Visualization Of Bundle Refuelling Impact Tests At AECL

R. Guduri, S. Palleck, K-S. Sim, A. Sun And A.M. Manzer*

Atomic Energy of Canada Limited (AECL)
Fuel Design Branch
2251 Speakman Drive
Mississauga, Ontario
Canada L5K 1B2

*CANTECH Associates Limited
5575 North Service Road
Burlington ON,
Canada L7L 6M1

ABSTRACT

Refuelling impact tests were performed in a flow visualization rig at Atomic Energy of Canada Limited (AECL) using an acrylic flow tube and simulated CANDU® channel components, under ambient temperature and pressure conditions with 37-element bundles. An acrylic tube was used as the inlet end of the PT, which facilitated the visualization and high-speed video recording of the impacting bundle movements.

This paper presents the results from the above investigative tests, giving the trends in the impact velocities, impact loads, and bundle condition for different coolant flow rates. The "impact velocity" versus travel distance trends are compared to previous work.

1. INTRODUCTION

During refuelling in "fuel with flow" CANDUs, the coolant sweeps the first new bundle downstream, causing it to accelerate and impact the fuel bundles already in the channel. The severity of the impact increases with bundle velocity, which

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depends on the acceleration distance and the coolant velocity in the end fitting. The accelerated bundle and fuel bundle string are required to withstand these impact forces during the normal flow-assisted fuelling.

Tests were conducted to measure impact velocities for a range of flow rates, to determine the effects of typical impacts to which bundles are subjected and to characterize the bundle velocity profile along the acceleration distance for various flows.

2. BACKGROUND

In 1976, AECL performed an impact qualification test in a hot pressurized test channel (at 10.41 MPa and 289 ºC) to qualify the 37-element fuel bundle for refuelling impacts in CANDU 6 reactors. During the qualification test, the inlet bundle accelerated from 0 to 2.63 m/s over 1.27 m in a channel flow rate of 26.7 kg/s. No significant deformation was found on the bundles and the sliding wear damage on the pressure tube (PT) was considered negligible. Based on this evidence, the 37-element bundle was qualified for refuelling impacts in CANDU 6 reactors.

A refuelling impact test of the CANFLEX-NU® fuel bundle was performed in 1996 in the KAERI CANDU Hot Test Loop facility (at 10.2 MPa, 267 ºC and at a flow rate of 31.5 kg/s), and the measured impact velocity at the instant of collision was 2.85 m/s inside straight sections of the PT at an acceleration distance of 1.25 m.

The above refuelling impact tests for 37-element bundle and CANFLEX bundle were performed to specific operating conditions and did not cover a wide range of operating conditions.

3. Model Equation

To relate the CANDU 6 refuelling impacts to those expected for FWF operation in 12 or 13 bundle channels in Bruce and Darlington, AECL developed an impact velocity model in 1994. The model was developed with the assumption that the net force acting on the impacting bundle is equal to the difference between the coolant hydraulic drag and the sliding friction force between the bundle and the PT. The bundle velocity characteristics can be predicted by these expressions:

Bundle terminal velocity for long acceleration distances:

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$$V_{term} = V_c - [1 - A_f / A_c]\sqrt{2\mu\, m\, g / K\rho\, A} \qquad (1)$$

Slope of the axial profile of the bundle velocity along the acceleration distance:

$$\frac{dV_b}{dx} = (\mu g / V_b)(V_{term} - V_b)(2V_c - V_b - V_{term})/(V_c - V_{term})^2 \qquad (2)$$

Where,
f is channel flow rate (kg/s),

V_c is velocity of coolant at upstream of the moving bundle in m/s = $V_c = \frac{f}{\rho\, A_c}$,

K is loss coefficient of head for a stationary fuel bundle,
ρ is coolant density at the fuel inlet in kg/m^3,
μ is dynamic sliding coefficient of friction of a fuel bundle sliding inside the coolant tube,
V_c' is coolant velocity within the moving bundle relative to the coolant tube (m/s),
$V_c' = (f / \rho - V_b A_f) / (A_c - A_f)$,
V_b is velocity of the moving bundle in m/s,
A is effective push area of the fuel bundle in m^2,
A_c is effective coolant area in open PT in m^2,
A_f is effective fuel bundle cross-section area in m^2,
m is bundle mass in kg, and
g is gravitational acceleration in m/s^2.

Using the above equations, bundle velocities were calculated for the 37-element bundle for the same flow of 26.7 kg/s as was used in the 1976 tests, with both light water and heavy water coolant, and compared in Figure 1. The calculated velocity matched well with the tested value at 1.27 m acceleration distance (difference is with in 7%). The comparison between light and heavy water shows that by testing the bundle impacts with light water, we have an advantage of testing the bundle with 10 % higher impact velocities than for the same flow of heavy water, owing to the difference in coolant densities between the two.

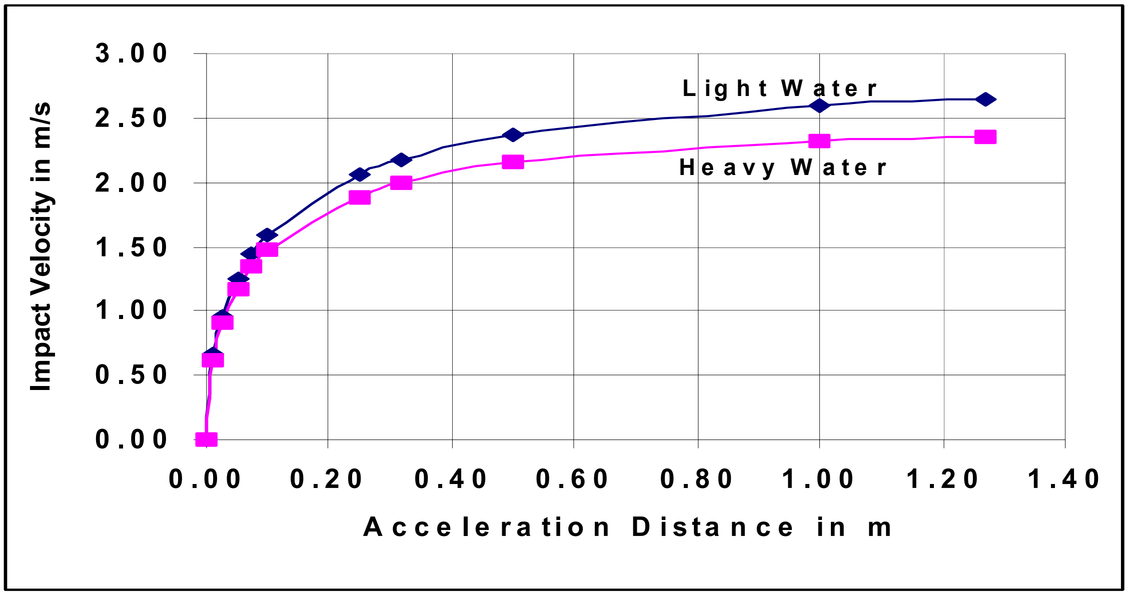


FIGURE 1 COMPARISON OF CALCULATED BUNDLE VELOCITY (37 ELE.) FOR LIGHT AND HEAVY WATER AT A FLOW RATE OF 26.7 KG/S

Using the above equations, the CANFLEX fuel bundle velocities were calculated for the refuelling impact test conditions done and the calculated velocities matched well with tested values at an acceleration distance of 1.25 m (difference is within 5.2%).

4. BUNDLE REFUELLING IMPACT TESTS IN FLOW VISUALIZATION RIG

Refuelling impact investigative tests were performed in a flow visualization rig at AECL in 2004 using an acrylic flow tube and simulated CANDU channel components, with light water at ambient temperature and pressure using 37-element CANDU 6 bundles, for new and aged PT conditions. The main intent of the tests was to visualize and measure the bundle impact velocities at higher flows and acceleration distances, in preparation for defining test conditions for advanced reactor designs.

These tests were designed and conducted in a flow visualization rig to determine the effects of typical impacts to which bundles are subjected and to generate information for modelling the impact velocities in-reactor conditions.

4.1 Test Conditions

The following were the test conditions during the above Refuelling impact investigative tests.

- Flow rates of 27, 32, 37, and 43 kg/s (light water at ambient conditions).
- The acceleration distance of 3.7 m in a simulated CANDU inlet section.

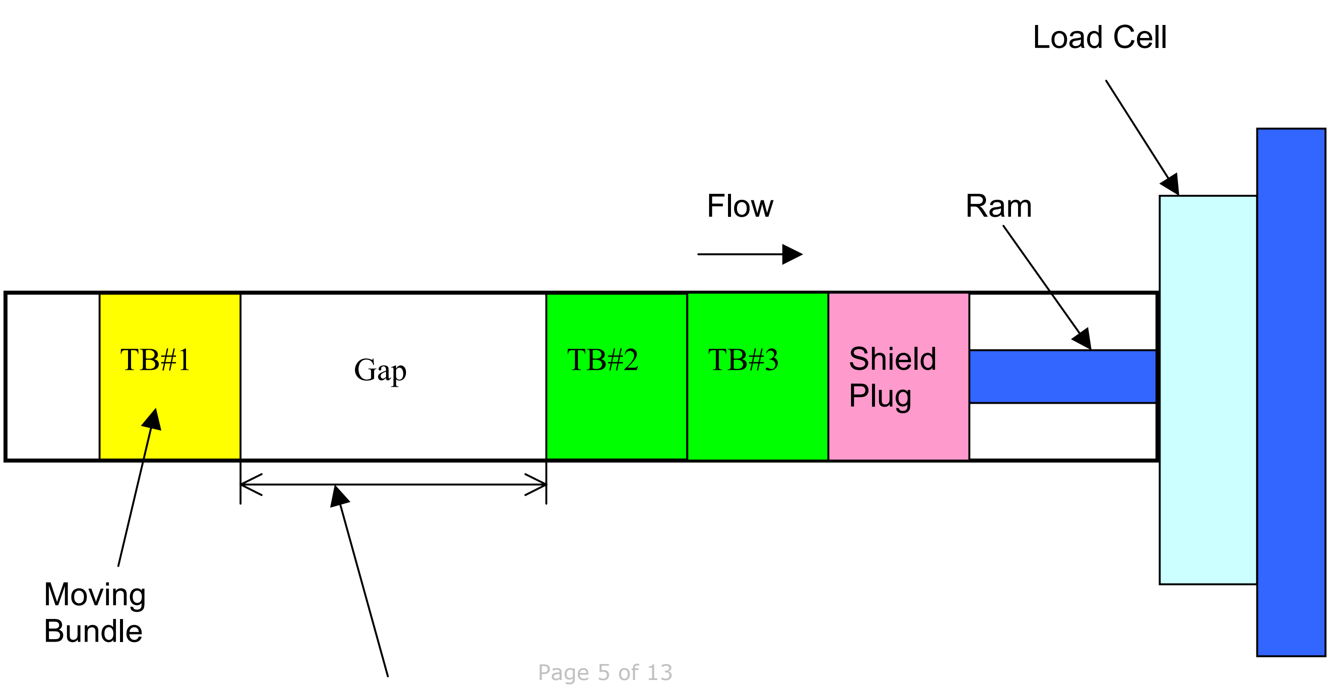
4.1.1 Bundle Orientation

Each of the two tests used three bundles, a moving or impacting bundle (TB#1), a stationary bundle receiving the impact (TB#2) and another stationary bundle (TB#3) against the shield plug (Figure 2). To simulate the angle of impact in an aged PT, a specially machined wedge-shaped end plate (Figure 3), with a conservative wedge angle of 3º was affixed to the upstream end (impacting end) of the stationary test bundle (TB#2).

4.1.2 TEST MEASUREMENTS AND RECORDS

A combination of a high-speed digital video camera (1 frame/msec) and a standard video camera recorded and measured the velocity and displacement of the impacting bundle. The impact force was measured using a load cell connected to the dummy shield plug. Before and after the tests, the following were checked to establish the bundle deformation if any:

- bundle diameter, element bow, element lengths over end plates, and end-plate profile for both ends, using dimensional characterization and
- bundle passage through kink tube (Bent Tube Gauge).



TB = Test Bundle

Support Frame

Acceleration Distance

FIGURE 2 REFUELLING IMPACT TEST BUNDLE CONFIGURATIONS

FIGURE 3 WEDGE_SHAPED END PLATE AFFIXED TO THE UPSTREAM END OF TB#2 TO SIMULATE AGED PT CONDITION

5. RESULTS

All the test fuel bundles passed through the bent tube gauge after the tests. There was no damage observed in the end plates and fuel elements of the test bundles during visual examinations of the bundles after testing. Figure 4 shows a photograph of the moving and stationary bundles at impact in the flow visualization rig.

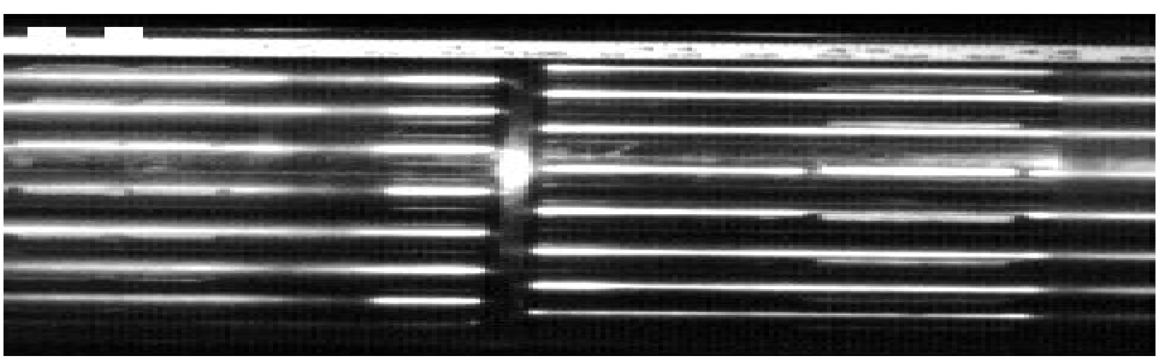


FIGURE 4 IMPACTING BUNDLES IN FLOW VISUALIZATION RIG AFTER THE IMPACT

5.1 Velocity at Impact

Figure 5 shows the velocity profiles of the moving bundle along the PT. Within the first metre of accelerating distance, the moving bundle velocity approached ~97% of terminal velocity at 27 kg/s and ~90% of terminal velocity at 43 kg/s. The average impact velocities at the flow rate of 27, 32, 37 and 43 kg/s were 2.63, 3.23, 3.85 and 4.55 m/s, respectively (see Table 1). The moving bundle velocity at impact increased with flow rate.

The model equations developed earlier were for hot-loop conditions. The applicability of the model for the recent test performed at ambient conditions was examined. Due to the differences in test pressure and temperature, the coolant density of light water is much higher. For calculations of impact velocities the relevant coolant density, the maximum head loss coefficient (K) and dynamic friction coefficient between acrylic and Zircaloy were used.

Figure 5 shows the comparison of bundle velocity as a function of flow rate and acceleration distance between measurements and calculations. The calculated terminal velocity matched with the test terminal velocities but the calculated velocities do not match well with test velocities during the early acceleration phase.

The model does not take into account the reduction in the head loss coefficient at the beginning of the acceleration when only a portion of the bundle is inserted into the axial flow region. Further this model does not take into account the increase in cross-section area in the vicinity of the rolled joint. This increase would lower the head loss coefficient when the bundle is travelling over the rolled joint. These factors are likely to result in a mismatch of bundle velocity at early acceleration distances.

Since the recent tests were performed at cold conditions, for in reactor hot-loop conditions the coolant density would be much lower. Therefore the test impact terminal velocity of 4.64 m/s would be achieved at a hot-loop flow rate of <39.2 kg/s (as compared to an ambient test flow rate of 43 kg/s in the acrylic flow channel).

5.3 Impact Force

The impact forces increased with increasing flow rate (see Table 1 below). Figures 6 and 7 show impact force profiles for tests at a maximum flow rate of

43 kg/s under new and aged PT conditions. After the initial impact, the moving bundle moves back for a small distance (rebounds) and then strikes against the stationary bundle with a lower impact force.

TABLE 1

Flow Rate (kg/s)	Impact Velocity (m/s) (new PT)	Impact Velocity (m/s) (aged PT)	Impact Force in lbs (kN) (new PT)	Impact Force in lbs (kN) (aged PT)
27	2.63	2.64	13770 (61)	10840 (48)
32	3.23	3.29	17330 (77)	14310 (64)
37	3.85	3.99	21530 (96)	16210 (72)
43	4.55	4.74	24020 (107)	18850 (84)

Impact forces for tests under new PT conditions are higher than those for aged PT conditions for the same acceleration distance. However, in the simulated aged PT condition (PT sag simulated by fixing the wedge-shaped end plate) the impact surfaces between the moving bundle and the stationary bundle are not parallel. Therefore, the impact force on the stationary bundle was not taken by the entire cross sectional area of the bundle. This means that the impact load may be concentrated on a few fuel elements instead of being uniformly distributed among all 37 elements.

At flow rates of 27, 32, and 37 kg/s, there was no significant deformation on the test bundles in the simulated condition of sagged PT, when the contacting surfaces between the moving bundle and the bundle receiving the impact were not parallel. Only at a 43 kg/s flow rate did the impacting bundle measurably deform retaining a permanent trapezoidal shape at about a 1.2° angle (the simulated aged PT angle of sag was 3°). Irradiation effects of the bundles receiving the impact were not considered.

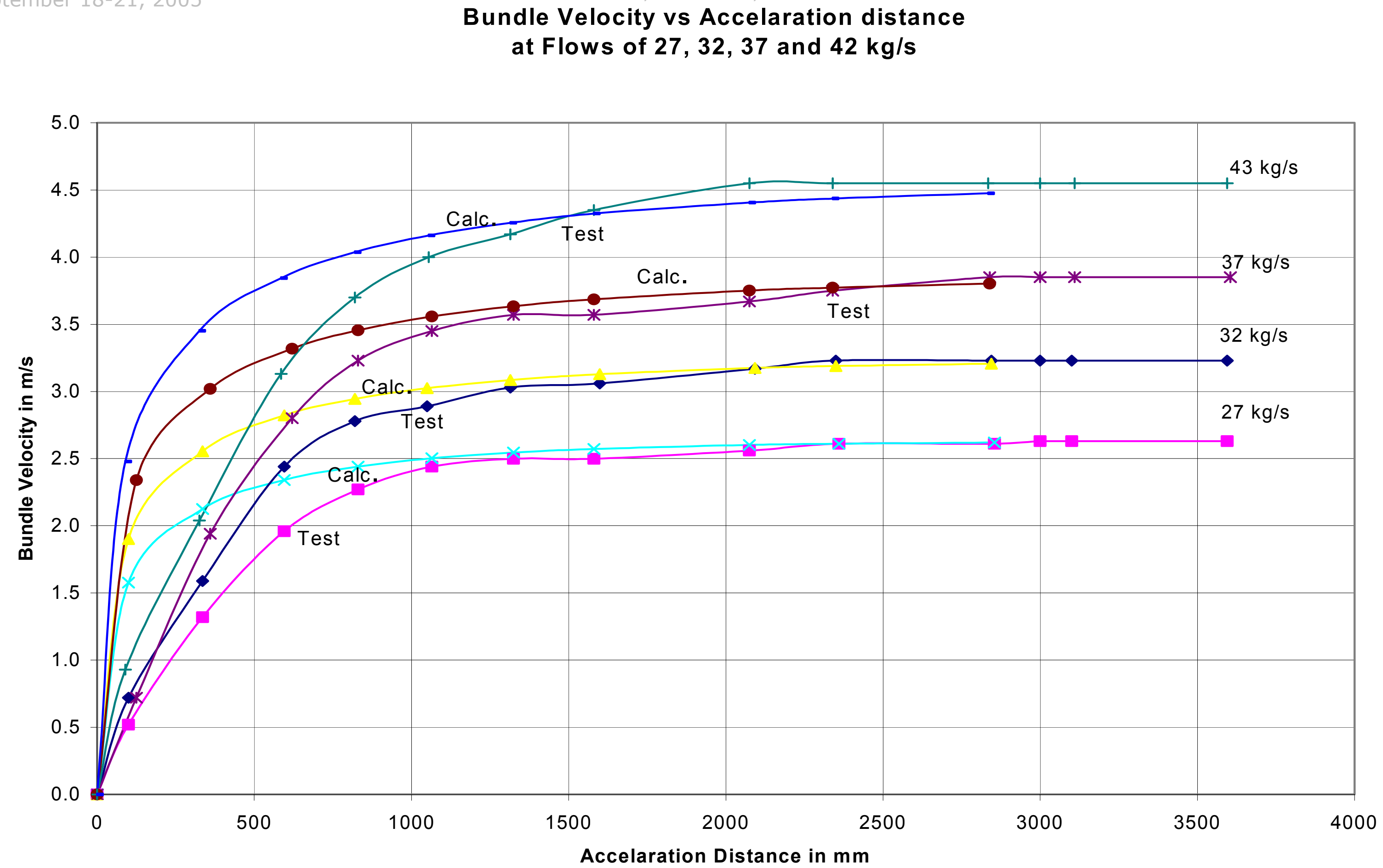


FIGURE 5 –37-ELEMENT BUNDLE VELOCITIES AT VARIOUS FLOW RATES AND COMPARISON WITH CALCULATED VELOCITIES FOR AMBIENT TEST CONDITIONS

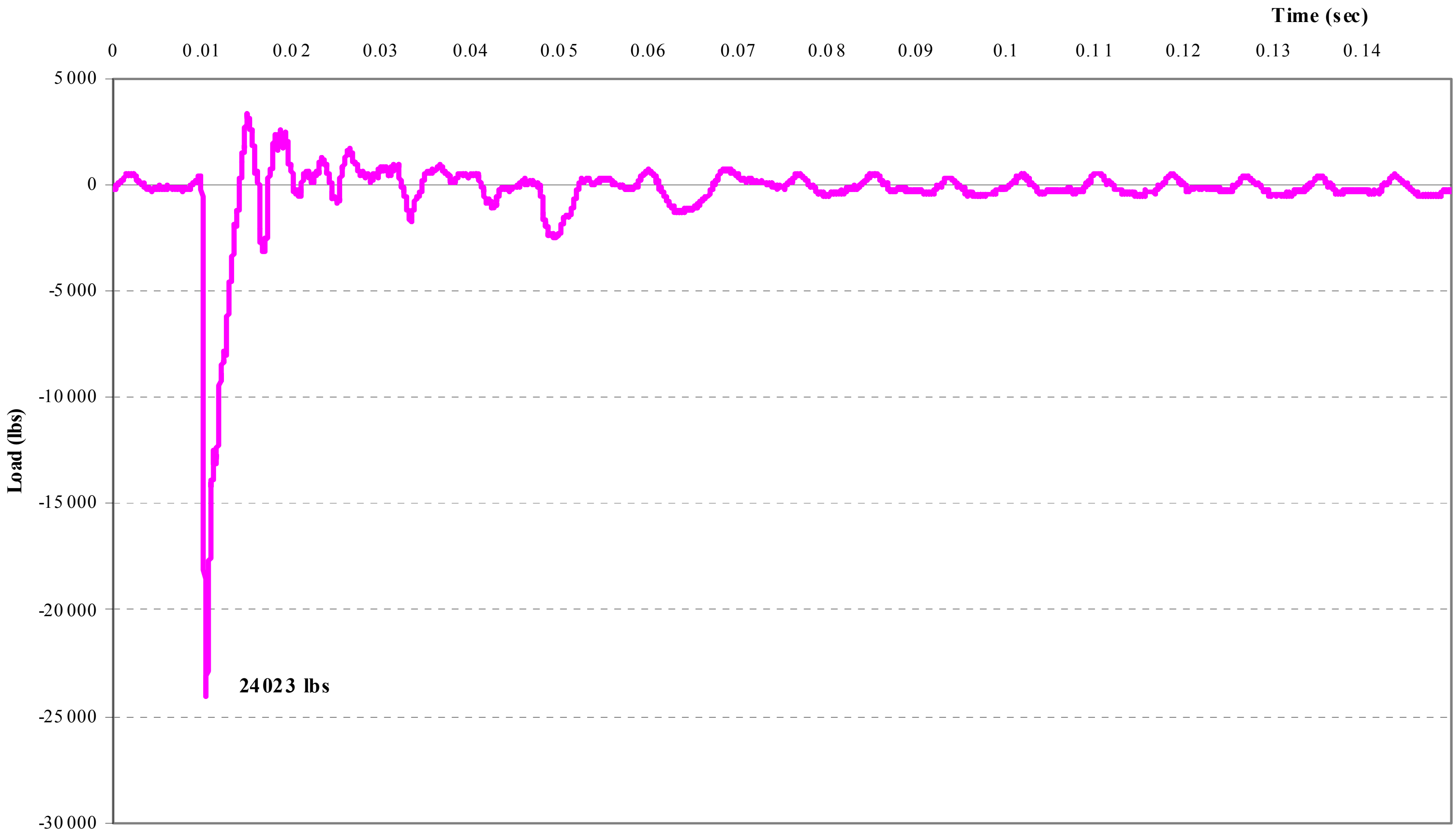


FIGURE 6 IMPACT FORCE MEASURED IN NEW PT CONDITIONS (43 KG/S FLOW)

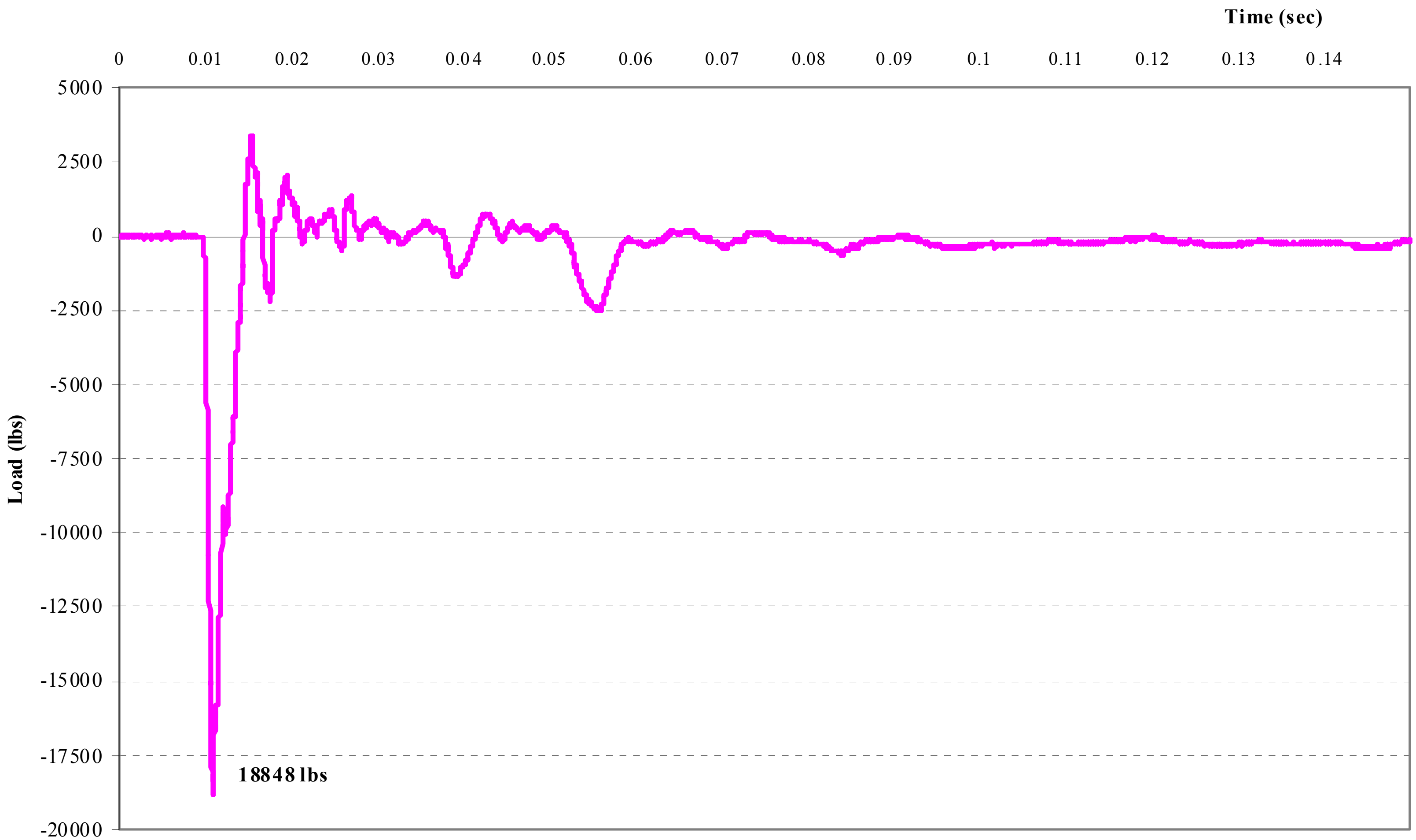


FIGURE 7 IMPACT FORCE MEASURED IN AGED PT CONDITIONS (43 KG/S FLOW)

5.3 Brief Comparison

Table 2 shows a brief comparison of the current tests with previous tests.

TABLE 2

Test Parameter	CANDU 6 37-el Tests-1976	CANFLEX Tests - 1996	37-Element Bundle Flow Viz. Test - 2004
Flow in kg/s (Pressure in MPa / Temperature in ºC)	26.7 (10.41/289)	31.44 (10.41 / 289)	43 (0.9 / 30)
Acceleration Distance (m)	1.27	1.25	3.7
Impact Force lbs (kN)	Not measured	Not measured	24020 (107) (New PT) 18850 (84) (Aged PT)
Impact Velocity (m/s)	2.63	2.85	4.64 (New PT) 4.74 (Aged PT)
Nature of Tests	Only for radially unsagged PT	Only for radially unsagged PT	For radially unsagged and sagged PT
Visualization	No	No	Yes

Current tests demonstrated bundle integrity at very high impact forces and impact velocities.

- Earlier tests of CANDU 37-element bundle and CANFLEX bundle, accounted only for axial creep of the PT by testing for longer acceleration distances, and radial creep was not addressed. Current tests considered for both axial and radial creep of an aged PT by affixing a wedge-shaped end plate to the upstream end of the impacted bundle. This test gave more confidence for advanced reactor designs, in which at the end of the PT life, the bundle receiving the impact may not be in the straight section but in the tilted section of the PT.
- Visualization of bundle movements before, during and after impact gave clarity and confidence.
- Differences in velocities at the same flows are due to coolant density differences due to test different test pressure and temperature conditions.

6. CONCLUSIONS

1. The fuel bundles remained intact and uncollapsed without significant damage at flow rates up to 43 kg/s. The 3° PT sag angle, which was used in the current tests, is conservative for end-of-life PT sag simulation, considering the predicted end-of-life PT sag from power reactors.
2. All the 37-element fuel bundles used in the tests survived the refuelling impact tests under new and aged PT conditions. All the test fuel bundles passed through the bent tube gauge after the tests.
3. Impact forces during tests under simulated sagged PT conditions were lower than those during tests under new PT conditions.
4. At flow rates up to 37 kg/s, there was no significant deformation on the test bundles in the simulated condition of sagged PT, when the contacting surfaces between the moving bundle and the bundle receiving the impact were not parallel. Only at a 43 kg/s flow rate did the impacting bundle measurably deform retaining a permanent trapezoidal shape at about a 1.2° angle (the simulated aged PT angle of sag was 3°).
5. The applicability of the model equations developed by AECL, for the different test conditions was examined. The model equations may be used after suitable normalization for the specific conditions to assess bundle terminal velocities.