusion

The research needs for thermal hydraulic are shown below.

Test rig

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Measurement System</th>
<th>Main Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>A large test section (partial-sized mock-up fuel bundle)</td>
<td>CT system with X-ray, Ultrasonic sensor, etc.</td>
<td>To examine thermal hydraulic performance such as critical power.</td>
</tr>
<tr>
<td>A small test section (single channel)</td>
<td>PDPA(Phase Doppler Particle Analyzer), PIV(Particle Image Velocimetry), etc.</td>
<td>To make and improve models in detailed two-phase flow analysis codes.</td>
</tr>
<tr>
<td>Additional test section</td>
<td>(depending on test purpose)</td>
<td>To use other tests which need vapor and/or water respectively.</td>
</tr>
</tbody>
</table>

Analytical methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Main Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subchannel analysis</td>
<td>To predict not only critical power, but also void fraction distribution to improve core analysis.</td>
</tr>
<tr>
<td>Detailed two-phase flow analysis</td>
<td>To make sub models in the subchannel analysis code. To propel technologies in many technical fields such as automobile, heat exchanger, etc.</td>
</tr>
</tbody>
</table>