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Test Report

CANFLEX Fuel Bundle Junction Pressure Drop

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제 출 문

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본 보고서를 "중수로용 개량핵연료 검증시험" 과제의 "CANFLEX Fuel Bundle Junction Pressure Drop(Test Report)" 기술 보고서로 제출합니다.

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Revision 0

Test Report

CANFLEX Fuel Bundle Junction Pressure Drop

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1. INTRODUCTION

To measure the most probable pressure drop for 12 randomly aligned bundles, two pressure drop tests are required: a bundle junction pressure drop test and a fuel string total pressure drop test.

The bundle junction pressure drop test is used to determine the junction pressure drop between a pair of bundles as a function of the angular alignment. From the relationship between pressure drop and alignment angles the average pressure drop for a pair of randomly aligned bundles can be estimated. This information is required for the Fuel String Total Pressure Drop Test. Because the Reynolds number for this test of about 60,000 is very low compared to the reactor Reynolds number of about 500,000, these test results only used to determine angular alignments for the fuel string pressure drop test. The results should not be used to calculate absolute pressure drop values.

This report describes the junction pressure drop test results which are to be used to determine the alignment angle between bundles to achieve the most probable fuel string pressure drop for randomly aligned bundles for use in the Fuel String Total Pressure Drop Test.

2. TEST FACILITY

2.1 Test Loop

Bundle junction pressure drop tests are conducted in the Cold Test Loop I at KAERI. The Cold Test Loop I is designed to simulate cold conditions in a single fuel channel of the CANDU-6 reactor primary system. The loop consists of a variable-speed motor pump, a test rig, a storage tank and related piping as shown in Figure 1. The loop design parameters are as follows:

Component	Specification	
Pump	Flow Rate	: 2 m^3/min,
	Head	: 100 m H_2O.
Test Rig	Material	: Acrylic Tube,
	Design Temp.	: 45 ℃,
	Design Press.	: 5.3 kg_f/cm^2.
Storage Tank	Inventory	: 3 m^3.

2.2 Test Rig

The test rig for the CANFLEX bundle test has the same geometry of CANDU-6 fuel channel to simulate the same flow conditions of the reactor. The schematic of the test rig is shown in Figure 2. It consists of the inlet end fitting with liner tube, outlet end fitting, and transparent acrylic tube. The water flows into the inlet end fitting side ports which are bolted to the inlet feeder and then flows through the holes of liner tube inside the inlet end fitting. The inside diameter of the transparent acrylic tube is same as that of the CANDU-6 reactor pressure tube, 103.385 mm.

There are 11 pressure taps on acrylic tube of the test rig to measure the pressure drop. These pressure taps are located right side of the acrylic tube from the point of viewed from flow outlet, and detailed description is shown in Figure 3. In these pressure taps, taps 1 and 7 are located across one bundle length including a bundle junction. Taps 3 and 6 are located across the bundle junction and used to measure the junction pressure drop in the rotational pressure drop test. Each pressure tap location is illustrated in Figure 3.

2.3 Test Fuel Bundle

The CANDU-6 reactor Standard 37-element and CANFLEX 43-element fuel bundles are used in the bundle junction pressure drop tests. The CANFLEX bundles were fabricated by KAERI based on the design specifications in Drawing CANFLEX-DW-37000-001 Rev. 0. The end views of the fuel bundles inside pressure tube are shown in Figure 4. Each fuel element contains UO_2 pellets in a Zircaloy-4 sheath. A graphite interlayer separates the sheath and the pellet to reduce the pellet-sheath interaction. End caps are resistance welded to the sheath extremities to seal the element. End plates are welded to the end caps to hold the elements in bundle configuration. Spacers are brazed to the elements at their mid-lengths to provide the desired inter-element separation. The bundle is spaced from the pressure tube by bearing pads brazed near the ends and at the middle of each outer element. Beryllium metal is alloyed with Zircaloy during brazing. The CANFLEX test fuel bundles have cylindrical buttons attached on the elements at two planes at element quarter points, to provide the CHF(Critical Heat Flux) enhancement.

2.4 Pressure Drop Test

2.4.1 Test Condition

The reference test conditions for bundle junction pressure drop tests are as follows:

a) mass flow rate is 23.9 kg/s,
b) water temperature is 30 ^{o}C.

The pressure drop test matrix is shown in Table 1.

2.4.2 Instrumentation

During the test the electrical signals from each instrument are gathered and processed using a data acquisition system which is controlled by computer program. Data acquisition system consists of a personal computer and a A/D converter board. The rotation angle of the bundle junction is controlled by the digital I/O module of the A/D converter board and a step motor.

The major measuring parameters and instruments are listed in Table 2. The flow rate to the test rig is measured by a turbine flow meter. Thermocouple is used to measure the test rig inlet temperature, and pressure transmitter is used to measure the test rig inlet pressure. As shown in Table 2 the pressure drops across taps are measured by the differential pressure transmitters, which were calibrated to offer the optimized measuring range for each measurement [1]. The detailed description for the Cold Test Loop I instrumentation is given in Appendix B in Reference 1.

3. TEST DESCRIPTION

3.1 Bundle Alignment and Loading

Four test fuel bundles are loaded in the transparent acrylic tube of the test rig in each test as shown in Figures 2 and 3. The two upstream bundles 1 and 2 are fastened to each other by two small stainless clips and are fixed by a fixing rod attached to the upstream end fitting flange. The two downstream bundles 3 and 4 are also fastened to each other by two stainless clips and can be rotated with a rotating rod attached to a stepping motor. The rotation directions are based on looking against flow direction. In the rotational bundle junction pressure drop tests, the upstream bundles are to be prevented from contacting the downstream bundles intimately, to reduce contact friction resulting from the rotation of bundle 3. The gap between bundles 2 and 3 will be essentially zero.

There are lines scribed on each end plate of CANFLEX bundles, which are equivalent to the vertical center line of # 35 rod of each bundle. And also, there are lines scribed on each end plate of CANDU 37-element bundles, which are equivalent to the vertical center line of the web of the end plate. So, the fastened bundles 3 and 4 are rotated relative to the scribed line of the fixed bundle 2. It was assured that the two scribed lines marked on the each end plate of bundles 2 and 3 were exactly lined up after one full rotation. The angular displacement of the one step of the step motor is 0.72 degree, therefore 500 data points can be obtained for one full rotation from 0 to 360 degree. These 500 data points are saved in floppy discs for later analysis.

Two types of fuel bundle string are to be tested; 4 CANFLEX bundle string, 4 CANDU 37-Element bundle string. Figure 5 illustrates bundle loading and junction types. From the point of view of junction alignment, the clockwise rotated BA and BB junctions are identical with the counter-clockwise rotated AB and AA Junction, respectively, where A denotes the marked end of a fuel bundle with a company monogram and B unmarked end. Therefore there are essentially two junction types of BA and BB for randomly loaded 12 bundles in the fuel channel.

To experimently find and confirm the average bundle junction pressure drop for all the possible junctions of the bundles aligned and loaded in the fuel channel, the following four sets of tests are to be performed:

a. a clockwise(CW) rotational bundle BA junction pressure drop test,
b. a counter-clockwise(CCW) rotational bundle BA junction pressure drop test,
c. a clockwise(CW) rotational bundle BB junction pressure drop test,
d. a counter-clockwise(CCW) rotational bundle BB junction pressure drop test.

The test setup procedure is as follows:

(1) Fasten and load the two upstream bundles 1 and 2 according to the test matrix, and attach the bundle 1 to a fixing rod.

(2) Fasten and load the two downstream bundles 3 and 4 according to the test matrix, and attach the bundle 4 to the rotating rod.

(3) Record the serial number of bundles in the log book.

(4) Install the inlet/outlet end fitting flanges.

(5) Install the step motor and coupling.

3.2 Test Run Procedure

Test procedure is as follows :

(1) Line up each scribed line of bundles 2 and 3.

(2) Fill the piping of the test loop with demineralized water.
All instrumentation lines and piping at high positions are bled.

(3) Run the pump.

(4) When the water temperature becomes stable at the test condition (30 °C), reduce the flow to zero and take set of readings.

(5) Adjust the flow rate to the reference value (23.9 kg/s).

(6) Then data acquisition/control system repeats the following procedures until the rotation angle reaches 360 degrees:

① Rotate the downstream bundles 3 and 4 with 0.72 degrees.
② Take measurements and save.

(6) Set flow to zero and take a set of readings to compare with the corresponding set of the start-up value.

4. DATA REDUCTION

The bundle junction pressure drop tests should be performed at a constant flow rate condition to obtain an accurate pressure drop curve as a function of the bundle junction alignment angle. However, because a small fluctuation of the flow rate may occur, all measured data are required to be scaled to a constant flow in order to deal with them under the same condition and to compensate the effect of flow rate fluctuation on pressure drops.

Since

$$\Delta P \propto \rho V^2, \tag{4.1}$$

where ΔP pressure drop,
ρ coolant density (kg/m^3),
V flow velocity (m/s).

$$V = \frac{M}{\rho A}, \tag{4.2}$$

where M mass flow rate (kg/s),
A flow area (m^2).

Applying Equations (4.1) and (4.2) for a test condition, and a reference condition, identified by T and R respectively, gives:

$$\Delta P_T \propto \frac{{M_T}^2}{{A_T}^2 \rho_T}, \tag{4.3}$$

$$\Delta P_R \propto \frac{{M_R}^2}{{A_R}^2 \rho_R} \tag{4.4}$$

From Equations (4.3) and (4.4)

$$\frac{\Delta P_R}{\Delta P_T} = \frac{\rho_T}{\rho_R} \left(\frac{M_R}{M_T}\right)^2 \left(\frac{A_T}{A_R}\right)^2. \tag{4.5}$$

As the flow area is the same for the same condition

$$\Delta P_R = \Delta P_T \frac{\rho_T}{\rho_R} \left(\frac{M_R}{M_T}\right)^2. \tag{4.6}$$

By assuming a constant water density condition, Equation (6.6) can be simplified as

$$\Delta P_R = \Delta P_T \left(\frac{M_R}{M_T}\right)^2. \tag{4.7}$$

Then the average bundle junction pressure drop is obtained by the following Equation:

$$\Delta P_{AVERAGE} = \frac{\Delta P_{R,1} + \Delta P_{R,2} + \ldots + \Delta P_{R,N}}{N}, \tag{4.8}$$

where N number of measurements.

5. TEST RESULTS

The junction pressure drop tests were performed as shown in Table 3. For each junction type of CANFLEX fuel bundle string, two junction pressure drop tests were performed under the same flow and temperature conditions. From Equation (4.7), all the present bundle junction pressure drop data are scaled to a constant flow rate of 23.9 kg/s as shown in Figures 6 - 17. Figures 6 - 13 show both sets of the clockwise and counter-clockwise rotational CANFLEX bundle junction pressure drop as a function of junction misalignment angle for the each junction type of BA and BB. Figures 14 - 17 show the pressure drop data for the rotational CANDU standard 37-element bundle junction pressure drop tests.

Comparing both pairs of the clockwise and counter-clockwise rotational pressure drop data for each CANFLEX bundle of BA and BB it can be noted that all the test data are reproducible, since the trends and magnitudes of the junction pressure drops of each pair of the two test data are almost the same. In all the BA or BB junction pressure drop data of CANFLEX bundle, however, the average pressure drop of the clockwise bundle pressure drop data is coincidentally around 0.3 kPa larger than that of the counter-clockwise bundle junction pressure drop data as shown in Figures 6 - 13. This discrepancy between the average clockwise and counter-clockwise bundle junction pressure drops is unexpected one and may be occurred due to the slight different bundle rotational-axes between the clockwise and counter-clockwise rotational bundle junction.

However, the rotational bundle junction of BA or BB of CANDU standard 37-Element bundle, the average value of the clockwise rotational bundle junction pressure drop data are almost the same as that of the counter-clockwise rotational bundle junction pressure drop as shown in Figures 14 - 17.

A floppy disc containing all measured pressure drop data is preserved as part of the test report at two remote storage locations in KAERI.

6. DETERMINATION OF BUNDLE ALIGNMENT ANGLE

To get the bundle alignment angle related to the most probable pressure drop of 12 bundle full string pressure drop test, the analysis of one junction pressure drop data was performed. This analysis was carried out to statistically find the relationship between the single junction pressure drop and the randomly aligned 11 junction pressure drop [2].

6.1 Analysis Procedure

(1) Convert all the measured pressure drop data to a constant flow rate 23.9 kg/s condition in order to deal with them under the same condition by using the Equation (4.7).
(2) Calculate the average pressure drop of all single junction pressure drop data by using the Equation (4.8) (CW and CCW data for the Type BA and BB junction).
(3) Assume that bundle misalignment angles are randomly and equally probable at each junction.
(4) Based on (3), make many data sets(300,000) of 11 junction pressure drop which are randomly generated by Monte Carlo method [2].
(5) Calculate the most probable pressure drop of 11 junction pressure drop data sets.
(6) Confirm the fact that eleven times of average single junction pressure drop is equal to the most probable pressure drop of 11 junction pressure drop data sets.
(7) Based on (6), select the bundle alignment angle related to the average junction pressure drop from the single junction pressure drop signature curve.

For the fuel string pressure drop test, the alignment angle to be used, should be determined by selecting a point where the pressure drop curve intersects the "average pressure drop" as shown in the relevant signature, all of which are shown in Figures 6 to 17 inclusive. An area of the curve with the least slope should be chosen, to obtain the alignment angle at which the pressure drop is least affected by inaccuracies of actual alignment of the test bundles.

6.2 Results

The signatures of junction pressure drop curve are different for the four case rotational data because the cross sectional view of endplate with fuel rods is not periodically symmetric as shown in Figure 4. For the 12 bundle loaded channel of CANDU-6 reactor, bundle misalignment at each junction is random. From the analysis, it is concluded that the most probable pressure drop of the randomly aligned 11 junction pressure drop data is equal to the eleven times of the average single junction pressure drop. Table 3 shows the bundle alignment angles for the maximum and the average single junction pressure drop, which angles are selected from the CW rotational and forward junction pressure drop curve according to the bundle alignment angles. Thus, the bundles are to be aligned CW as listed in Table 4 for the 12 bundle fuel string pressure drop tests.

7. CONCLUSION

To measure the most probable pressure drop across a randomly aligned and loaded string of 12 bundles, the bundle junction pressure drop test is performed in a short rig to determine the dependence of pressure drop on angular alignment at the junction between a pair of bundles. From the pressure drop versus alignment relationship, a junction angular alignment in a pair of fuel bundles can be estimated to produce the most probable bundle string pressure drop. In all the CANFLEX bundle of Type BA or Type BB junction pressure drop data, however, the average pressure drop of the counter-clockwise bundle pressure drop data appear to be coincidentally around 0.3 kPa larger than that of the counter-clockwise bundle junction pressure drop data. This may be due to the slightly different bundle rotational-axes between the clockwise and counter-clockwise rotational bundle junction. This is equivalent to a variation of approximately 1.15% between clockwise and counter-clockwise pressure drop measurements, which is greater than the pressure drop measurement accuracy of ±0.32%.

However, in the CANDU-6 37-element bundle of Type BA or Type BB junction pressure tests, the clockwise and counter-clockwise bundle junction pressure drop data have no difference between them. From the analysis, it is concluded that the most probable pressure drop of the randomly aligned 11 junction pressure drop data is equal to eleven times the average single junction pressure drop. Table 3 shows the bundle alignment angles for the maximum and the average single junction pressure drop, which angles are selected from the CW rotational and forward junction pressure drop curve according to the bundle alignment angles. Thus, the bundles are to be aligned CW and forward directionally at each junction for the 12 bundle fuel string pressure drop tests.

8. REFERENCES

1. Test Procedure, "CANFLEX Fuel Bundle Junction Pressure Drop", KAERI/TP-CX121 Revision 0, July 1994.

2. H.C. Suk, Y.O. Lee, J.S. Jun, K.S. Sim and C.H. Chung, "Relationship between the single and eleven junction pressure drops across a randomly aligned and loaded twelve bundles in CANDU fuel channel", KAERI-TR-566/95, November 1995.

Table 1 Pressure Drop Test Matrix

Fuel Bundle String	Junction Type	Rotation Direction	Rotation Angle (Degree)	Temp. (℃)	Flow Rate (Kg/s)
CANFLEX Bundle	BA	CW	0 - 360	30	23.9
CANDU-37 Ele. Reference Bundle	BB	CCW			

Table 2 Instrumentation

Measurement	Model/Serial No.	Instrument
- Data acquisition and processing	TriGem 486 P, A1151 009005 DT-2825, 06214 RP-2--500-5B, 84150	- Personal Computer(486) - A/D converter board - Step motor
- Flow rate	OMEGA FTB-111, 45485	- Turbine flow meter
- Temperature	TMS-150, 015920	- Thermocouple
- Pressure	Rosemount 3051CG, 94162	- P/T (System pressure)
- Pressure drop	Rosemount 3051CD, 104019 Rosemount 3051CD, 104020	- D/P-1 (Junction, Tap 3-6) - D/P-2 (One bundle, Tap 1-7)

Table 3 Data File of the Junction Pressure Drop Test

Fuel Bundle String	Junction Type		Rotation Direction	File Name	Date/Mon./Year
CANFLEX Bundle	Test-1	BA	CW	43T1BACW	07/11/1994
		BA	CCW	43T1BACCW	07/11/1994
		BB	CW	43T1BBCW	07/11/1994
		BB	CCW	43T1BBCCW	07/11/1994
	Test-2	BA	CW	43T2BACW	07/11/1994
		BA	CCW	43T2BACCW	07/11/1994
		BB	CW	43T2BBCW	07/11/1994
		BB	CCW	43T2BBCCW	07/11/1994
CANDU-37 Ele. Reference Bundle	Test-1	BA	CW	37T1BACW	25/10/1994
		BA	CCW	37T1BACCW	25/10/1994
		BB	CW	37T1BBCW	25/10/1994
		BB	CCW	37T1BBCCW	25/10/1994

Table 4 Selection of Bundle Alignment Angles for the Most Probable and the Maximum Pressure Drop Tests in the Hot Test Loop

	CANFLEX bundle	CANDU 37-Element Bundle
Angle for the most probable pressure drop test (degree)	28 degree in the clockwise direction	31 degree in the clockwise direction
Angle for the maximum pressure drop test (degree)	41 degree in the clockwise direction	49 degree in the clockwise direction

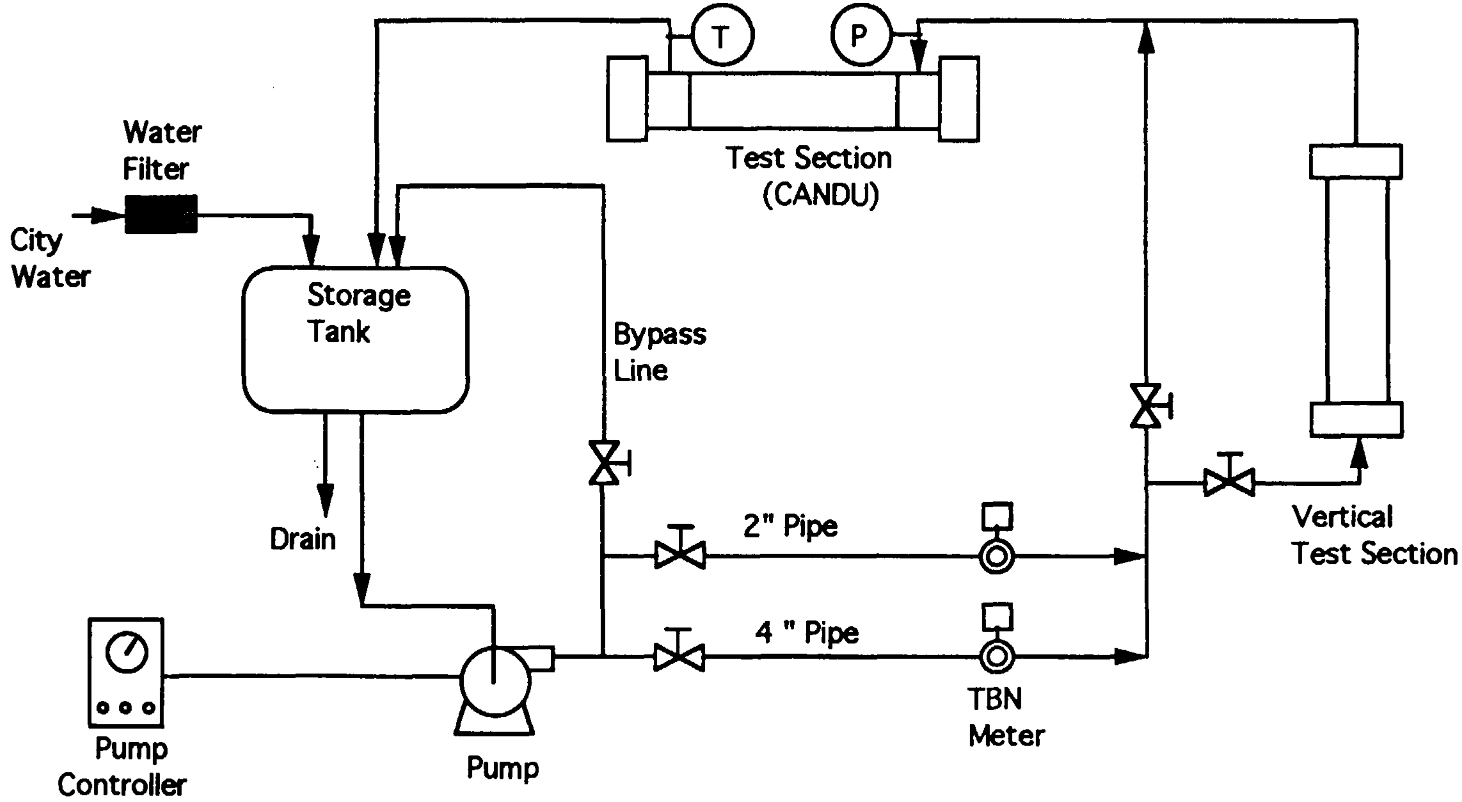


Figure 1 Schematic of the Cold Test Loop I

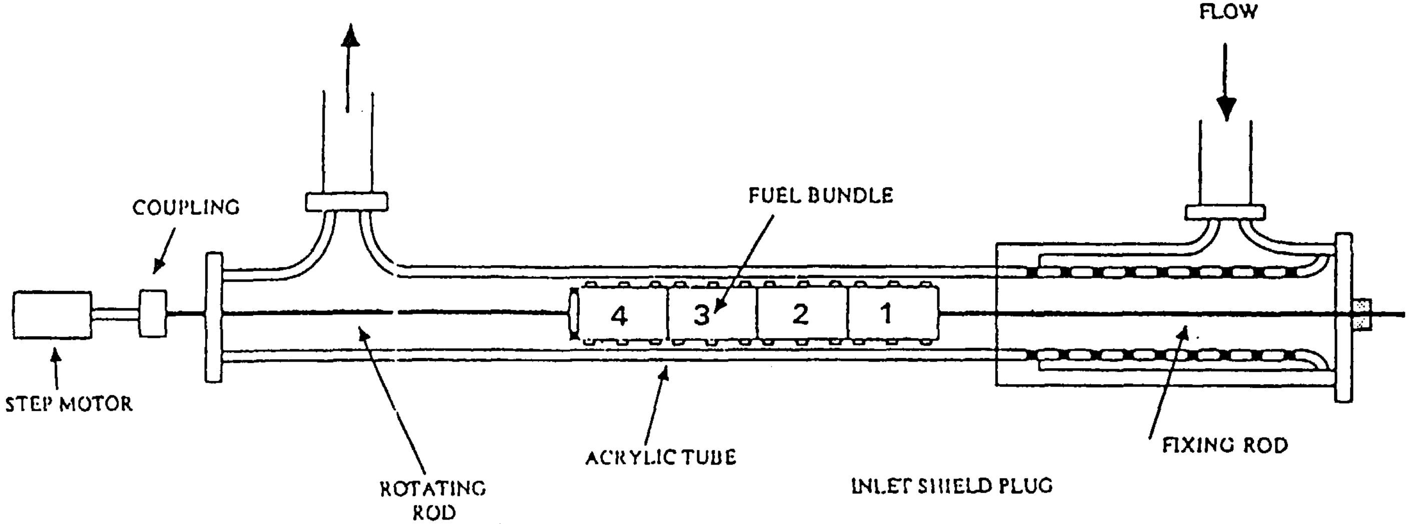
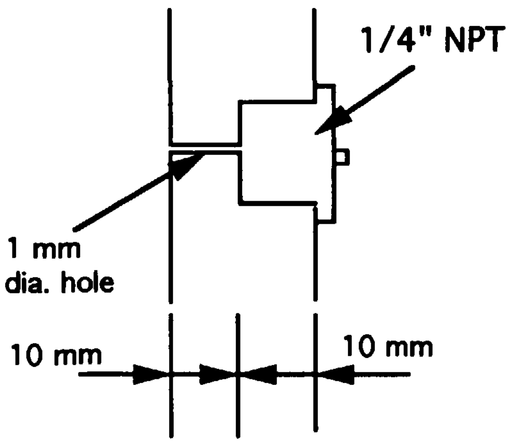
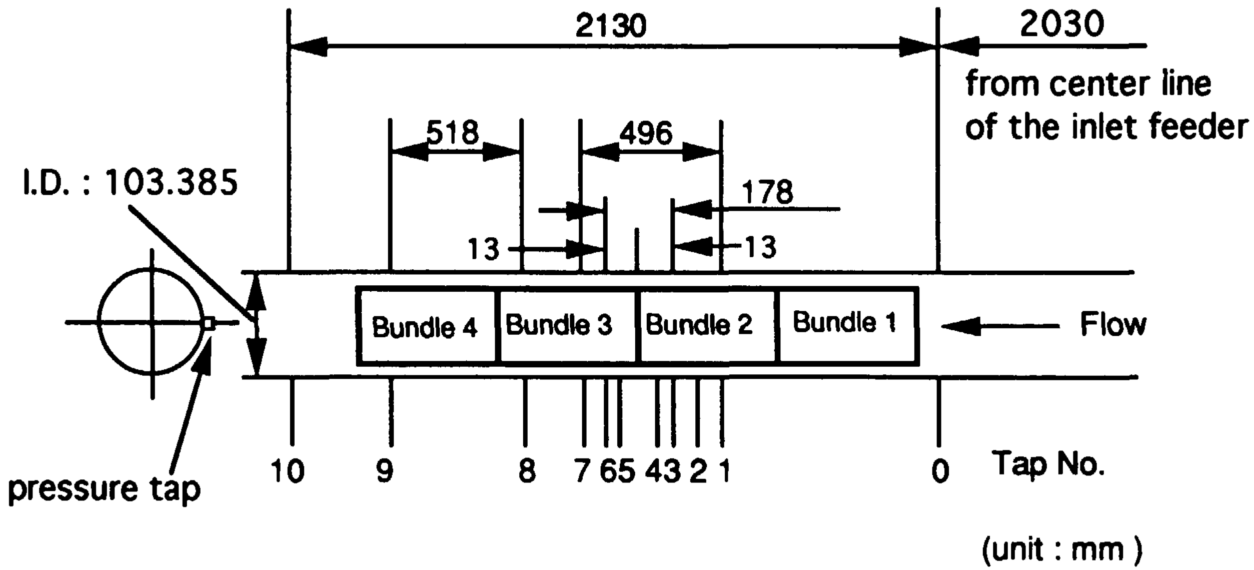
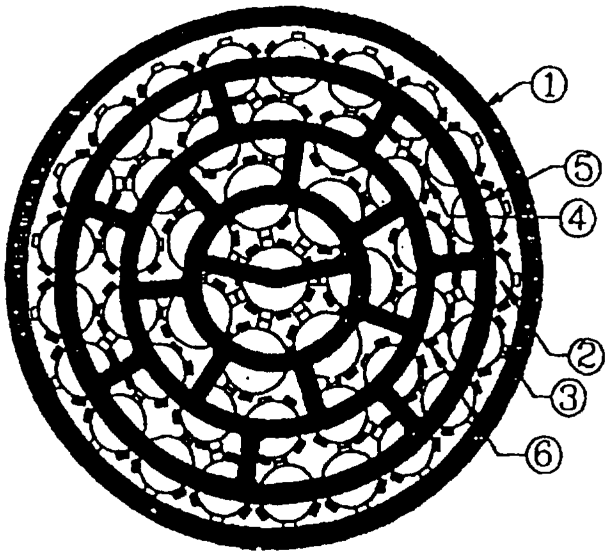


Figure 2 Schematic of the Test Rig

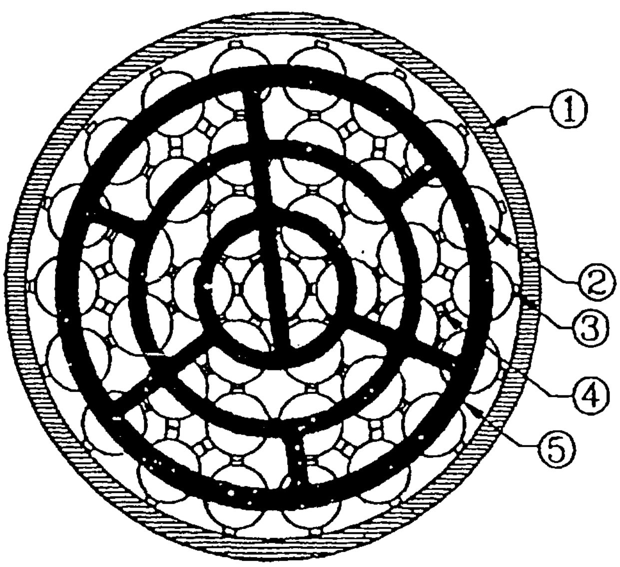


Detailed pressure tap





(a) End View of CANFLEX Bundle Inside Pressure Tube



(b) End View of CANDU-6 Standard Bundle Inside Pressure Tube

1. Pressure tube	2. Fuel elements	3. Bearing pads
4. Inter element spacers	5. End Plate	6. CHF enhancement pads

Figure 4 End Views of the CANFLEX and CANDU-37 Element Fuel Bundle

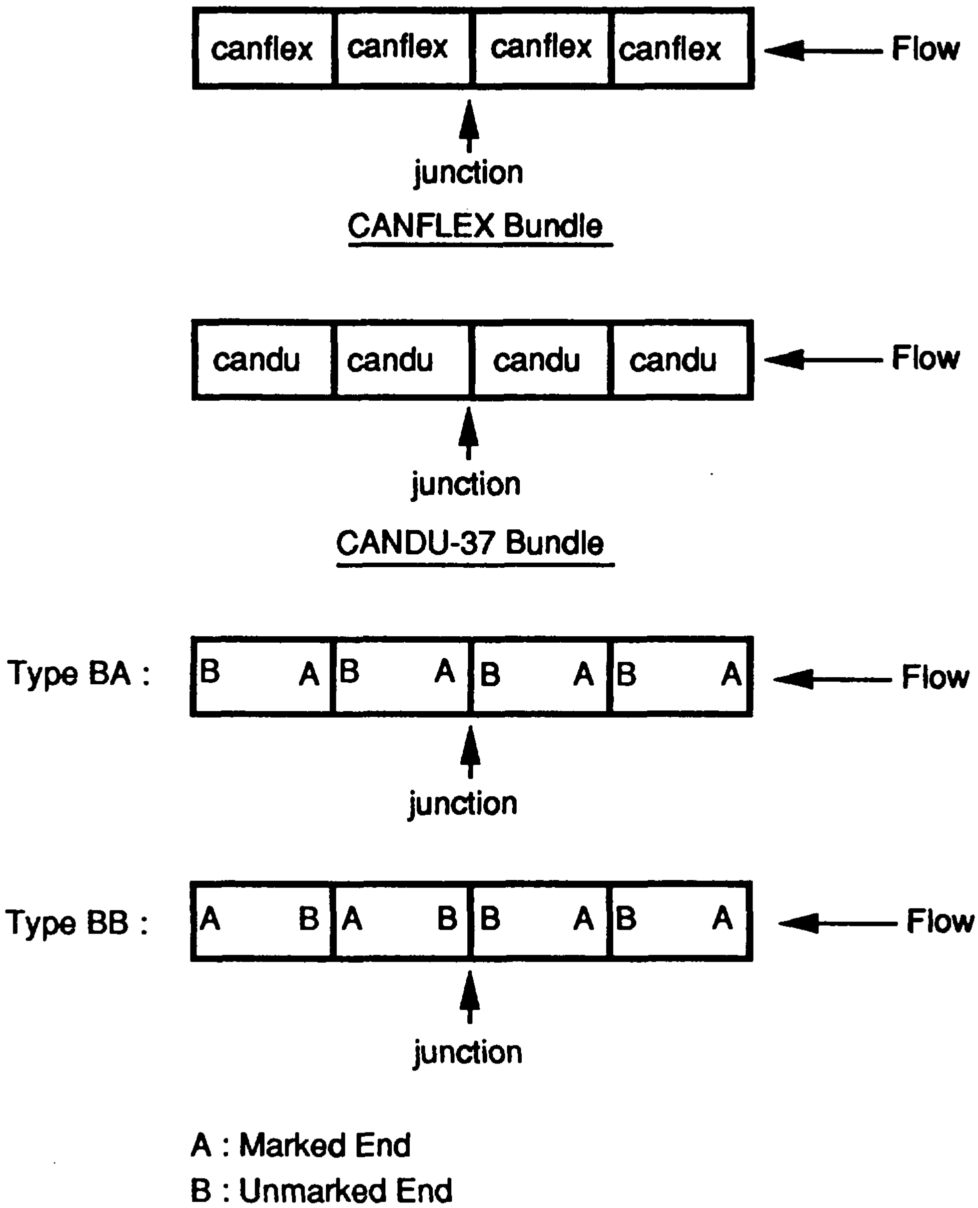


Figure 5 Bundle Loading and Junction Types

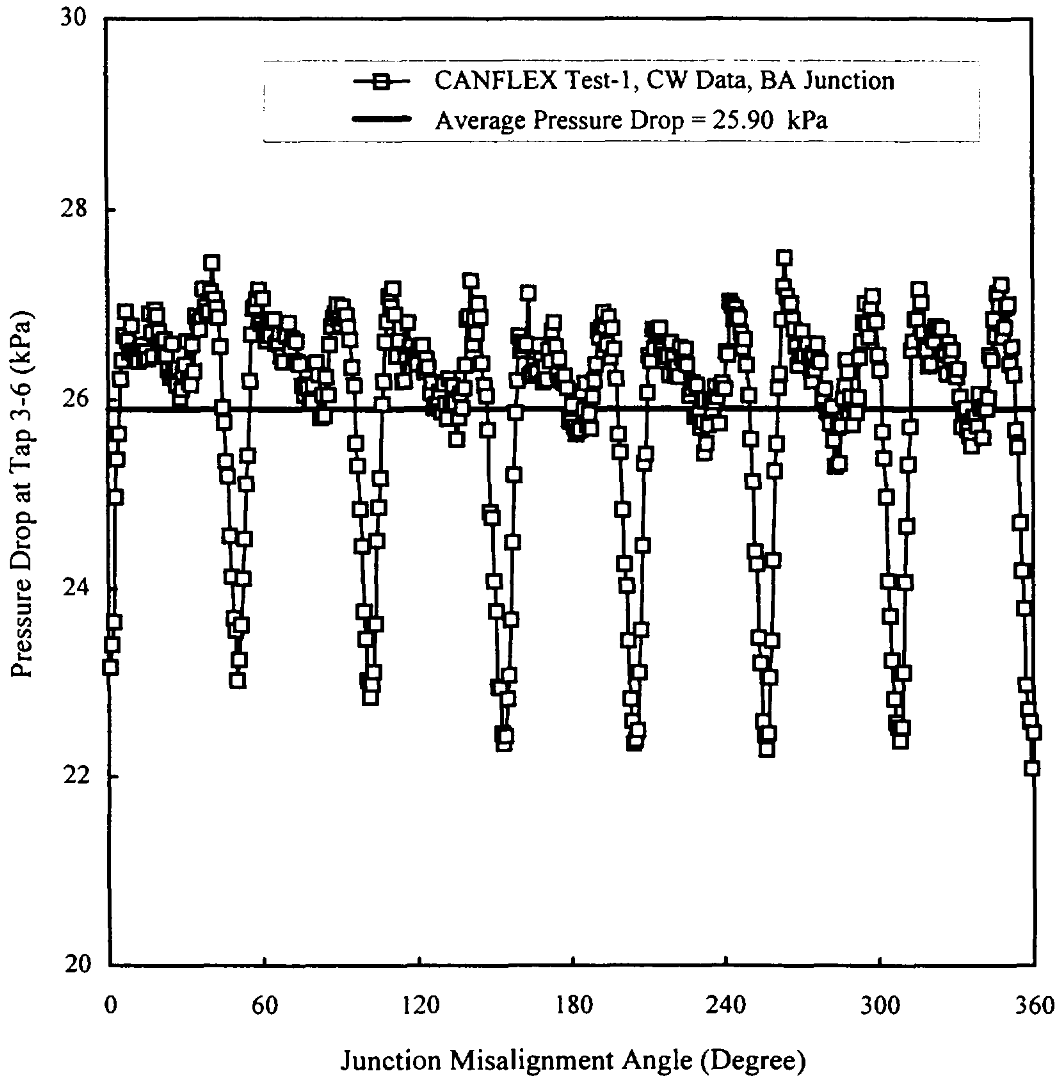


Figure 6 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-1, Clockwise(CW) Data with BA Junction

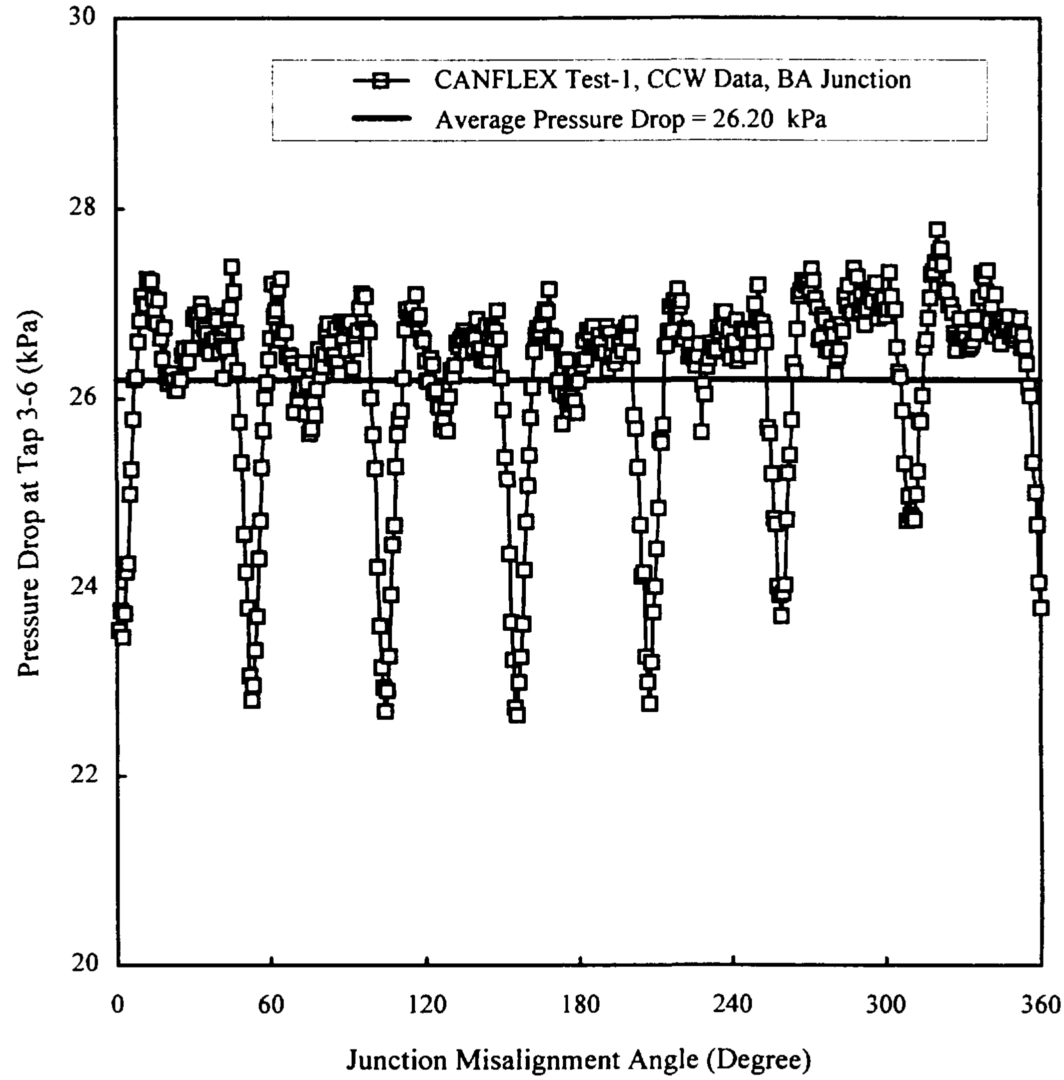


Figure 7 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-1, Counter Clockwise(CCW) Data with BA Junction

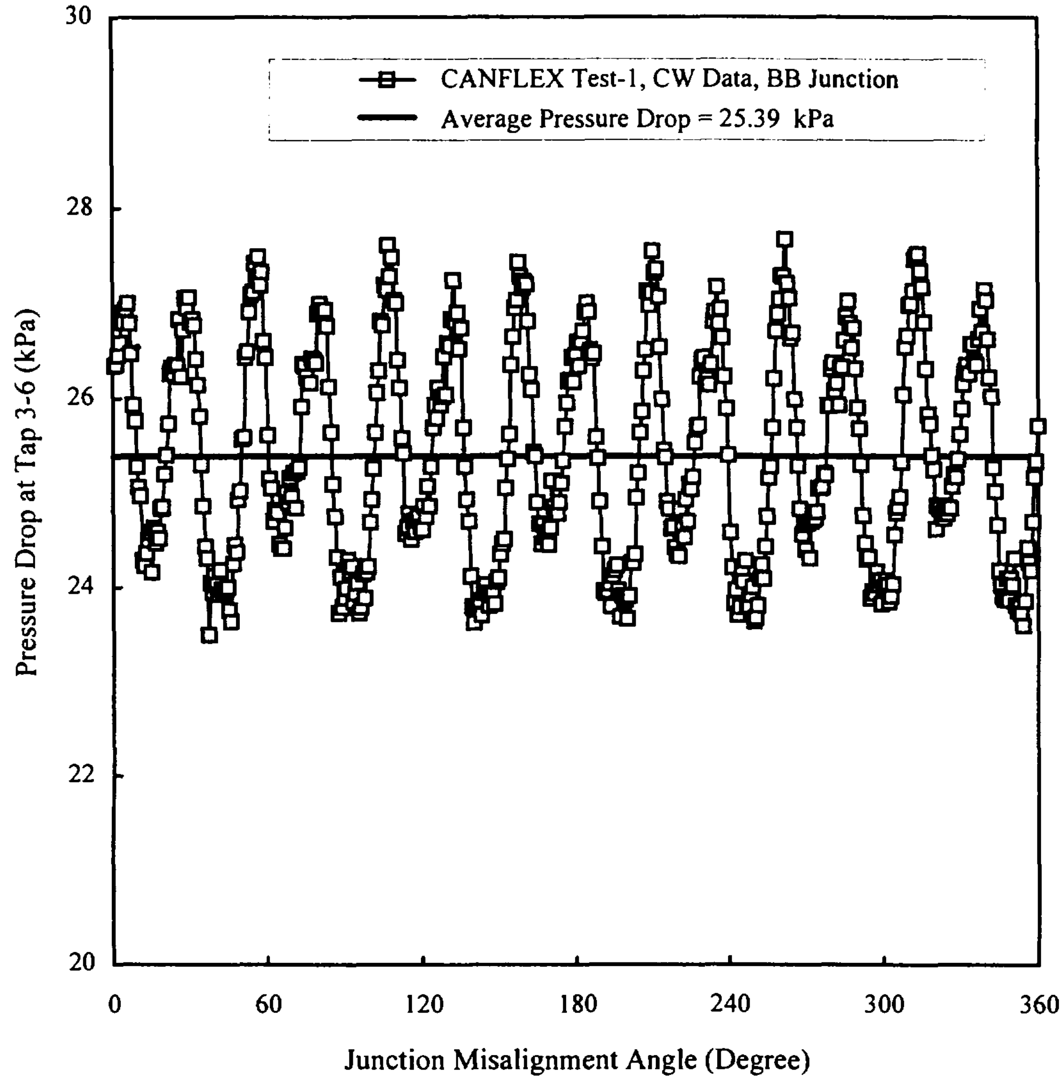


Figure 8 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-1, Clockwise(CW) Data with BB Junction

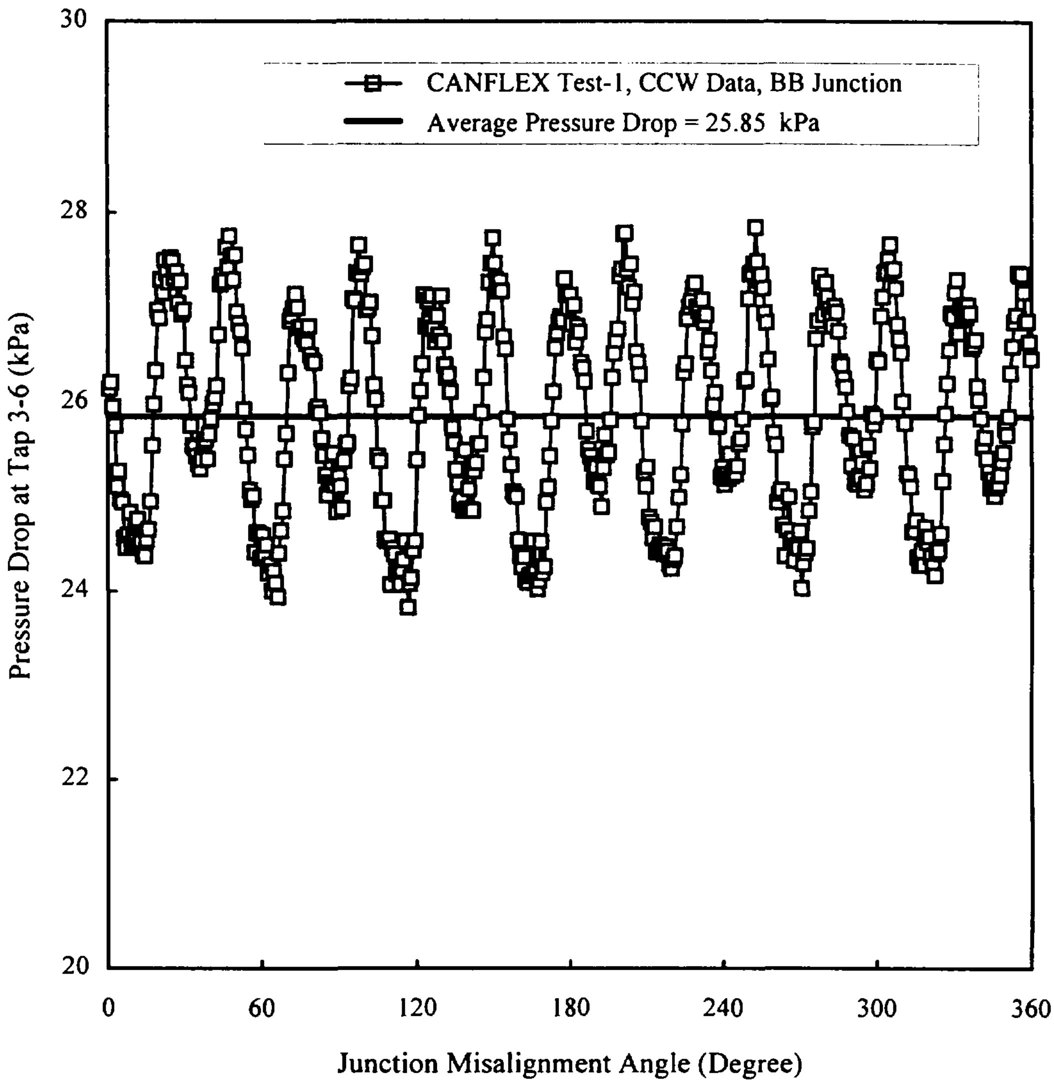


Figure 9 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-1, Counter Clockwise(CCW) Data with BB Junction

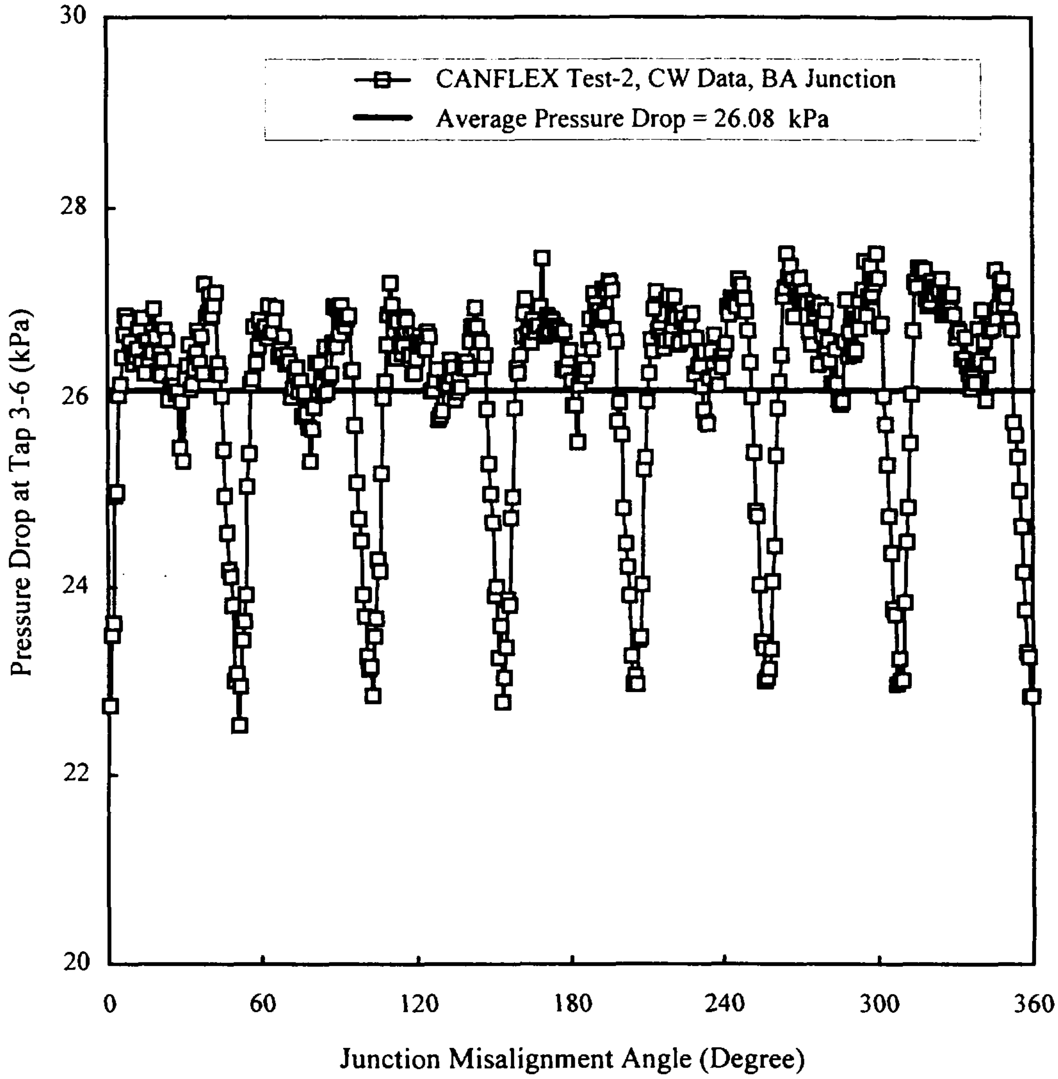


Figure 10 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-2, Clockwise(CW) Data with BA Junction

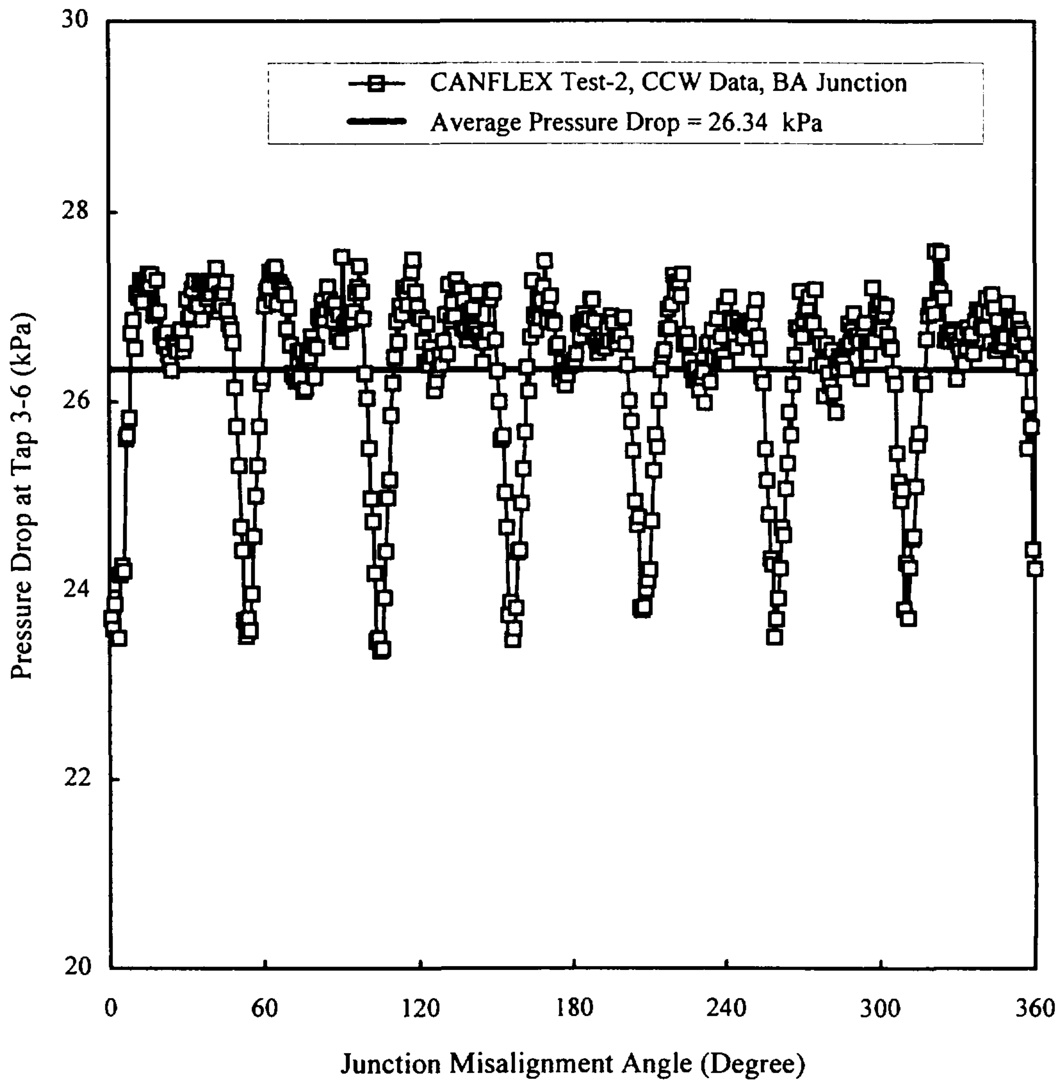


Figure 11 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-2, Counter Clockwise(CCW) Data with BA Junction

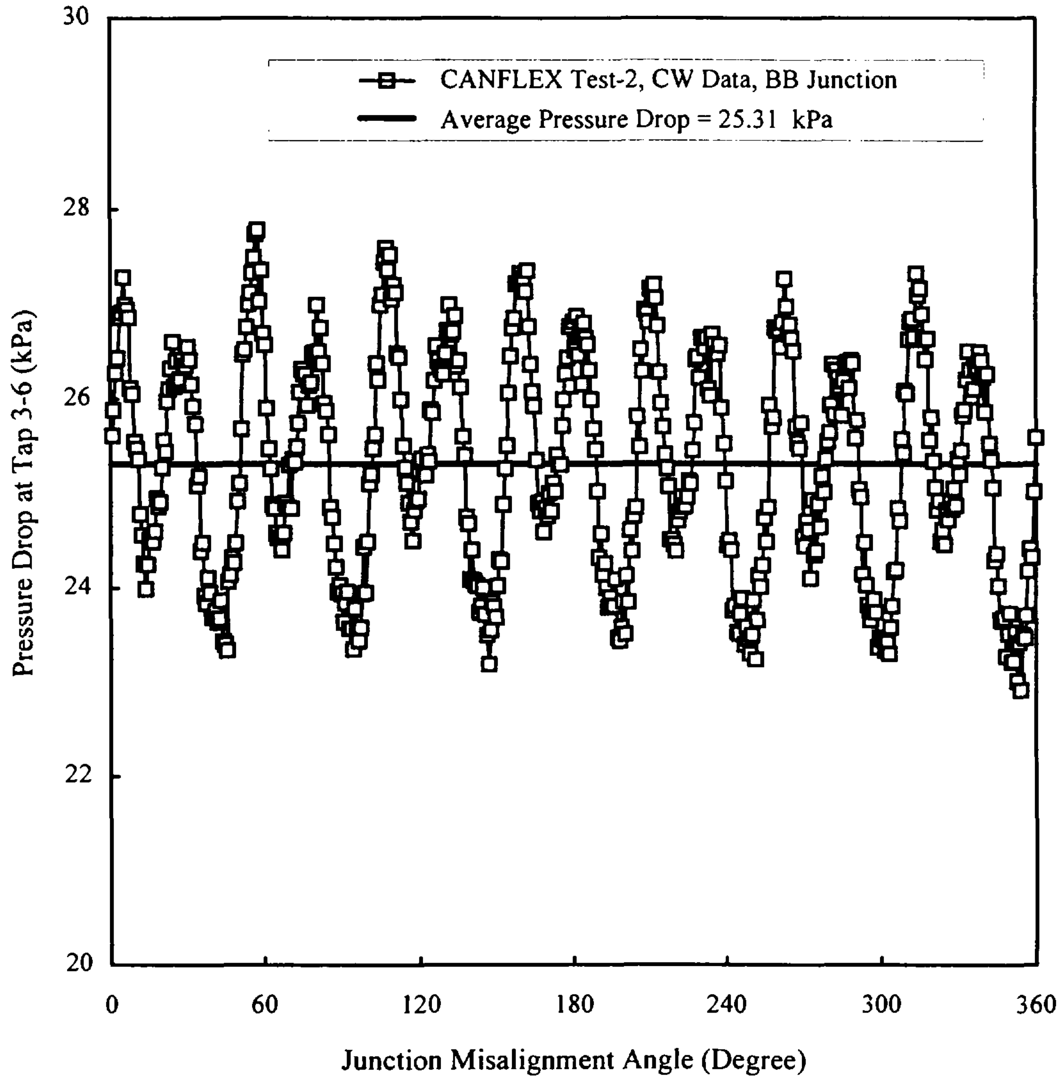


Figure 12 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-2, Clockwise(CW) Data with BB Junction

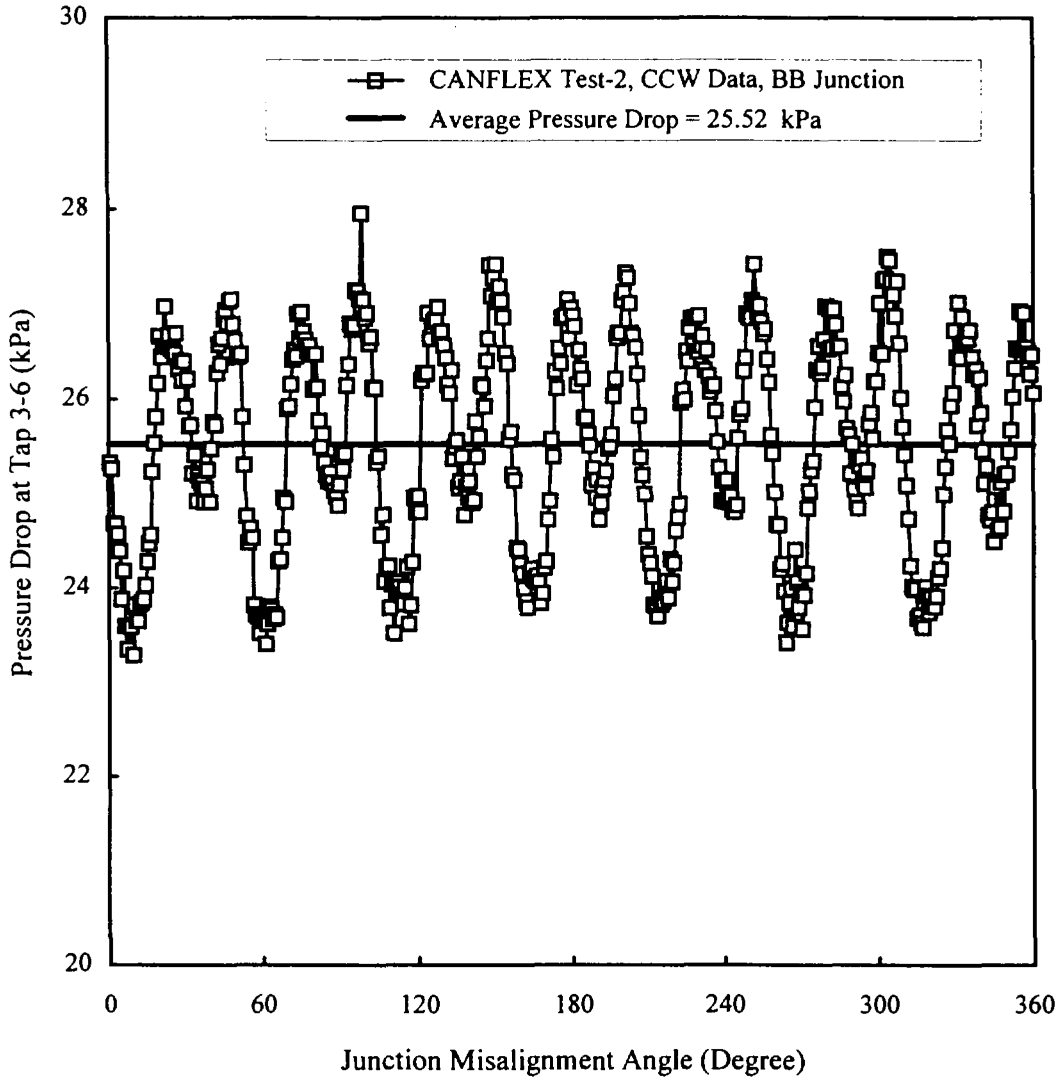


Figure 13 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANFLEX Test-2, Counter Clockwise(CCW) Data with BB Junction

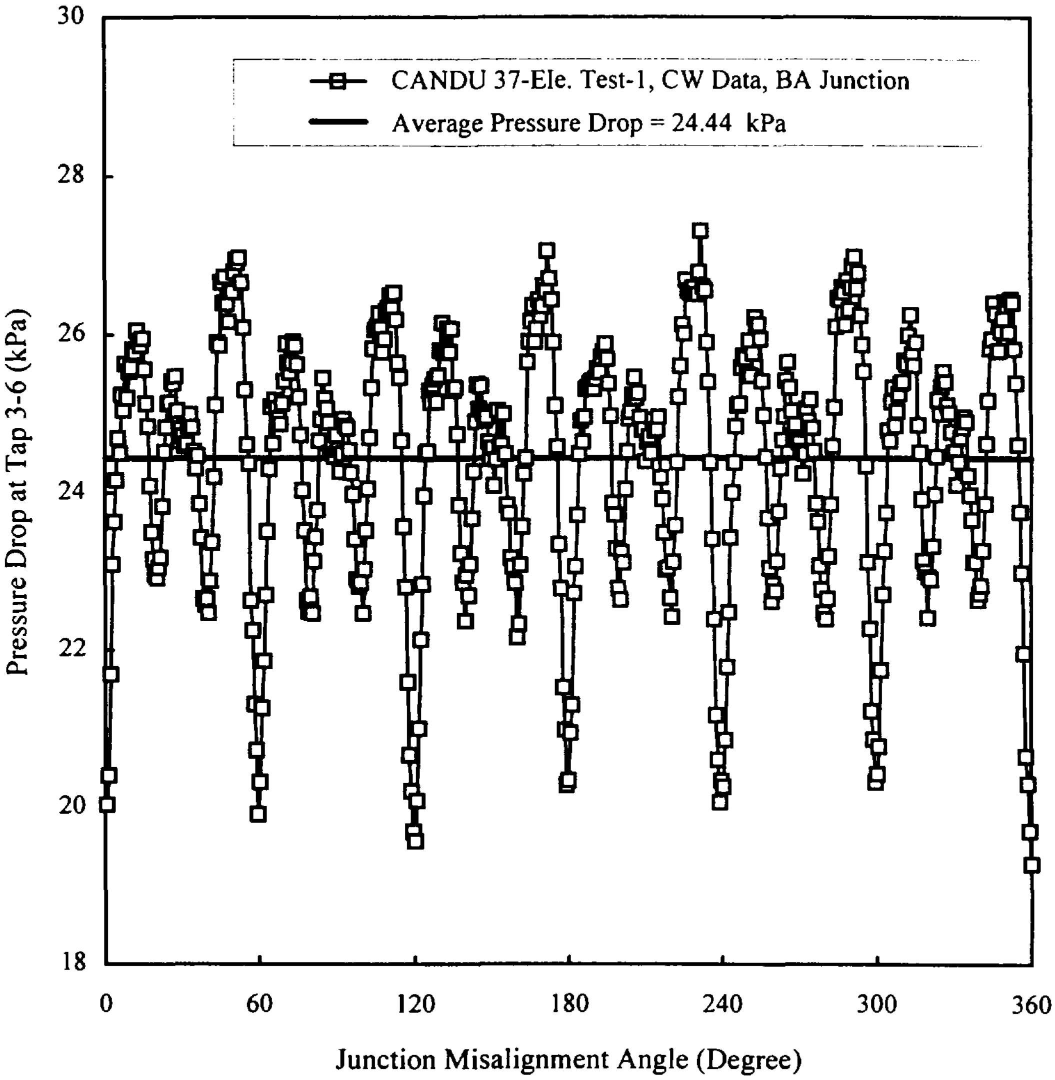


Figure 14 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANDU 37-Ele. Test-1, Clockwise(CW) Data with BA Junction

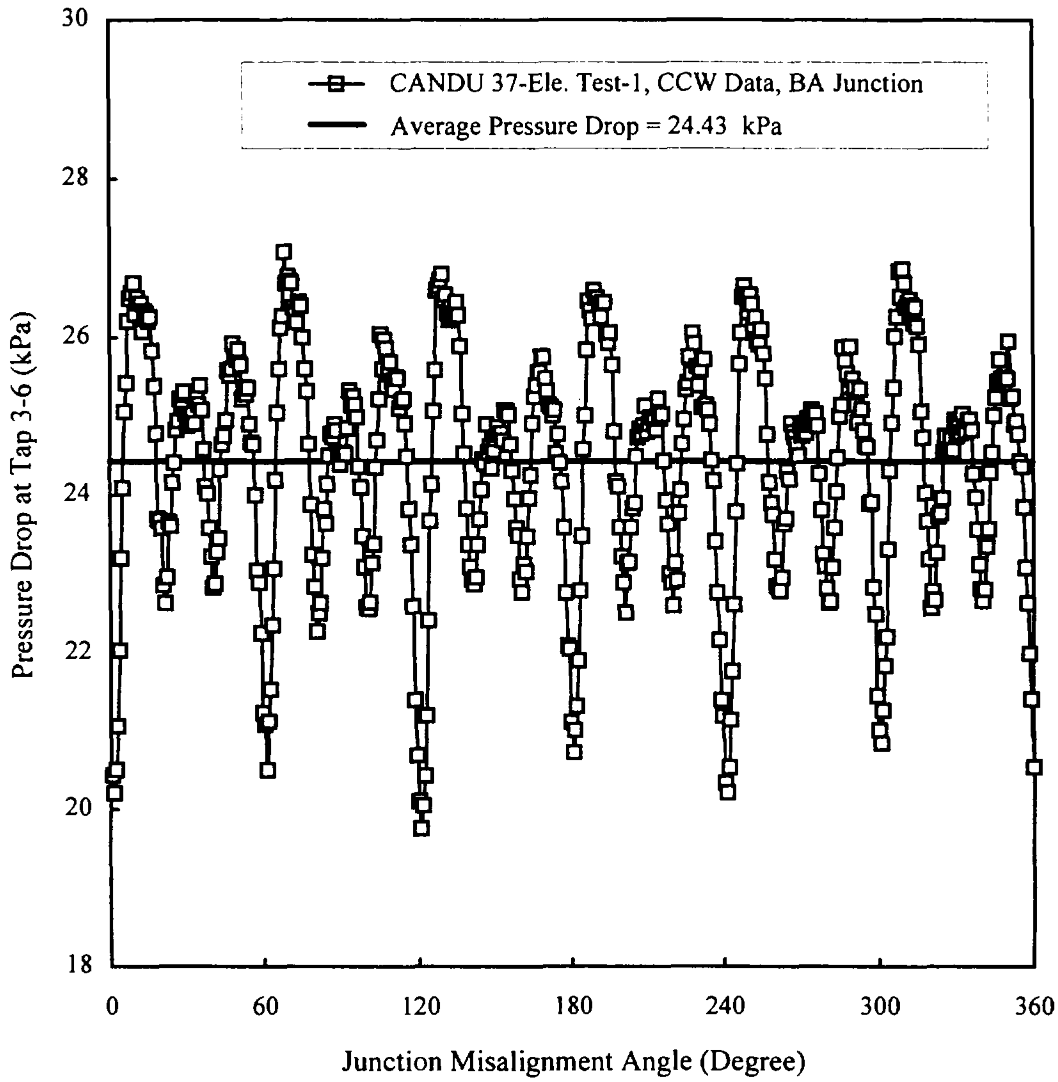


Figure 15 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANDU 37-Ele. Test-1, Counter Clockwise(CCW) Data with BA Junction

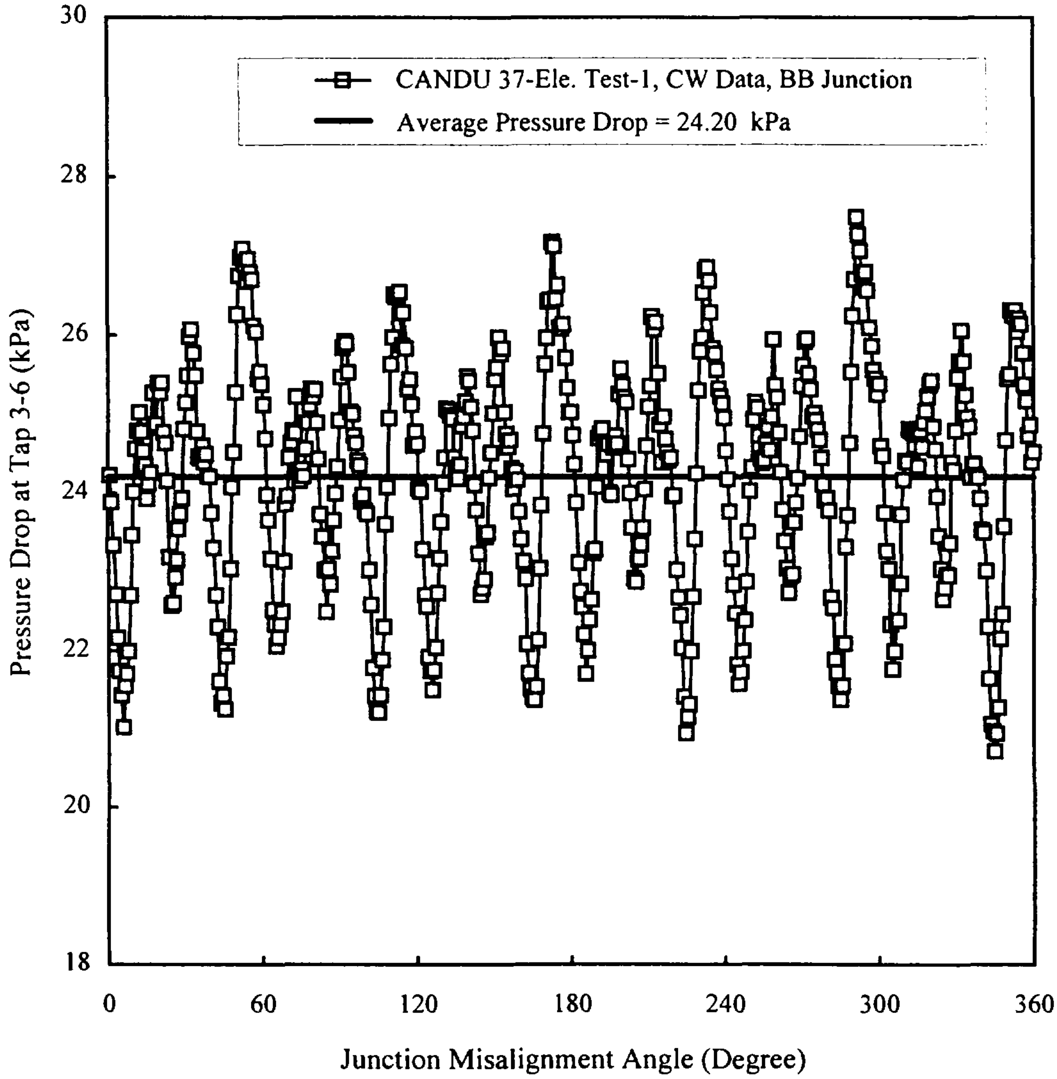


Figure 16 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANDU 37-Ele. Test-1, Clockwise(CW) Data with BB Junction

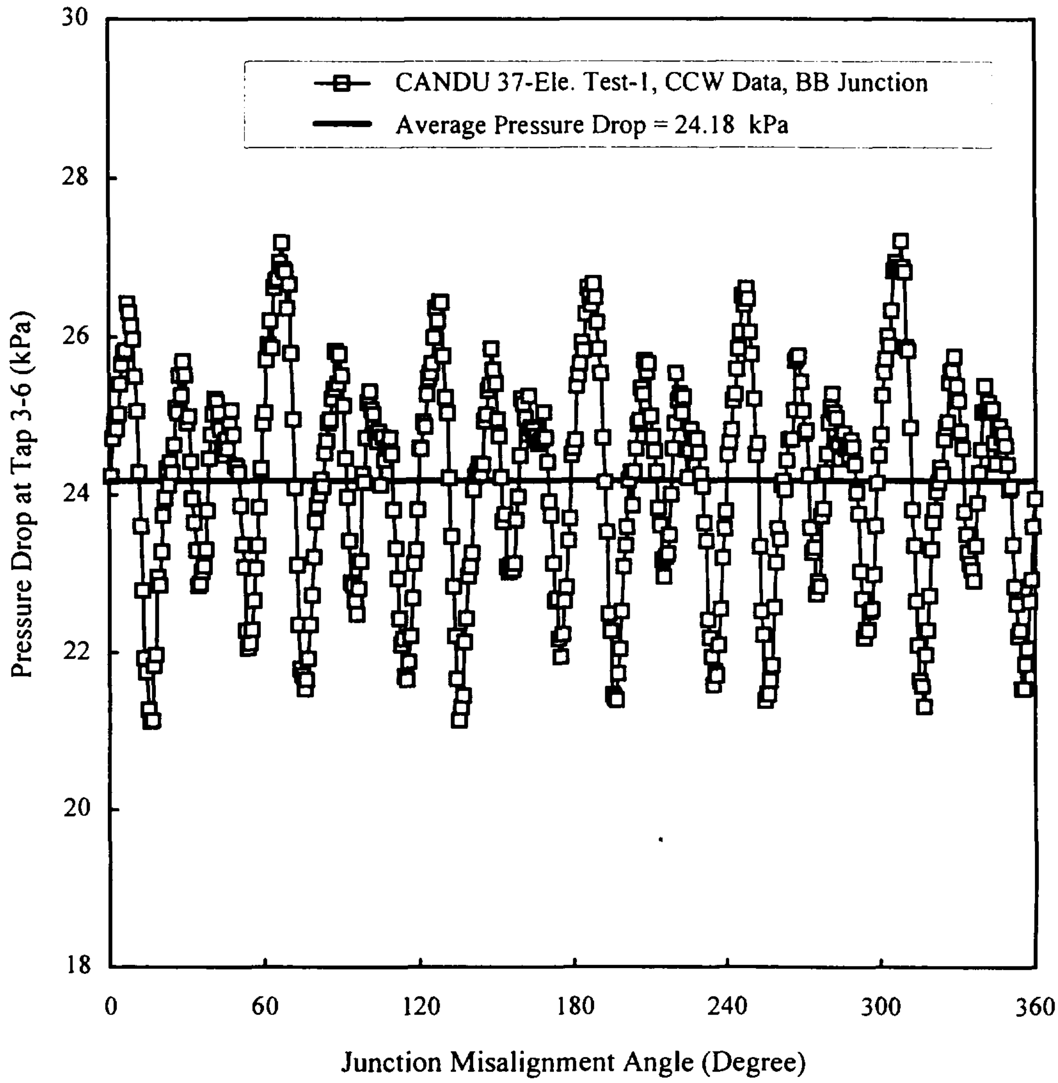


Figure 17 Pressure Drop at Tap 3-6 versus Junction Misalignment Angle, CANDU 37-Ele. Test-1, Counter Clockwise(CCW) Data with BB Junction

서 지 정 보 양 식

수행기관보고서번호	위탁기관보고서번호	표준보고서번호	INIS 주제코드
KAERI/TR-793/96		KAERI/TP-CX121	

제목/부제	CANFLEX Fuel Bundle Junction Pressure Drop (Test Report)
주저자 및 부서명	정흥준 (열유동실험분야)
연 구 자 및 부 서 명	정장환, 전지수, 홍성덕, 장석규, 김복득

출 판 지	대 전	발행기관	한국원자력연구소	발행년	1996. 11
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참고사항	CANFLEX 핵연료 국제 공동 연구개발 (Canada, AECL)

비밀여부	공개( ), 대외비( ), __급비밀	보고서종류	기술보고서
연구위탁기관		계약 번호	

초록 (15-20줄내외)

본 보고서에서는 설계가 확정된 CANFLEX 핵연료다발과 현재 CANDU 원자로에 장전되고 있는 CANDU-37 핵연료다발에 대한 회전 압력강하시험 결과를 기술하였다. 회전 압력강하시험 결과로부터 CANFLEX 및 CANDU-37 핵연료다발 각각에 대한 최대/최빈 압력강하 정렬각도를 도출하였다. 각각의 최대/최빈 압력강하 정렬각도는 Fuel String Total Pressure Drop Test 에 이용된다.

주제명키워드 (10단어내외)	CANFLEX 핵연료, 회전압력강하, 핵연료다발렬 압력강하시험, 정렬각도, 최빈 압력강하.

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<tr><td>Title/ Subtitle</td><td colspan="7">CANFLEX Fuel Bundle Junction Pressure Drop (Test Report)</td></tr>
<tr><td colspan="2">Auther and Department</td><td colspan="6">H. J. Chung (Fuel Themal-hydraulics Test Dept.)</td></tr>
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<tr><td colspan="8">Abstract (15-20 Lines)

This report describes the junction pressure drop test results which are to be used to determine the alignment angle between bundles to achieve the most probable fuel string pressure drop for randomly aligned bundles for use in the Fuel String Total Pressure Drop Test.</td></tr>
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