Hydraulic Test of
the Full Scale US-APWR Fuel Assembly

Non Proprietary Version

May 2011

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## Revision History

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Table of Contents

1.0 INTRODUCTION ........................................................................................................... 1-1

2.0 GENERAL DESCRIPTION ............................................................................................ 2-1
   2.1 Test Facility .............................................................................................................. 2-1
   2.2 Fuel Assembly ......................................................................................................... 2-1

3.0 FLOW INDUCED VIBRATION AND LONG-TERM FLOW TESTS ......................... 3-1
   3.1 Objective .................................................................................................................. 3-1
   3.2 Procedure ................................................................................................................. 3-1
   3.3 Test Results ............................................................................................................. 3-7
   3.4 Evaluation ............................................................................................................... 3-18

4.0 FUEL ASSEMBLY PRESSURE DROP AND LIFT FORCE TESTS ....................... 4-1
   4.1 Overview .................................................................................................................... 4-1
   4.2 Fuel Assembly Pressure Loss Measurement Test .................................................. 4-2
   4.3 Fuel Assembly Lift Force Measurement Test ......................................................... 4-7
   4.4 Evaluation ............................................................................................................... 4-11

5.0 CONCLUSIONS ........................................................................................................... 5-1

6.0 REFERENCES .............................................................................................................. 6-1
List of Tables

Table 2.2-1  Test Fuel Assembly Design Specifications ........................................................................ 2-2
Table 3.2-1  Accelerometers Installed in the Fuel Rods of the Mockup Fuel Assembly ................................................................. 3-3
Table 3.3.2-1  Vibration Amplitude of Fuel Rods at 302°F (150°C) Water Temperature in the Long Term Flow Test ........................................................................ 3-9
Table 4.2.3-1  Measured Pressure Drop of the US-APWR fuel Assembly ......................................................... 4-6
Table 4.2.3-2  The Validity of the test ..................................................................................................................... 4-6
Table 4.4-1  Pressure Drop Comparison between the Design and Measured Values for the US-APWR Fuel Assembly ............................................................................. 4-14
Table 4.4-2  Lift Force Comparison between the Design and Measured Values for the US-APWR Fuel Assembly ............................................................................. 4-14

List of Figures

Figure 2.1-1  Fuel Assembly Hydraulic Test Loop Pictorial ................................................................. 2-3
Figure 2.2-1  US-APWR Fuel Assembly Schematic ................................................................................. 2-4
Figure 3.2-1  Cell Size Distribution in Middle Grid Spacers ............................................................................ 3-4
Figure 3.2-2  Location of Accelerometers in Fuel Rods/Fuel Assembly for Fuel Assembly Vibration Measurement ........................................................................ 3-5
Figure 3.2-3  Location of Accelerometers in Fuel Rods/Fuel Assembly for Fuel Rod Vibration Measurement ........................................................................ 3-6
Figure 3.3.1-1  Acceleration Spectrum during Flow Velocity Sweep (BOL Condition: Grid Spacer No.3 and No.6) ........................................................................ 3-10
Figure 3.3.1-2  Acceleration Spectrum during Flow Velocity Sweep (EOL Condition: Span No. 2 and No.1) ........................................................................ 3-11
Figure 3.3.1-3  Acceleration Spectrum during Flow Velocity Sweep (EOL Condition: Span No.10 and No.6) ........................................................................ 3-12
Figure 3.3.1-4  Acceleration Spectrum during Flow Velocity Sweep (Gap Condition: Span No.10 and No.1) ........................................................................ 3-13
Figure 3.3.2-1  Fuel Rod Vibration Response (5.5m/s and 302°F) ............................................................................ 3-14
Figure 3.3.2-2  Frequency Distribution of Measured Wear Depth ............................................................................. 3-17
Figure 3.3.2-3  Visual Appearance of the Maximum Wear Depth for Gapped Cell Conditions ............................................................................. 3-17
Figure 3.4-1  Comparison of Measured and Calculated Amplitude ............................................................................. 3-19
Figure 3.4-2  Comparison between Measured and Calculated Wear Depth for EOL ............................................................................. 3-21
Figure 3.4-3  Comparison between Measured and Calculated Wear Depth for JC ............................................................................. 3-21
Figure 3.4-4  Comparison between Measured and Calculated Wear Depth for Gap ............................................................................. 3-22
Figure 3.4-5  Wear Scar Shape Schematic ................................................................................................. 3-22
Figure 4.2.2-1  Pictures of the Full Scale Fuel Assembly Mock-up ........................................................................ 4-4
Figure 4.2.2-2  Location of Pressure Taps in the Lift Force Test ........................................................................ 4-5
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.3-1</td>
<td>Fuel Assembly Pressure Loss Coefficient</td>
<td>4.6</td>
</tr>
<tr>
<td>4.3.3-1</td>
<td>Measured versus Calculated Lift Force</td>
<td>4-9</td>
</tr>
<tr>
<td>4.3.3-2</td>
<td>Lift Force Test Results</td>
<td>4-10</td>
</tr>
<tr>
<td>4.3.3-3</td>
<td>Lift Force Test Results (retest)</td>
<td>4-10</td>
</tr>
<tr>
<td>4.4-1</td>
<td>Top Nozzle Spring Characteristics and Holddown Force</td>
<td>4-14</td>
</tr>
<tr>
<td>4.4-2</td>
<td>Holddown Spring Load-Deflection Curve</td>
<td>4-14</td>
</tr>
<tr>
<td>4.4-3</td>
<td>Holddown Spring Load-Deflection Curve per Fuel Assembly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(4 Holddown Spring Sets)</td>
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1.0 Introduction

This report documents the test procedures, conditions and results of the hydraulic tests which were performed on a US-APWR mockup fuel assembly to confirm and validate the evaluation of fuel rod fretting wear, fuel rod hydraulic vibration characteristics, the fuel assembly pressure drop and the lift force due to coolant flow.

All the tests were conducted in compliance with the Quality Assurance Program requirements for Nuclear Facilities (ASME NQA-1).
2.0 GENERAL DESCRIPTION

2.1 Test Facility

The test fuel assembly is installed in the fuel assembly hydraulic facility, which consists primarily of a circulation pump, test section, flow meter, water storage tank, pressure control tank and heat exchanger. Figure 2.1-1 shows a schematic of the fuel assembly hydraulic test loop.

The hydraulic test facilities for full scale prototype fuel assembly, located at the NDC (Nuclear Development Corporation), are used to investigate the long term fuel rod fretting wear, hydraulic fuel rod vibration properties, pressure loss and lift force of the fuel assembly.

The facility is located in an underground pit.

2.2 Test Fuel Assembly

The design specification and the schematic overview for the US-APWR test fuel assembly are shown in Table 2.2-1 and Figure 2.2-1, respectively.

The tests are performed on a prototype fuel assembly that is hydraulically the same as the actual US-APWR 14 ft fuel assembly with a plugging device: Inconel-718 top and bottom grid spacers, 9 Zircaloy-4 intermediate grid spacers, 264 fuel rods, 24 control rod guide thimbles and 1 instrumentation tube. The fuel rods were filled with lead-antimony pellets to simulate the overall fuel rod weight. The rods contained a preloaded coil spring in the upper plenum and a spacer in the lower plenum.
### Table 2.2-1 Test Fuel Assembly Design Specifications

<table>
<thead>
<tr>
<th><strong>Fuel Assemblies</strong></th>
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<tbody>
<tr>
<td>Fuel Rod Array</td>
<td>17 x 17</td>
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<tr>
<td>Number of Fuel Rods</td>
<td>264</td>
</tr>
<tr>
<td>Number of Control Rod Guide Thimbles</td>
<td>24</td>
</tr>
<tr>
<td>Number of In-Core Instrumentation Guide Tube</td>
<td>1</td>
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<td>Number of Grid Spacers</td>
<td>11</td>
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<table>
<thead>
<tr>
<th><strong>Fuel Rods</strong></th>
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<tr>
<td>Outer Diameter</td>
<td>0.374 in (9.50mm)</td>
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<tr>
<td>Cladding Thickness</td>
<td>0.0224 in (0.570mm)</td>
</tr>
<tr>
<td>Active Fuel Length</td>
<td>165.4 in (4,200mm)</td>
</tr>
<tr>
<td>Pellet Material</td>
<td>Antimony-Lead- and Tungsten-Copper-</td>
</tr>
<tr>
<td>Pellet Diameter</td>
<td>0.322 in (8.19 mm)</td>
</tr>
<tr>
<td>Pellet Density</td>
<td>match UO$_2$ weight</td>
</tr>
<tr>
<td>Plenum</td>
<td>Upper &amp; Lower</td>
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<tr>
<td>Cladding</td>
<td>ZIRLO</td>
</tr>
<tr>
<td>Top &amp; Bottom Grid Spacers</td>
<td>Inconel 718</td>
</tr>
<tr>
<td>Intermediate Grid Spacers</td>
<td>Zircaloy-4</td>
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<tr>
<td>Control Rod Guide Thimbles and In-Core Instrumentation Guide Tube</td>
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<td>Nozzles</td>
<td>Stainless Steel</td>
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<td>Holddown Springs</td>
<td>Inconel 718</td>
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</tbody>
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*NOTE: Inconel 718 is a nickel-chromium-iron alloy 718.*
Figure 2.1-1  Fuel Assembly Hydraulic Test Loop Pictorial
Figure 2.2-1  US-APWR Fuel Assembly Schematic
3.0 Flow Induced Vibration and Long Term Flow Tests

3.1 Objective

The objective of the hydraulic vibration test is to quantify that acceptable flow induced vibration of the fuel rods and the fuel assembly occur over a range of flow velocities and temperatures.

The objective of the long term flow test is to validate the computational models used for flow induced vibration and fretting wear predictions of the US-APWR fuel assembly. The vibration characteristics were measured during the test and the wear scars were measured after the flow test. Analysis results for these test conditions were compared with the measurements to validate the models.

3.2 Test Procedure

A test fuel assembly with a thimble plug assembly was loaded in the test section of hydraulic test loop shown in Figure 2.1-1. The top and bottom nozzles are engaged by fuel-guide pins on corresponding upper and lower core plate simulators and the top nozzle hold-down springs are compressed, consistent with cold in-core conditions.

The test fuel assembly has 9 intermediate grid spacers of Zircaloy-4, in which grid cell sizes were adjusted to simulate as-fabricated (Beginning of life, BOL), the middle of life (MOL), end of life (EOL) and just contact (JC) and non contact (Gap) conditions, and as-fabricated top and bottom grid spacers of Inconel 718. of clearance was set between fuel rod and its support in the Gap condition. Figure 3.2-1 shows the location of the various cell sizes in each grid spacer.

To measure the fuel rod and assembly vibration amplitude, 12 fuel rods with installed accelerometers are loaded in the test fuel assembly. Figure 3.2-2, Figure 3.2-3 and Table 3.2-1 show the cell positions and grid spacer elevation of accelerometers installed in the fuel rods. The accelerometers in the fuel rods at grid spacer and were installed to measure the acceleration response of the fuel assembly for the even and odd vibration modes, respectively. The accelerometers for the fuel rod vibration were installed at the center of the spans, consistent with the peak modal response locations of the fuel rod.

The hydraulic vibration test was performed in advance of the long term flow test. A flow sweep from startup (zero-flow) to MDF (mechanical design flow) was performed and the acceleration response of the 12 fuel rods was measured. After the flow velocity sweep test, dwell tests were performed where the accelerations were measured at representative constant flow velocities.

The 1000 hour long term flow test was conducted to study the fuel rod fretting wear characteristics. The accelerometers in the fuel rods were at the same positions as in the hydraulic vibration test. Additionally, in order to identify abnormal vibration conditions during testing, accelerations experienced by the fuel rods and fuel assembly were measured once per 100 hours to monitor the variation of the vibration amplitude and frequency. The wear scars were measured after the 1000 hour test. The test operating conditions and primarily the grid cell size effect are used in benchmarking the computational wear analysis. The wear analysis models are then adjusted to in reactor operating conditions to evaluate the wear depth associated with reactor operating conditions.
< Hydraulic Induced Vibration Test Conditions >

Coolant: De-ionized Water

Coolant flow velocity: Flow sweep from startup (0m/sec) to 18 ft/sec (5.5 m/sec) for complete flow spectrum measurement, and representative constant flow velocity (dwell) such as 3.3m/s (60% of MDF), 4.4m/s (80% of MDF) and 5.5m/s (100% of MDF) for discrete flow spectrum measurement

Temperature: 86°F (30°C), 122°F (50°C), 176°F (80°C), 212°F (100°C), 248°F (120°C), and 302°F (150°C)

Pressure: 87 psi to 131 psi (0.6 MPa to 0.9MPa)

< Long Term Flow Test Conditions for Fuel Rod Cladding Wear >

Duration: 1000 hours

Coolant: De-ionized Water

Coolant flow velocity: 18 ft/sec (5.5 m/sec)

Temperature: 302°F (150°C)

Pressure: Over 85 psi (0.59 MPa)
Table 3.2-1  Accelerometers Installed in the Fuel Rods of the Mockup Fuel Assembly  
(Grid No.1 and Span No.1 at Top of Fuel Assembly)
Figure 3.2-1  Cell Size Distribution in Middle Grid Spacers
Figure 3.2-2  Location of Accelerometers in Fuel Rods/Fuel Assembly for Fuel Assembly Vibration Measurement
Figure 3.2-3  Location of Accelerometers in Fuel Rods/Fuel Assembly for Fuel Rod Vibration Measurement
3.3 Test Results

3.3.1 Hydraulic Vibration Test Result

(1) Fuel Assembly Vibration

Figure 3.3.1-1 shows the flow sweep results at 302°F that were obtained at grid spacer and in fuel rods with BOL conditions. There is no abnormal increase of the acceleration or resonant characteristics of flow induced vibration of the fuel assembly over the range of flow velocities it is expected to experience. The same trend is also observed at different test temperatures. It can be concluded that abnormal flow induced vibration of the fuel assembly does not occur.

(2) Fuel Rod Vibration

Figure 3.3.1-2 thorough Figure 3.3.1-4 show the flow sweep results at 302°F which were obtained from fuel rods with EOL and Gap conditions. No abnormal increase was observed in the acceleration spectrum during the velocity variation from low to high velocity. The same trend is also observed in the different fuel rods and the different temperatures. It can be concluded that unexpected flow induced vibration of the fuel rod does not occur in the US-APWR fuel assembly.

3.3.2 Long Term Flow Test Result

(1) Fuel Rod Amplitude

Fuel rod vibration responses at 5.5m/s and 302°F, shown in Figure 3.3.2-1, are representative vibration responses. The 12 accelerometers in the x and y plots in Figure 3.3.2-1 show the acceleration spectrum at the middle span and grid spacer position of the fuel rods for BOL, EOL and Just Contact (J/C) cell conditions. The accelerometer signals were monitored throughout the test.

To obtain the amplitude displacement, the measured acceleration signals were double integrated with respect to time using a low frequency cut-off. Since the rod vibration is basically random, these measured data were reduced to the mean value and standard deviation.

Table 3.3.2-1 shows the mean amplitude for the different cell conditions. The amplitude is defined as follows.

\[
u = \sqrt{\frac{1}{2} \sum \left( \frac{A_{fi}}{2\pi f_i} \right)^2 \frac{1}{H_B}}
\]

where

\[u : \text{Amplitude}, \quad A_{fi} : \text{RMS acceleration at frequency of } f_i \text{ (Hz) by FFT}
\]

\[f_i : \text{Frequency (0 through 200Hz)}, \quad H_B : \text{Correction Coefficient for Hanning Window}\]
There is little difference in the span 1 and span 10 in spite of the different cell conditions. This is because the cell conditions in the top and bottom grids are BOL and the difference of the middle grid cell conditions does not influence the vibration. The amplitudes at span 10 are larger than those at span 1, because the length of span 1 is larger than that of span 10.

(2) Fretting Wear

The fuel rods were visually inspected and the depth of wear scars at the grid spacer springs and dimples was measured at the completion of the 1000 hour hydraulic test. The frequency distribution of the measured wear depth is shown in Figure 3.3.2-2. The deepest wear depths occurred at the spring position in grid spacer [ ], which had the GAP cell condition, with a value of about [ ]. The visual appearance of the wear scar is shown in Figure 3.3.2-3.
Table 3.3.2-1 Vibration Amplitude of Fuel Rods at 302°F (150°C) 
Water Temperature in the Long Term Flow Test
Figure 3.3.1-1  Acceleration Spectrum during Flow Velocity Sweep  
(BOL Condition: Grid Spacer No.3 and No.6)
Figure 3.3.1-2  Acceleration Spectrum during Flow Velocity Sweep  
(EOL Condition: Span No. 2 and No.1)
Figure 3.3.1-3  Acceleration Spectrum during Flow Velocity Sweep
  (EOL Condition: Span No.10 and No.6)
Figure 3.3.1-4  Acceleration Spectrum during Flow Velocity Sweep  
(Gap Condition: Span No. 10 and No.1)
Figure 3.3.2-1  Fuel Rod Vibration Response (5.5m/s and 302°F)
Figure 3.3.2-1 (Continued)  Fuel Rod Vibration Response (5.5m/s and 302°F)
Figure 3.3.2-1 (Continued)  Fuel Rod Vibration Response (5.5m/s and 302°F)
Figure 3.3.2-2 Frequency Distribution of Measured Wear Depth

Figure 3.3.2-3 Visual Appearance of the Maximum Wear Depth for Gapped Cell Conditions
3.4 Evaluation

The calculated span-amplitude distributions are compared with the measured amplitude in Figure 3.4-1, which shows good agreement for each cell condition. The measured amplitude was obtained in the same manner described in the Section 3.3.2.

The wear calculation described in the Reference (1) was performed for the fuel rods in each case of a BOL, EOL, Just Contact and Gapped cell condition. Figure 3.4-2 through Figure 3.4-4 show the comparison of calculated and measured wear depth. In the Figure 3.4-2, wear

These results suggest that the treatment of fuel rod vibration and wear calculation model gives the conservative wear evaluation in EOL and J/C condition which are more important in the evaluation, although additional treatment is needed to more accurately express the actual behavior at a gapped cell. It was confirmed that the vibration and wear calculation model proved to be useful in evaluating the fretting wear of fuel rod.
Figure 3.4-1  Comparison of Measured and Calculated Amplitude
Figure 3.4-1 (Continued)  Comparison of Measured and Calculated Amplitude
Figure 3.4-2  Comparison between Measured and Calculated Wear Depth for EOL

Figure 3.4-3  Comparison between Measured and Calculated Wear Depth for JC
Figure 3.4-4  Comparison between Measured and Calculated Wear Depth for Gap

Figure 3.4-5  Wear Scar Shape Schematic
4.0 FUEL ASSEMBLY PRESSURE DROP AND LIFT FORCE TESTS

4.1 Overview

The fuel assembly lift force is used in designing the fuel assembly holddown springs. The fuel assembly lift force is calculated by the following equation, which is derived from the conservation of momentum equation.

\[
L = \Delta P_{FA} \times A
\]

\[
= \frac{1}{2} \rho V^2 K \times A
\]

- \( L \): Fuel Assembly Lift Force
- \( \Delta P_{FA} \): Fuel Assembly Pressure Loss
- \( \rho \): Coolant Density
- \( V \): Flow Velocity
- \( K \): Pressure Loss Coefficient
- \( A \): Fuel Assembly Pitch Squared (control surface)

Two types of full scale US-APWR fuel assembly mockup hydraulic tests were conducted to confirm the accuracy of the lift force calculation.

The first full scale hydraulic flow test is a fuel assembly pressure loss measurement test to determine the fuel assembly fuel assembly loss coefficient for the calculation of the fuel assembly lift force. In this test, the pressure loss coefficient over an appropriate range of Reynold’s Numbers was determined by using a wide range of flow rates and temperatures.

The second full scale hydraulic flow test is a fuel assembly lift force measurement test. In this test, a load cell was installed on the lower core support plate to measure the fuel assembly lift force. The purpose of the test is to confirm that the lift force calculation method using the equation described above is applicable to the US-APWR fuel assembly. A comparison was made between the lift force measured by the load cell and the lift force calculated with the above equation, and it was confirmed that good agreement is obtained. The other purpose is to confirm that the holddown spring force can meet the design requirement. In this test, the fuel assembly was lifted off by increasing the flow velocity, and it was confirmed that holddown spring force at the lift-off was in good agreement with the design value. In addition, the holddown spring height, after the test loop is disassembled, was measured to confirm that the decrease of the holddown spring force due to the additional plastic deformation of the holddown spring that occurs due to the fuel assembly lift-off is consistent with the holddown spring load-deflection curve.
4.2 Fuel Assembly Pressure Loss Measurement Test

4.2.1 Objective
The purpose of the test is to determine the fuel assembly pressure loss coefficient for the lift force calculation during cold startup, hot full power and pump-over-speed event.

In this test, the pressure loss coefficient over an appropriate range of Reynolds Numbers was measured by using a wide range of flow rates and temperatures.

4.2.2 Test procedure
A full scale fuel assembly mock-up was used in the test, and the pressure loss over a wide range of Reynolds Numbers was measured. An overview of a full scale fuel assembly mock-up is shown in Figure 4.2.2-1.

The lower core support plate and the upper core plate are simulated in the test section, and one fuel assembly was installed in the fuel assembly test loop shown in Figure 2.1-1.

The pressure loss, which is a difference in the upstream and downstream pressure of the fuel assembly, was measured. By changing the coolant temperature and the flow rate, the Reynolds’s Number was changed in the range from and the pressure loss in this Reynolds Number range was measured continuously. With this pressure loss data, the pressure loss coefficient of the fuel assembly was calculated.

Figure 4.2.2-2 shows the location of the pressure taps.

The validity of the test was confirmed by comparing between the pressure loss coefficient of the entire core (1) and the total value, which is the sum of the pressure loss coefficient of the lower core support plate (2), the fuel assembly (3), and the upper core plate (4).

The test conditions are as follows:

Flow Rate Conditions
- Fluid:
- Temperature:
- Pressure:
- Reynolds Number:

Data Reduction Method
The pressure loss is expressed by the following equation:

\[ \Delta P = DH \times K \]

\( \Delta P \): Pressure Loss
\( DH \): Dynamic Pressure \( (DH = \frac{1}{2} \rho V^2) \)
\( K \): Pressure Loss Coefficient

Therefore, the pressure loss coefficient can be obtained by the equation below.

\[ K = \frac{\Delta P}{DH} \]
The fuel assembly pressure loss was measured in the test. With this pressure loss, the pressure loss coefficient was calculated on the basis of the above equation.

### 4.2.3 Test Results

The relationship between the Reynolds Number and the pressure loss coefficient of the fuel assembly are shown in Figure 4.2.3-1.

The fitting of the pressure loss coefficient to the Reynolds Number was performed, and the pressure loss coefficient was calculated by extrapolating it to the hot full power reactor coolant condition. The lift force was calculated using this pressure loss coefficient.

In addition, within the range of error, the pressure loss coefficient of core (Zone (1)) shows agreement with the sum of the pressure loss coefficient of the lower core support plate (2), fuel assembly (3), and upper core plate (4), as shown in Table 4.2.3-2.

Table 4.2.3-1 shows the pressure loss of fuel assembly during cold startup, hot full power operation and the pump over-speed event.
Figure 4.2.2-1 Pictures of the Full Scale Fuel Assembly Mock-up
Figure 4.2.2-2 Location of Pressure Taps in the Lift Force Test
Figure 4.2.3-1  Fuel Assembly Pressure Loss Coefficient

Table 4.2.3-1 Measured Pressure Drop of the US-APWR Fuel Assembly

Table 4.2.3-2 The Validity of the test
4.3 Fuel Assembly Lift Force Measurement Test

4.3.1 Objective

The primary purpose of the test is to confirm that the lift force calculation method using the equation described above is applicable to the US-APWR fuel assembly.

The secondary purpose of the test is to duplicate the additional plastic deformation of the holddown spring that occurs due to the fuel assembly lift-off, for the validation of the holddown spring force calculated by the load deflection curves after additional permanent deflection of the holddown spring.

4.3.2 Test procedure

In this test, the fuel assembly lift force and pressure loss were measured by using the same test equipment as that used in the pressure loss measurement test. In order to measure the fuel assembly lift force, a load cell was installed on the location where the fuel assembly is in contact with the lower core support plate.

To generate the additional plastic deformation in the holddown springs, the flow rate was increased until the fuel assembly was lifted off the lower core support plate. If the measured value of the load cell installed on the lower core support plate did not change when the flow velocity was incrementally increased, the fuel assembly lifted-off at that velocity. After the fuel assembly was lifted off, the flow velocity was decreased, and it was confirmed from the measured value of the load cell that the fuel assembly came back into contact with the lower core support plate.

The test conditions are as follows:

- Fluid:
- Temperature:
- Pressure:
- Flow Velocity:
- Measurement:

4.3.3 Test Results

(1) Validation test of the Lift Force Calculation Method

(a) Measured Value of Fuel Assembly Lift Force:

The fuel assembly lift force was measured using the load cell installed on the lower core support plate.

\[ L_i = F_0 - F_i \]

\( L_i(\text{N}) \): Fuel Assembly Lift Force
\( F_0(\text{N}) \): Load Cell Measurement at Zero Flow Velocity (Initial Value)
\( F_i(\text{N}) \): Load Cell Measurement at Discrete Flow Velocities (m/s)
(b) Calculated Value of Fuel Assembly Lift Force

The fuel assembly lift force was calculated by the following equation.

\[ L_{pi} = \Delta P_{FA} \times A \]

- \( L_{pi}(N) \): Fuel Assembly Lift Force
- \( \Delta P_{FA}(Pa) \): Measured Fuel Assembly Pressure Loss
- \( A \): Fuel Assembly Flow Path Cross-Section (Flow Path Cross-Section at Inspected Height)

The fuel assembly pressure loss measurement in the test was used to calculate the lift force concurrently with the lift force measurement by the load cell.

(c) Validation of the Lift Force Calculation Method

The measured value of fuel assembly lift force and the calculated value of fuel assembly lift force are compared in Figure 4.3.3-1. The lift force calculated from pressure loss is in good agreement with the lift force measured in the test. Therefore, it was confirmed that the calculation method for the lift force is valid.
The holddown spring heights were measured for 12 leaf spring (3x4 sets) after the fuel assembly was removed from the test loop and the holddown springs are removed from the top nozzle. As results, the average permanent deflections of the holddown springs were obtained to be 20.8 mm (standard deviation: 0.9 mm).

Figure 4.3.3-1 Measured versus Calculated Lift Force
Figure 4.3.3-2  Lift Force Test Results

Figure 4.3.3-3  Lift Force Test Results (retest)
4.4 Evaluation
Thus, it was confirmed that the holddown spring additional plastic deformation that occurs by the fuel assembly lift-off was consistent with the holddown spring load-deflection curve.
Table 4.4-1 Pressure Drop Comparison between the Design and Measured Values for US-APWR Fuel Assembly

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<th>Event</th>
<th>Pressure Loss Used in Fuel Design (KPa)</th>
<th>Pressure Loss Measured in Test (KPa)</th>
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<tr>
<td>Cold Startup</td>
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<td>272</td>
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<td>Hot Full Power</td>
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<td>173</td>
</tr>
<tr>
<td>Pump Over-speed</td>
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</tbody>
</table>

Table 4.4-2 Lift Force Comparison between the Design and Measured Values for the US-APWR Fuel Assembly

<table>
<thead>
<tr>
<th>Event</th>
<th>Lift Force used in Fuel Design (N)</th>
<th>Lift Force using Measured Pressure Drop (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Startup</td>
<td>17690</td>
<td>12578</td>
</tr>
<tr>
<td>Hot Full Power</td>
<td>10919</td>
<td>8000</td>
</tr>
<tr>
<td>Pump Over-speed</td>
<td>15724</td>
<td>11052</td>
</tr>
</tbody>
</table>
Figure 4.4-1 Top Nozzle Spring Characteristics and Holddown Force
(Same as Figure 4.6-2 of Reference (1))

Figure 4.4-2 Holddown Spring Load-Deflection Curve
(Based on Figure 4.4-2 of Reference (2))
Figure 4.4-3 Holddown Spring Load- Deflection Curve per Fuel Assembly
(4 Holddown Spring Sets)
5.0 CONCLUSION

The hydraulic vibration test of the mockup US-APWR fuel assembly was performed to verify that no excessive flow induced vibration of the fuel rods and the fuel assembly occur over a range of flow velocities and temperatures. As a result, it can be concluded that acceptable flow induced vibration of the fuel rod and fuel assembly will occur in the US-APWR fuel assembly.

The 1000 hour long term flow test is to verify the computational models for flow induced vibration and fretting wear of the US-APWR fuel assembly. It was confirmed that the vibration and wear calculation model is appropriate in evaluating the fretting wear of fuel rods.

The pressure loss coefficient to be applied in the lift force calculation was measured using the full scale fuel assembly mock-up. In this test, the flow rate and temperature were changed, and the pressure loss coefficient in the Reynolds Number ranging from 40,000 to 300,000 was measured. The test result showed that the pressure loss used in fuel design is conservative.

The lift force on the fuel assembly was measured using a full scale fuel assembly mock-up and a load cell installed on the lower core support plate.

The test result showed that the lift force measured by the load cell was in excellent agreement with the lift force from the calculation. Thus, it was confirmed that the lift force calculation method is applicable to the US-APWR fuel assembly.

Moreover, in this test, the fuel assembly was lifted off by increasing the flow velocity and it was confirmed that the holddown spring force at the lift-off condition shows good agreement with the design values and therefore the holddown spring forces satisfy the design requirement.
6.0 REFERENCES

(1) US-APWR Fuel System Design Evaluation, MUAP-07016-P(R3) and MUAP-07016-NP(R3), August 2010

(2) MHI's Amended Responses to the NRC's Requests for Additional Information on Topical Report MUAP-07008-P(0) “Mitsubishi Fuel Design Criteria and Methodology” UAP-HF-09538, November 30, 2009