4. Experience Base for ACR Fuel

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Washington, DC

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AECL

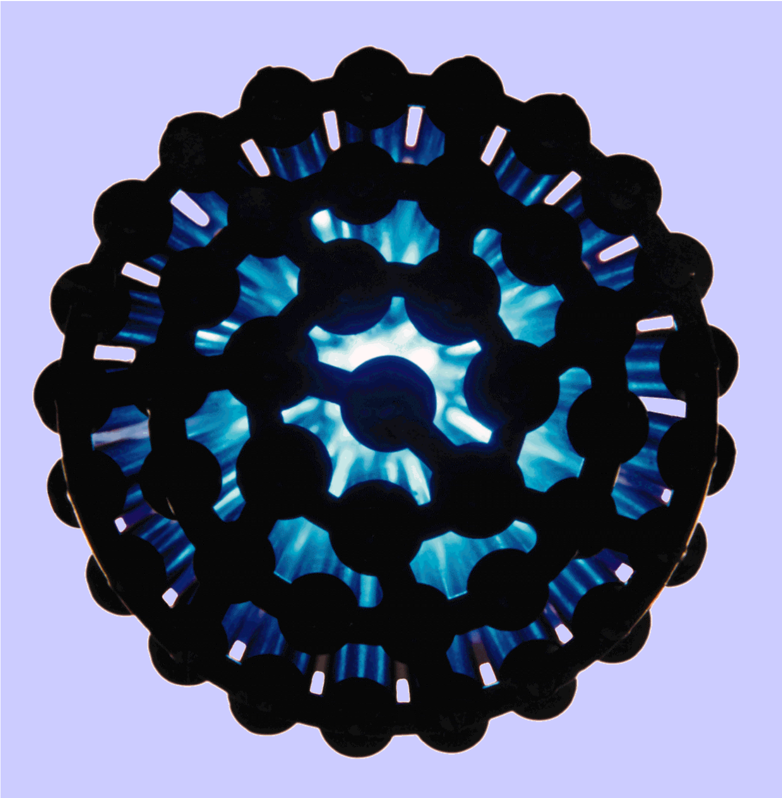
TECHNOLOGIES INC.

Outline

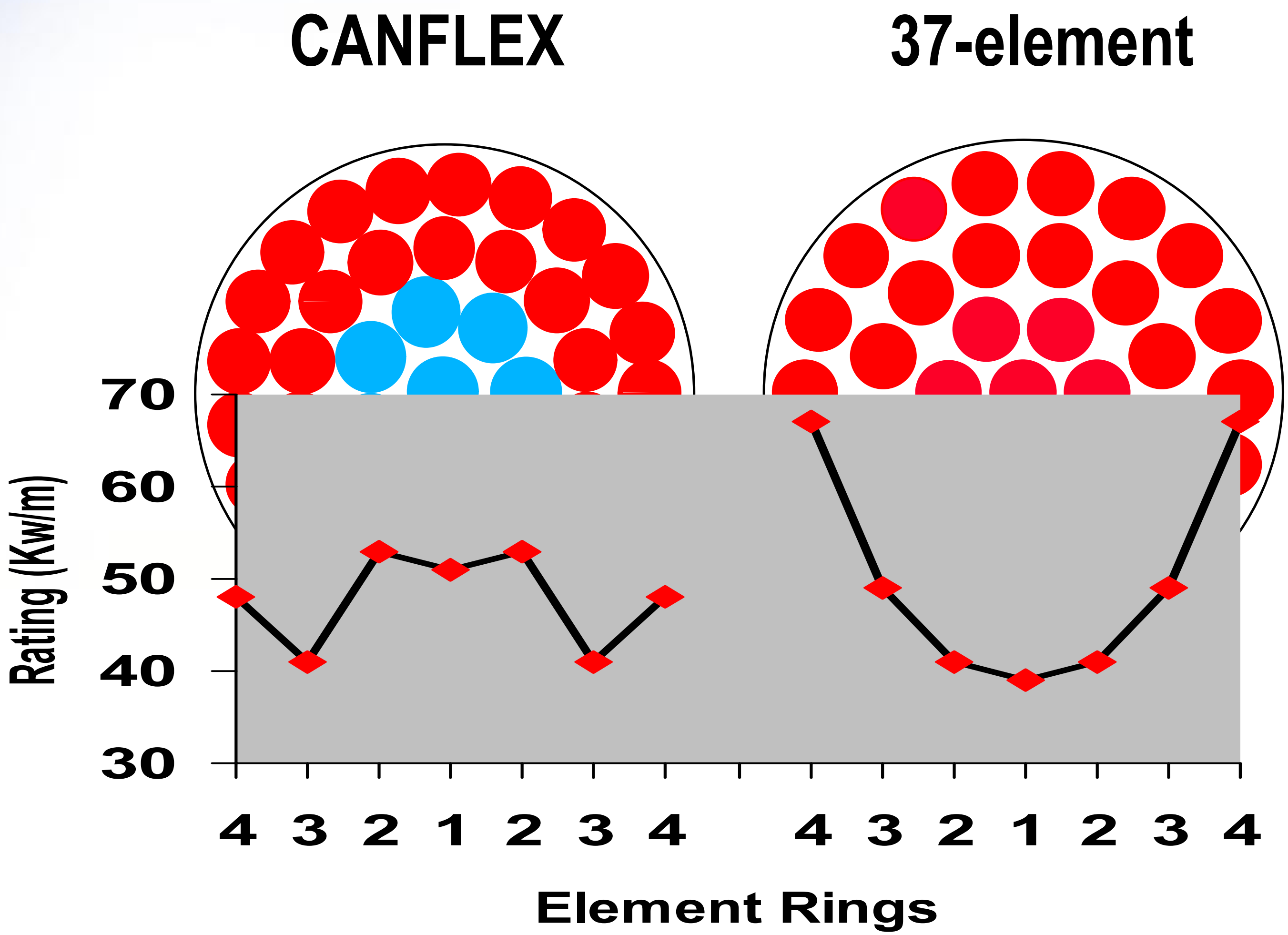
- CANFLEX development and qualification
- Enriched fuel / extended burnup experience
- Low Void Reactivity Fuel (LVRF)
  - dysprosium-doped fuel
- Generic advanced fuel development in AECL

CANFLEX Fuel

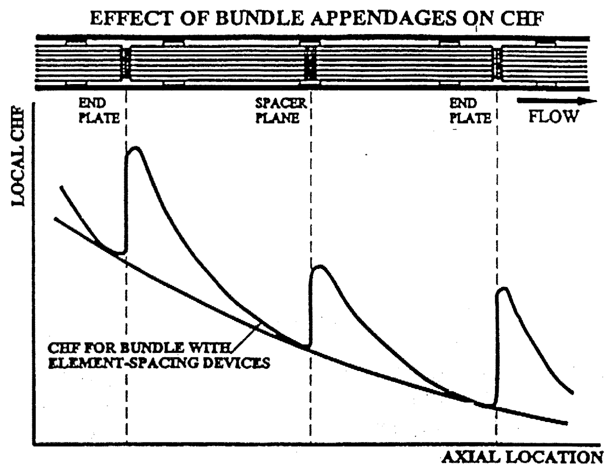
- 43 elements, 2 sizes
  - 8 central elements 13.5 mm (0.53”) in diameter
  - 35 outer elements 11.5 mm (0.45”) in diameter
- ~20% lower peak rating than for 37-element fuel (for same bundle power)
  - facilitates achievement of higher burnup
- CHF-enhancing buttons
  - increase coolant turbulence
  - higher operating margins

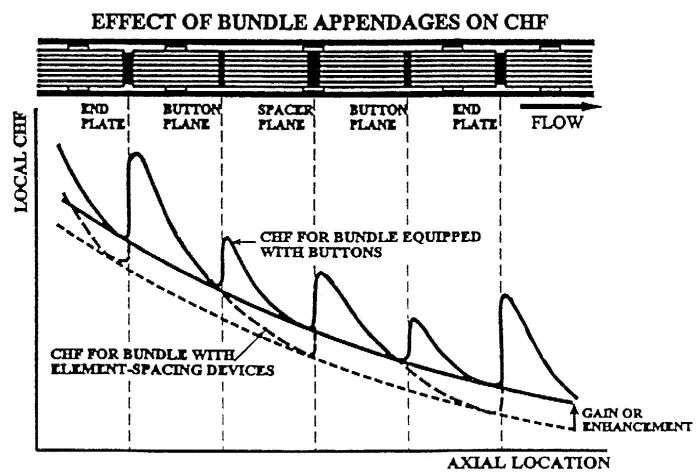


Linear Element Ratings (NU)

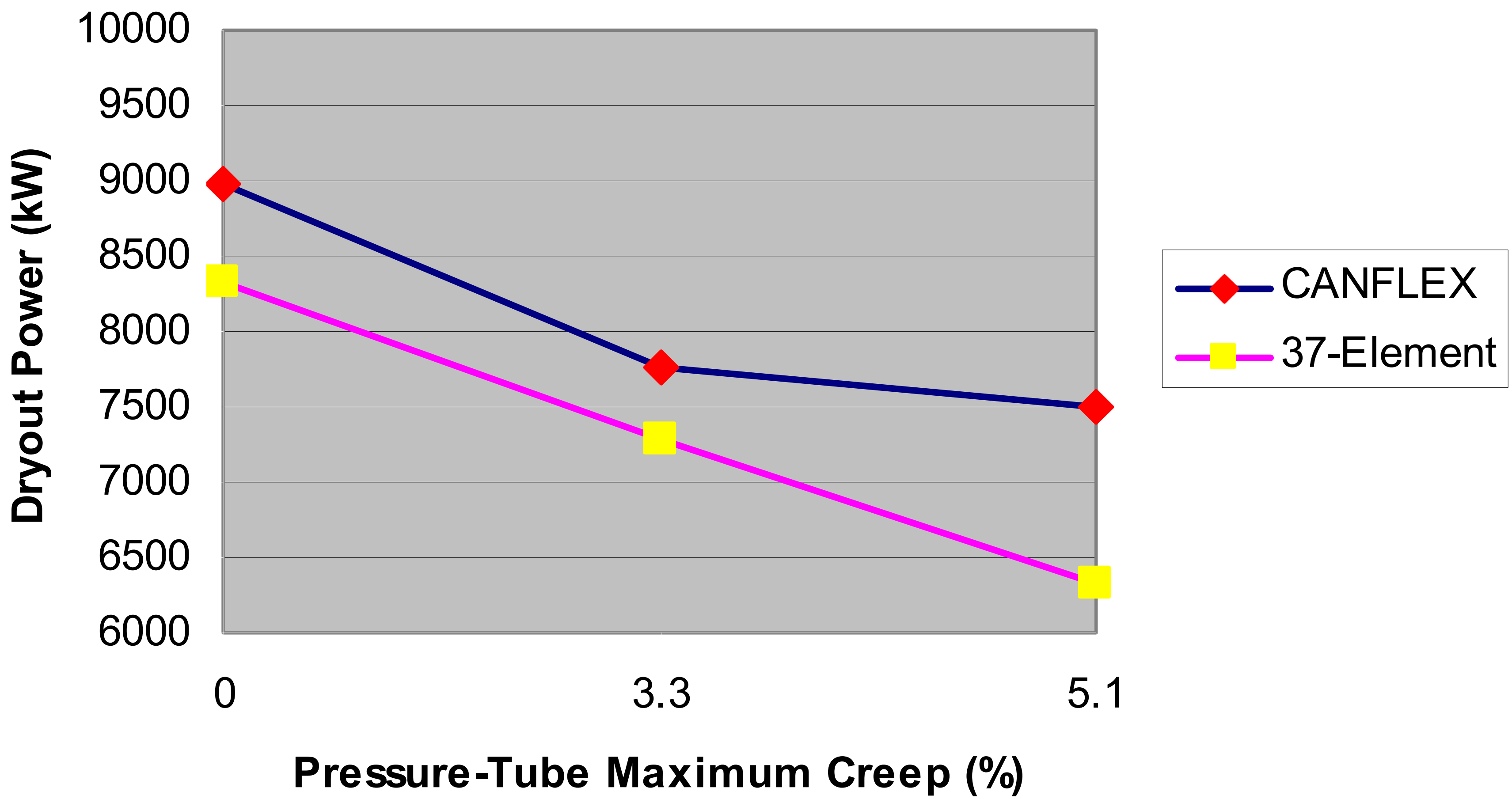


Effect of Appendages on CHF





CANFLEX Thermal Hydraulic Performance



Summary of CANFLEX Mk 4 Qualification

- Design requirements documented in Design Requirements, Design Verification Plan
- Analysis and tests confirm that CANFLEX meets all requirements
  - strength
  - impact and cross-flow
  - fueling machine compatibility, endurance
  - sliding wear
  - fuel performance (NRU)
  - CHF thermal hydraulic
- Demonstration irradiation (DI) in Point Lepreau 1998 to 2000
  - 2 channels, 24 bundles
- Design qualification program documented in Fuel Design Manual
- Formal industry-wide Design Reviews conducted for DI and full core implementation
- Ready for commercial implementation in CANDU 6 reactor

Design Verification Plan

- QA Program
  - CAN3-N286-86 Appendix D (to qualify CANFLEX for use in CANDU 6 reactor)
- Analyses
  - sliding wear, crevice corrosion*, thermal hydraulic, power ramp, seismic*
- In-reactor tests
  - high burnup, high power, power ramp in NRU
  - 24-bundle demonstration irradiation in PLGS
- Out-reactor tests: fueling machine compatibility, refueling impact, endurance, strength, cross flow, pressure drop
- CHF Tests: freon, full scale water
- Documents: Technical Specification, Drawing, Design Manual
- Design Review: industry-wide
- Other: Physics DM, ZED-2 tests

** Qualification by engineering judgement*

Documentation for Qualification Tests

- Qualification testing for CANDU fuel follows a set of AECL procedures that meet the requirements of CAN3-N286.2, “Design Quality Assurance for Nuclear Power Plants”

- Test Specifications (includes acceptance criteria)
  - Component Verification Specifications (CVS)
- Test procedures
  - prepared to ensure tests meet the requirements of the CVS
- Test Reports
  - Component Verification Reports (CVR)

Qualification Test Comparison (37/43 fuel designs)

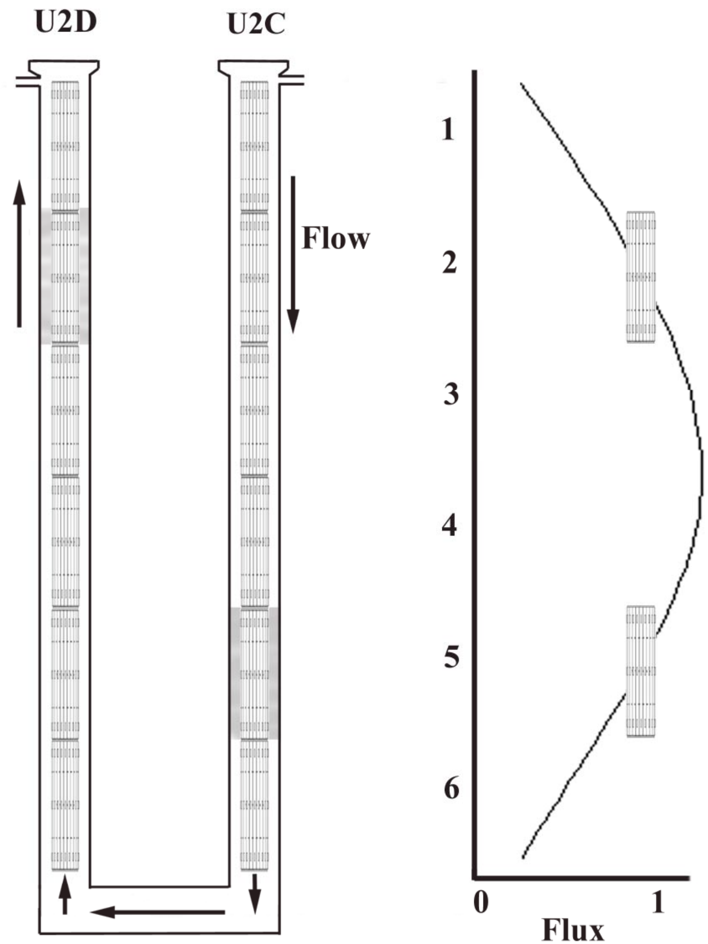
	CANDU 6 37-element	CANDU 6 CANFLEX NU
In-Reactor		
High Power	1	2
Power Ramp	1	2
High Burnup	0	1
Out-Reactor		
•Pressure Drop (full channel)	1	1
•Endurance	2	1
•Strength	1	1
•Refueling Impact	2	1
•Sliding Wear	1	0 (assessment only)
•Cross Flow	0	2
•Bundle Rotation Test (DP)	1 (high pressure)	1 (low pressure)
•Seismic	1	0 (assessment only)
Demonstration Irradiation	Bruce A	24 B @ Lepreau

NRU Tests

- Objective to demonstrate acceptable irradiation performance of CANFLEX UO_2 fuel elements for both NU and SEU fuel cycles
- 8 CANFLEX UO_2 bundles irradiated in NRU
  - overall performance similar to 37-el bundle
  - wide range of powers and burnups
- CANFLEX-NU requirements bounded
  - high power (typical and bounding powers)
  - power ramp (refueling power ramps simulated)
  - burnup (normal and high burnup)

NRU Fuel Irradiation Loops

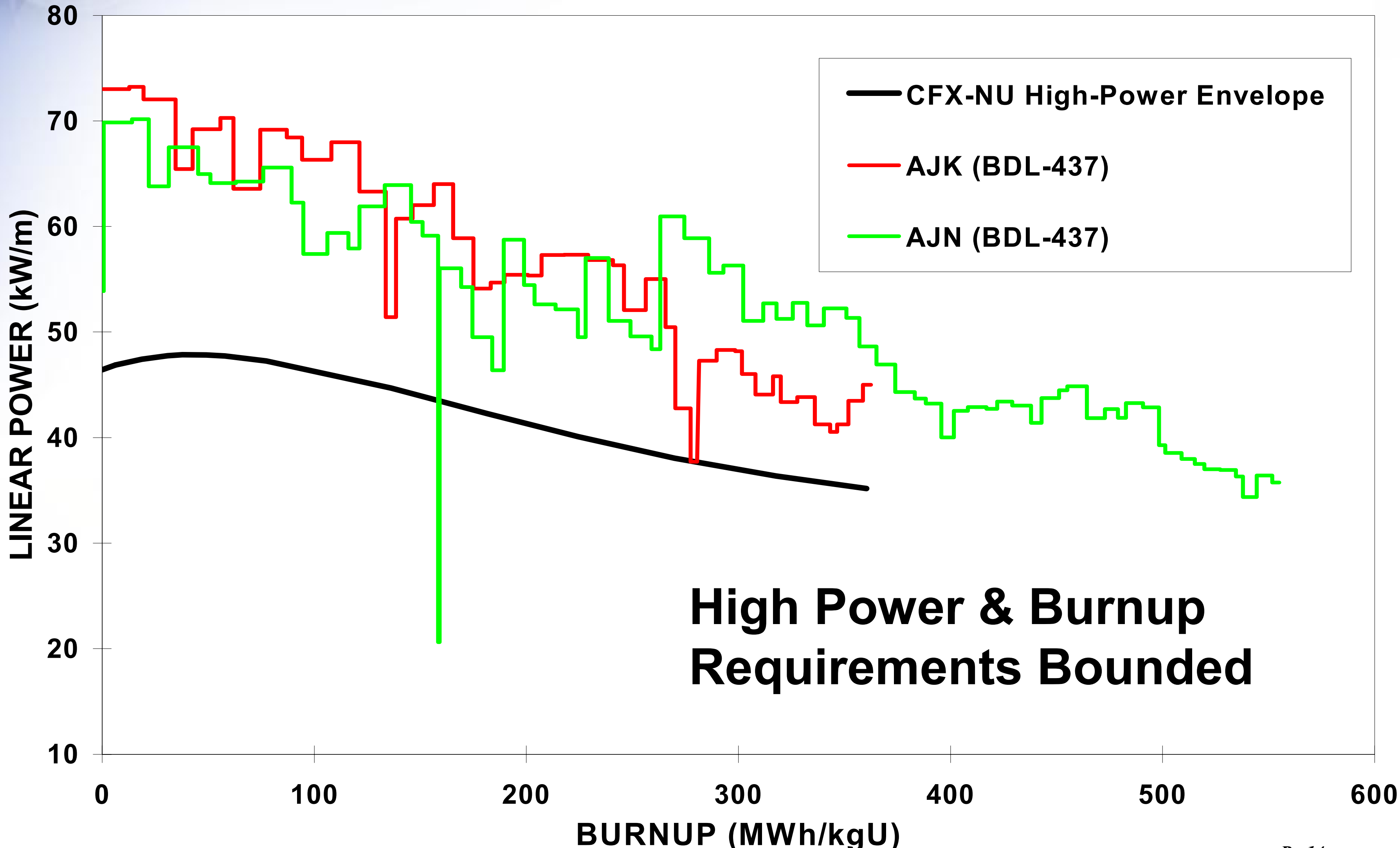
- Irradiation in 6-bundle fuel strings (full scale) in U1/U2 loops of the NRU reactor in Chalk River
- 3 test sections available (can accommodate 18 CANDU fuel bundles)
- Central element removed from bundles for NRU tie-rod
- Typical CANDU operating conditions
  - 260-305 °C
  - 9.5-10.9 MPa
  - similar chemistry
- Movement of bundle in string can produce power ramp



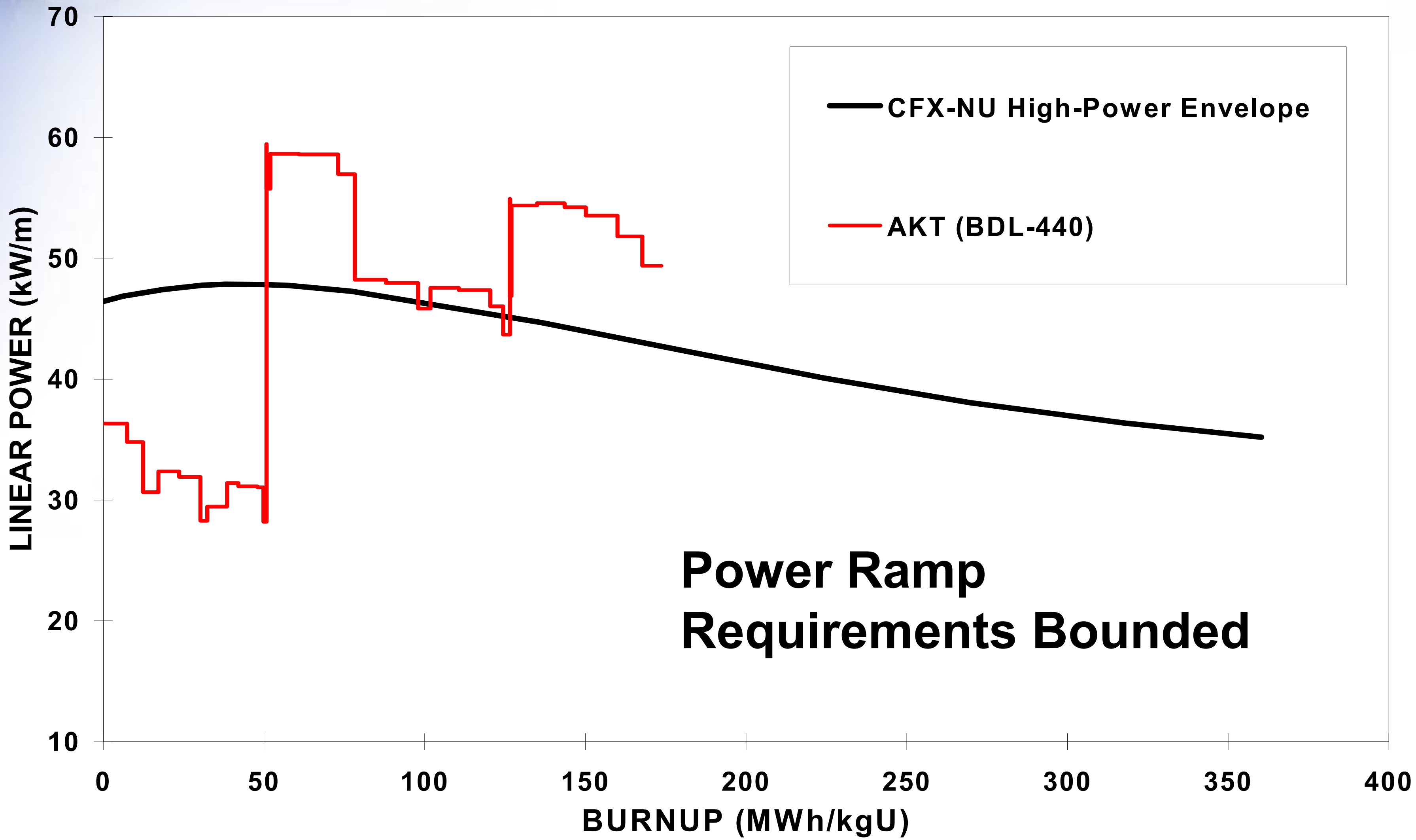
CANFLEX Irradiations

TEST	BUNDLE	POWER (kW/m)	BURNUP (MWd/kgU)
BDL-437	AJJ	35-69	12.9
	AJK	29-73	15.5
	AJL	47-83	3.8
	AJM	27-69	22
	AJN	29-70	23
BDL-440	AKT	20-59	7.3
BDL-443	AKV	19-49	18.3
	AKW	18-45	13.0+

Summary of NRU High Power Tests

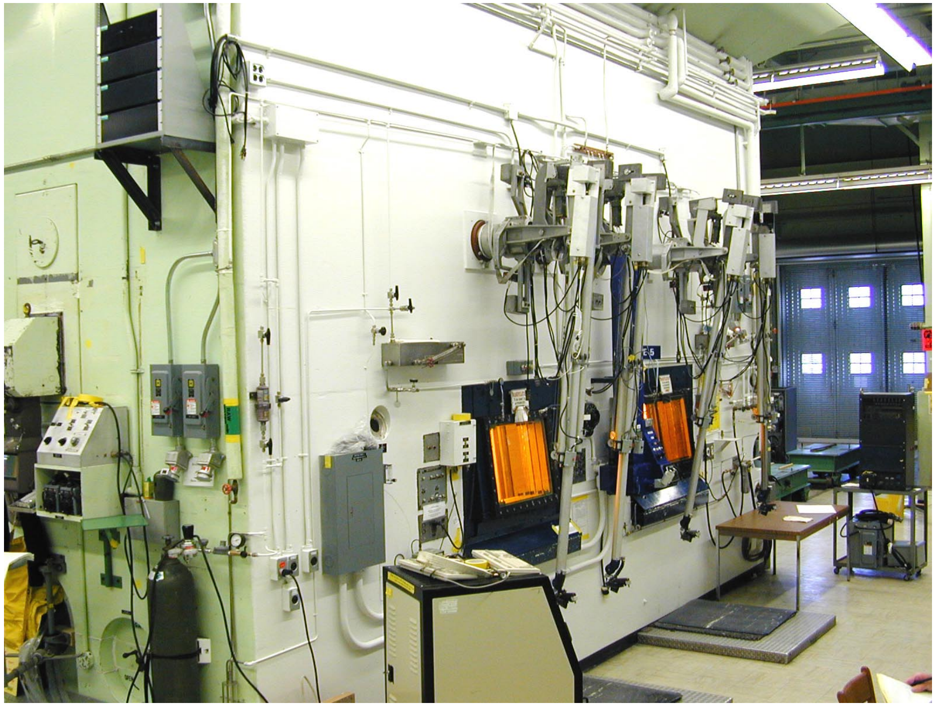


Summary of NRU Power Ramp Tests



PIE Measurements

- Visual examinations
- Fuel dimensioning
- Gamma scanning
- Gas-puncture analysis
- H/D analysis
- Burnup measurement
- Clad metallography
- Pellet ceramography



Out-Reactor Qualification Tests

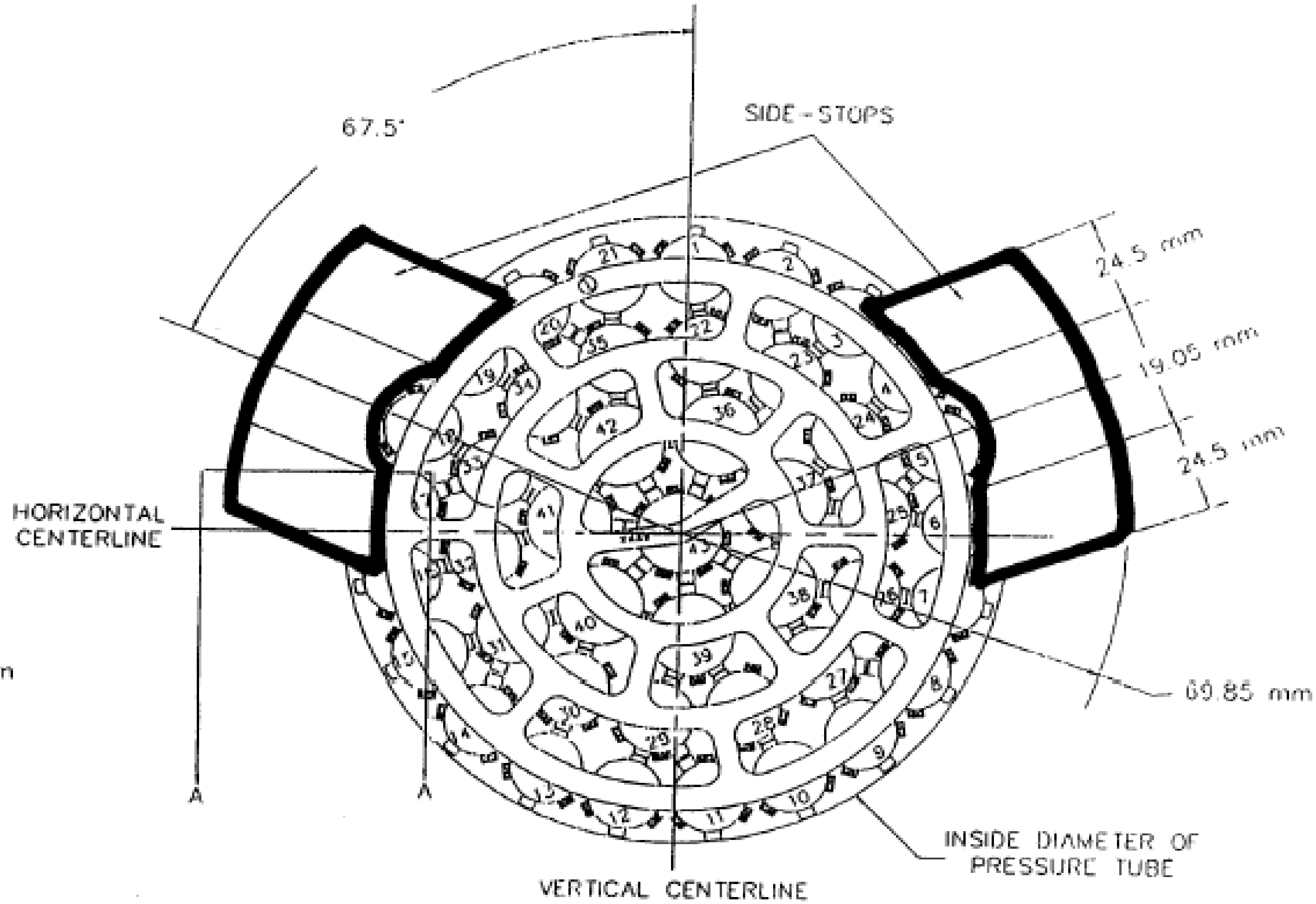
- Thermal hydraulic / pressure drop*
- Strength*
- Fueling machine compatibility*
- Refueling impact*
- Endurance*
- Cross flow*
- Sliding wear
- Seismic

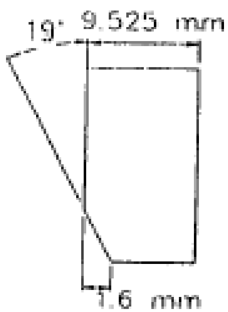
* 6 out-reactor tests performed for CANFLEX

Strength Tests

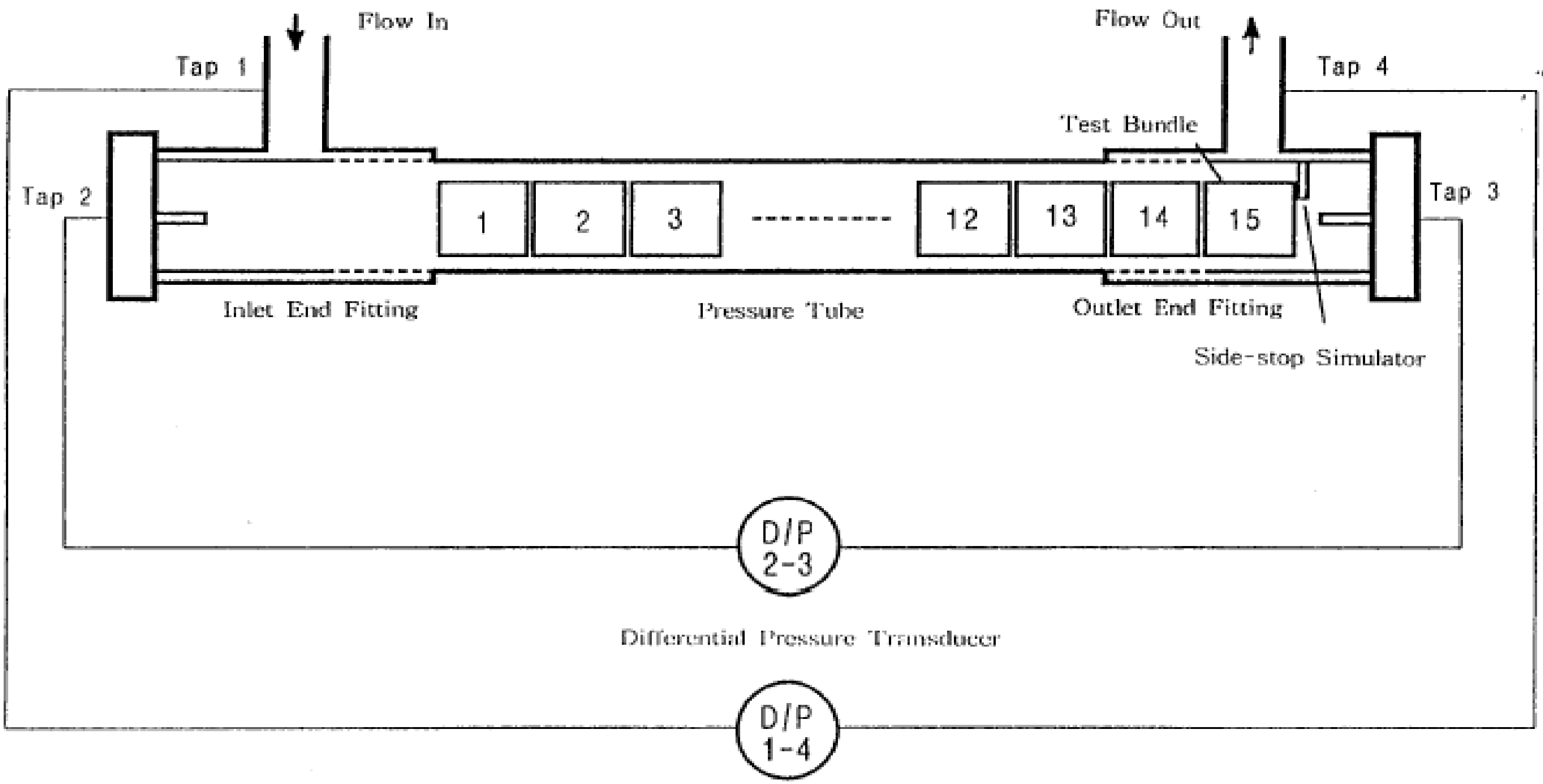
- Objective
  - to show that CANFLEX fuel can successfully withstand the axial drag loads when the downstream bundle is supported either by both side stops (normal operation) or by only a single side stop (abnormal operation with failure of one side stop)
- Acceptance criteria
  - no significant distortion
  - no significant fuel element length change and/or endplate profile change
  - bundles must pass the bent tube gauge test
  - no significant bearing pad wear, or marking of the fuel element endcaps
- Results
  - tests performed at 120C, 11.2 MPa, minimum load of 7300 N, for 15 m
  - post-test bundle geometry measurements showed no significant distortion (element length, bow, etc.)

Fueling Machine Side-Stops for CANFLEX Strength Tests





Strength Test Set-up



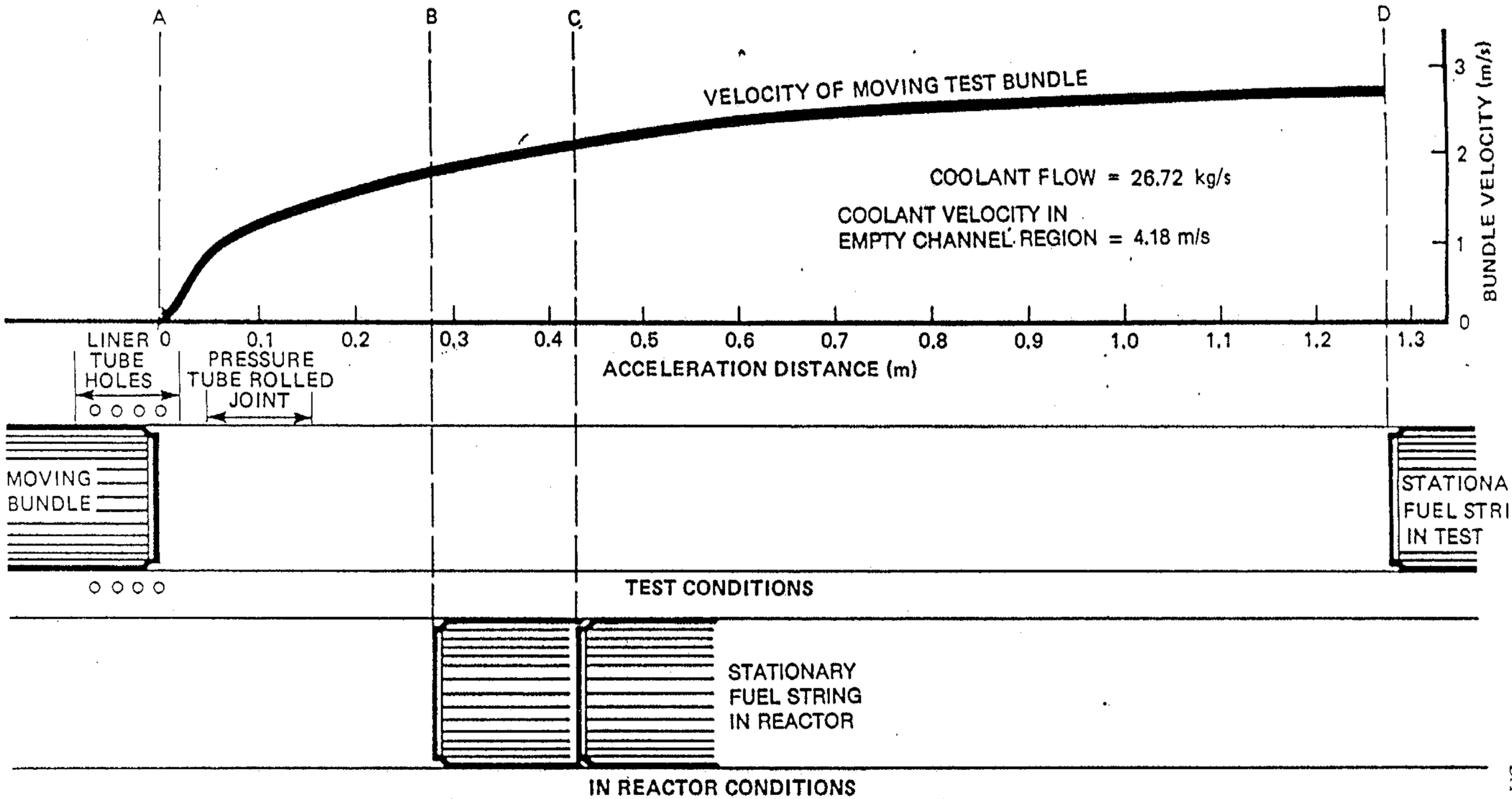
Fueling Machine Compatibility Test

- Objective
  - to show that CANFLEX fuel bundles are compatible with the CANDU 6 fueling machine and with the grappling tool
- Acceptance criteria
  - test bundles shall not become damaged nor cause any malfunction to the fuel handling equipment
- Results
  - tests performed in the Wolsong fueling machine and full scale test fuel channel using 4 CANFLEX and eight 37-element bundles, under typical reactor operating conditions of pressure, temperature and flow; 2 cold cycles and four hot cycles performed
  - 10 bench tests of the CANDU 6 fueling machine grappling tool were performed, with two different bundle orientations, on two separate bundles, for a total of 40 tests
  - all results normal

Refueling Impact Test

- **Objective**
  - to show that CANFLEX fuel can successfully withstand the normal refueling impacts (up to 0.5 m acceleration distance, and 30 kg/s channel flow)
- **Acceptance criteria**
  - no significant distortion or damage to the fuel bundle endplate, or to the fuel elements; waviness of the endplates should be within the bundle specification.
  - no significant distortion which would prevent the bundles from passing through the kinked tube gauge test
  - no visible damage to the pressure tube from impacts of the fuel bundle; the depth of the scratches should be less than the design allowance for pressure tube wear
- **Results**
  - all results normal

Refueling Impacts (CANDU 6)



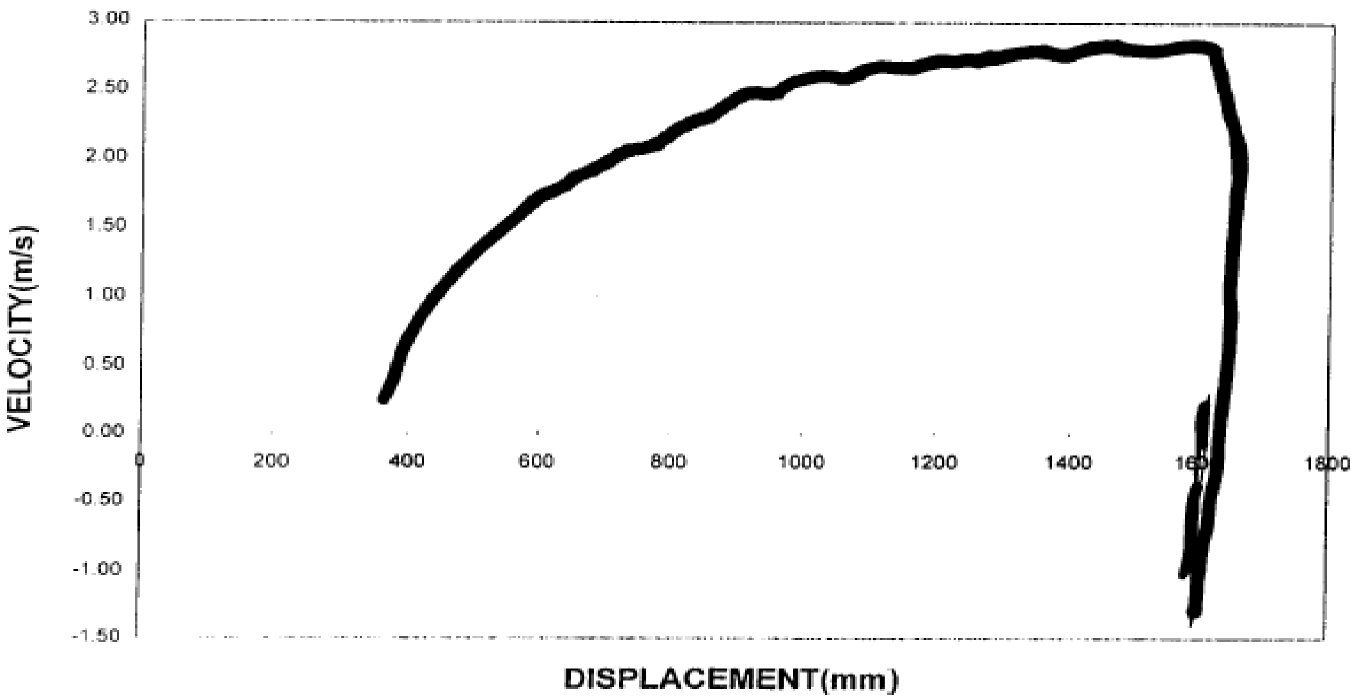
A – POSITION OF MOVING BUNDLE BEFORE ACCELERATION

B – POSITION OF FUEL STRING IN-REACTOR BEFORE PRESSURE TUBE AXIAL CREEP

C – POSITION OF FUEL STRING IN-REACTOR AFTER PRESSURE TUBE AXIAL CREEP

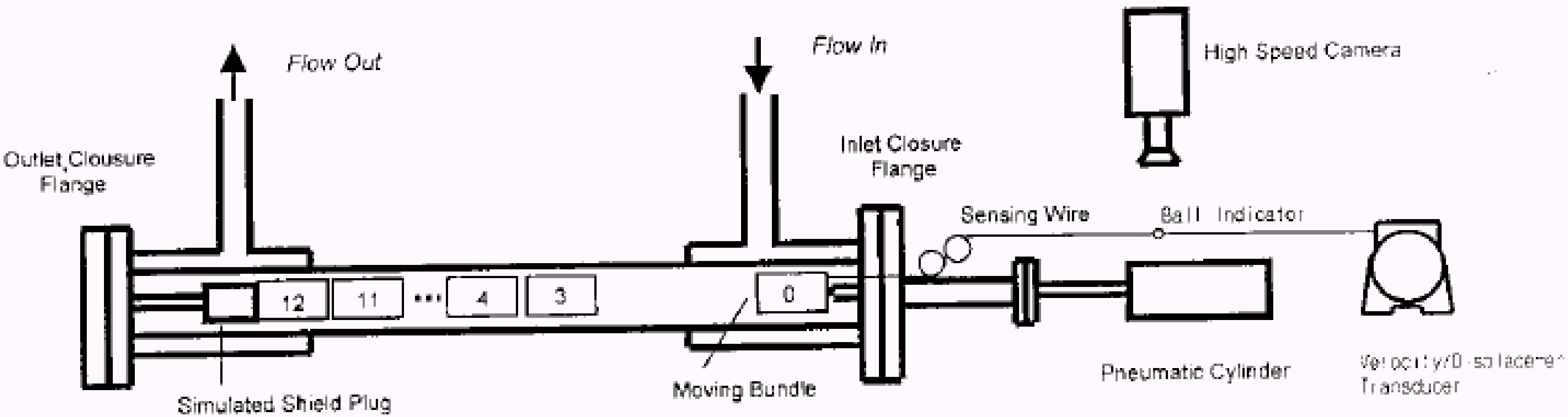
D – POSITION OF FUEL STRING IN OUT-REACTOR TEST

Refueling Impacts (CANFLEX)



Velocity versus Displacement of the Moving Bundle
(Measured by Vel./Disp. Transducer)

Impact Test Apparatus



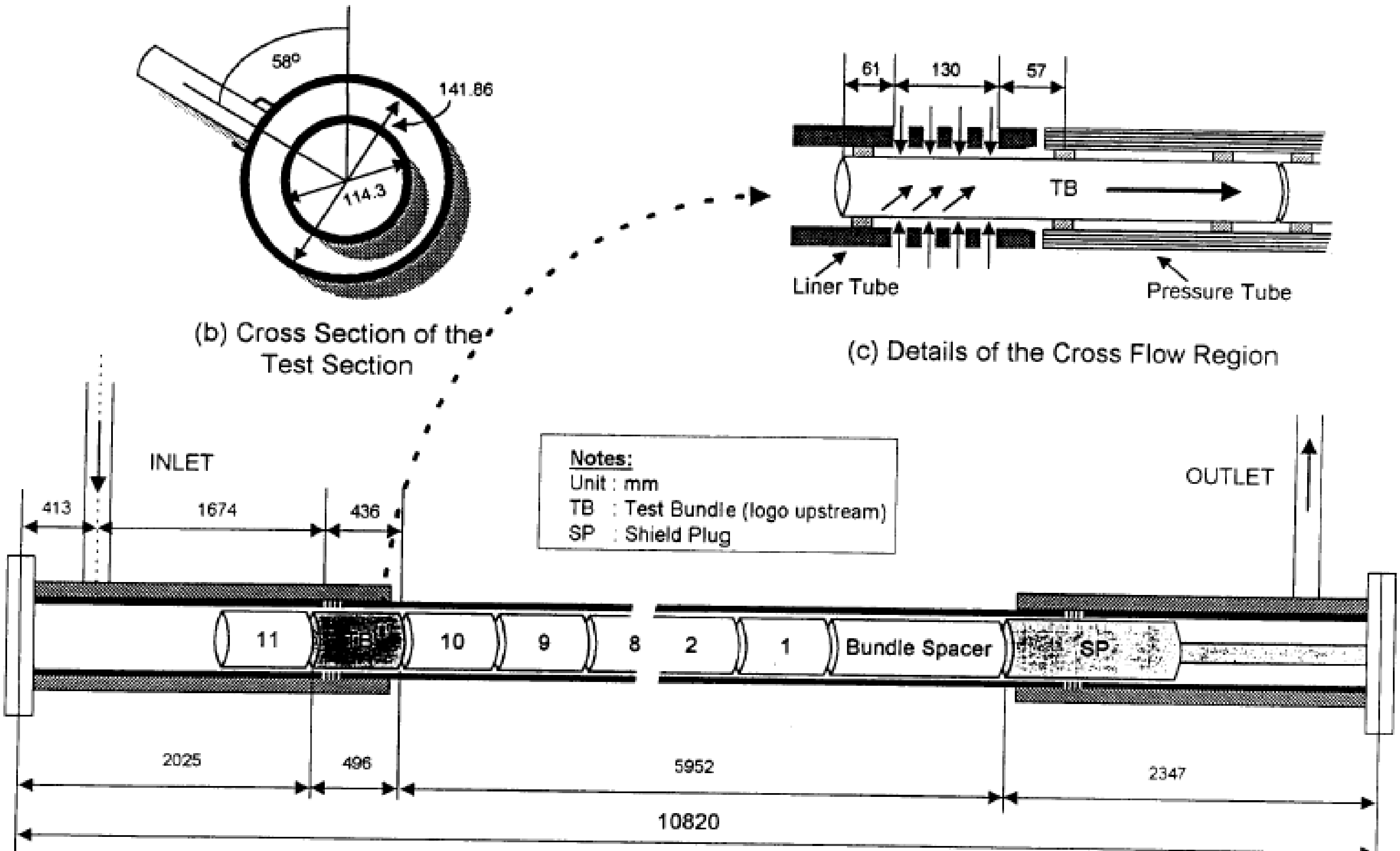
Mechanical Fretting Endurance Test

- Objective
  - to show that the fretting of the pressure tube and CANFLEX fuel bundles are acceptably low under in-reactor flow, temperature and pressure conditions, for representative bundle dwell periods
- Acceptance criteria
  - the material loss due to fretting of the inter-element spacers and of the pressure tube must be within the wear allowances
- Results
  - all results normal

Cross-flow Endurance Test

- **Objective**
  - show that CANFLEX fuel can successfully survive up to 4 hours in the cross-flow region of the liner of a CANDU 6 channel
    - the holes in the liners of the fuel channel inlet and outlet end fittings are locations where coolant enters and exits causing high coolant velocities in the radial direction (normal refueling results in the bundles being in the cross flow for only a few minutes)
- **Acceptance criteria**
  - the bundle must meet all dimensional requirements of a new fuel bundle, & must be free of failures of the endplate-to-endcap welds, and free of cracks or failures in the endplates
  - the inter-element spacers must maintain a minimum spacing between elements of 1 mm
  - the bundle must pass the bent tube gauge test
  - there is to be no spacer interlocking of the test bundle
- **Results**
  - bundle passed

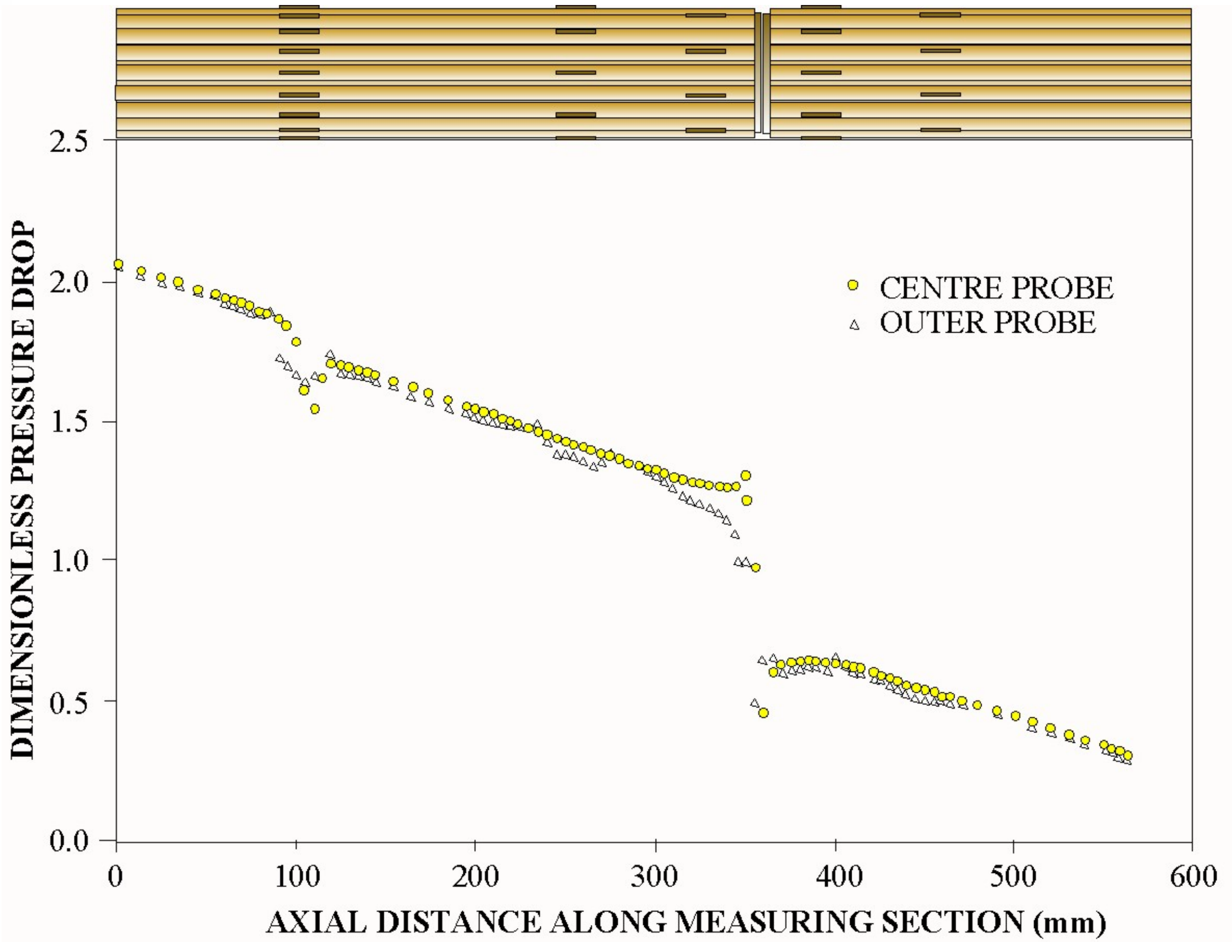
Test Bundle Location in Cross-flow Region



Thermal Hydraulic Parameters

- Fuel string pressure drop
  - establishes channel flow based on pump characteristics
- CHF
  - determines trip set-points for
    - Neutron Overpower Protection (NOP) system (loss-of-regulation accident)
    - process trip parameters for other accidents (such as loss-of-flow)
  - a determinant in setting reactor power, operating margins
- Post-dryout (PDO) behavior
  - establishes behavior in operation beyond dryout
    - heat transfer, and drypatch stability and spreading

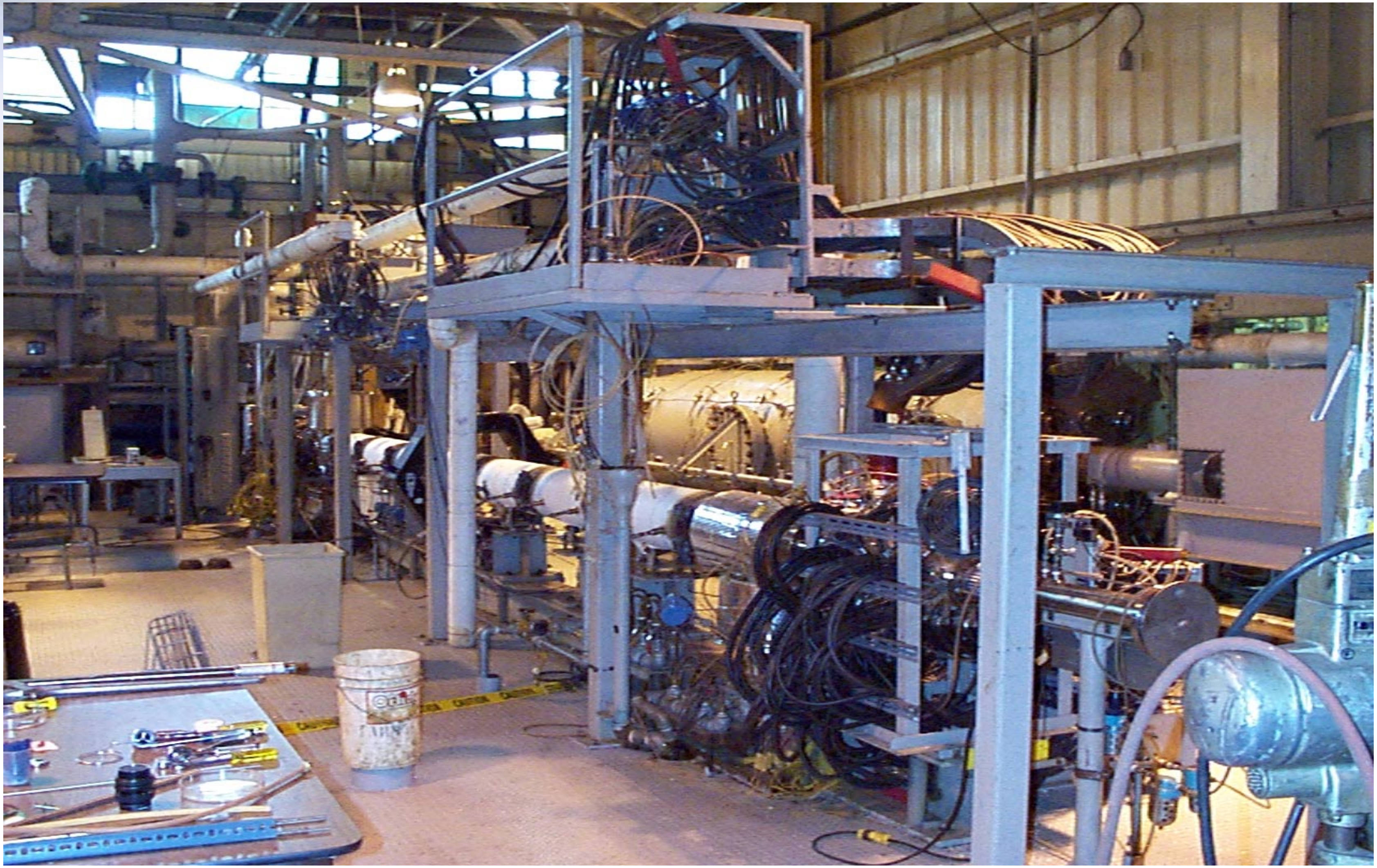
Axial Pressure Profiles Along Fuel Bundles



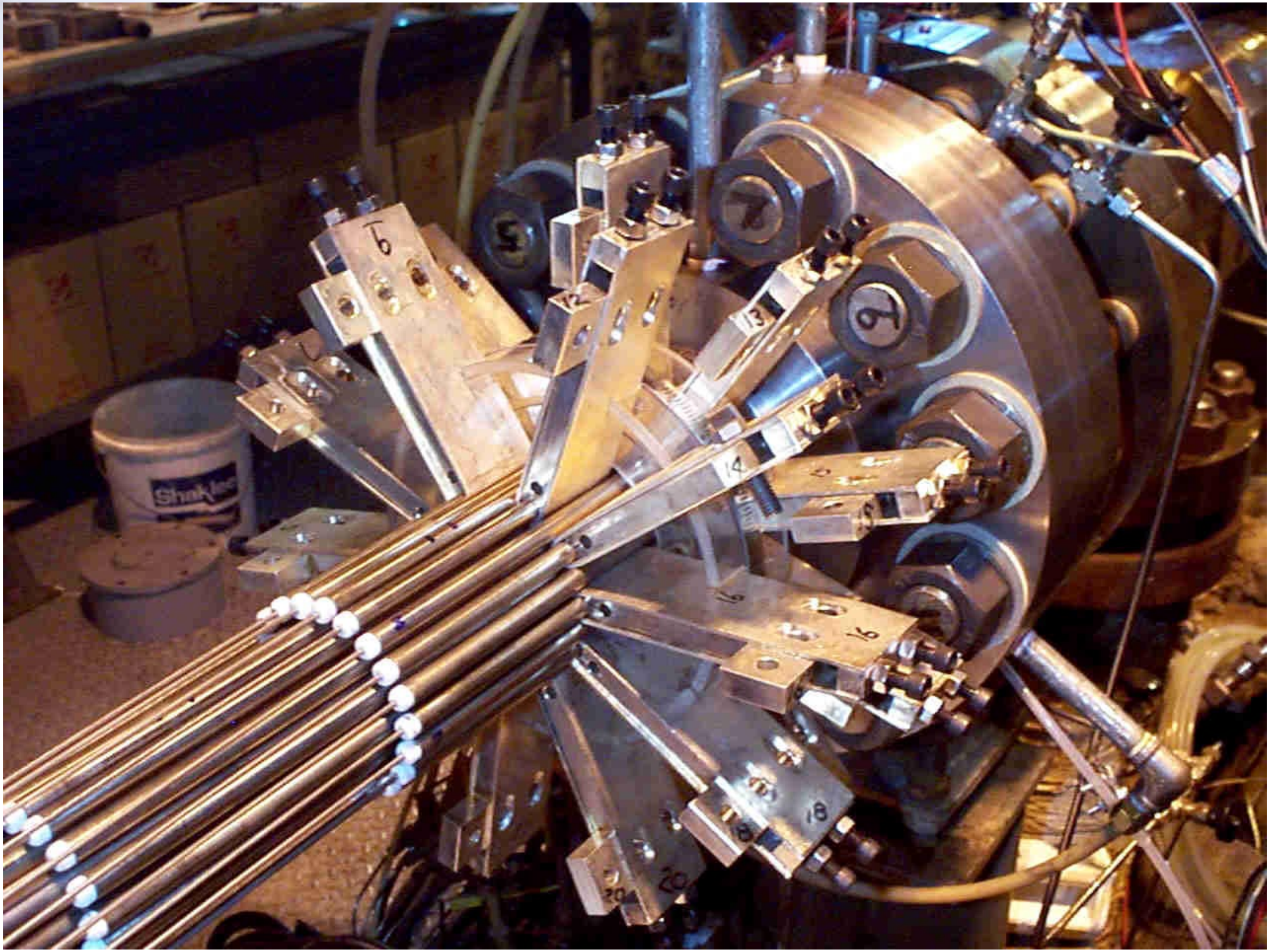
Water CHF Program

- Objectives:
  - produce thermal hydraulic data required for licensing CANFLEX fuel in CANDU reactors
  - secure regulatory approval of the enhanced CHF performance over the 37-element fuel
- CHF testing of CANFLEX Mk 4 in 0%, 3.3% and 5% crept channels
- CHF correlations prepared for the NUCIRC and CATHENA codes
- Bundle dryout power increase up to 17%, and CCP enhancement up to 8% demonstrated
- Report prepared for use in licensing

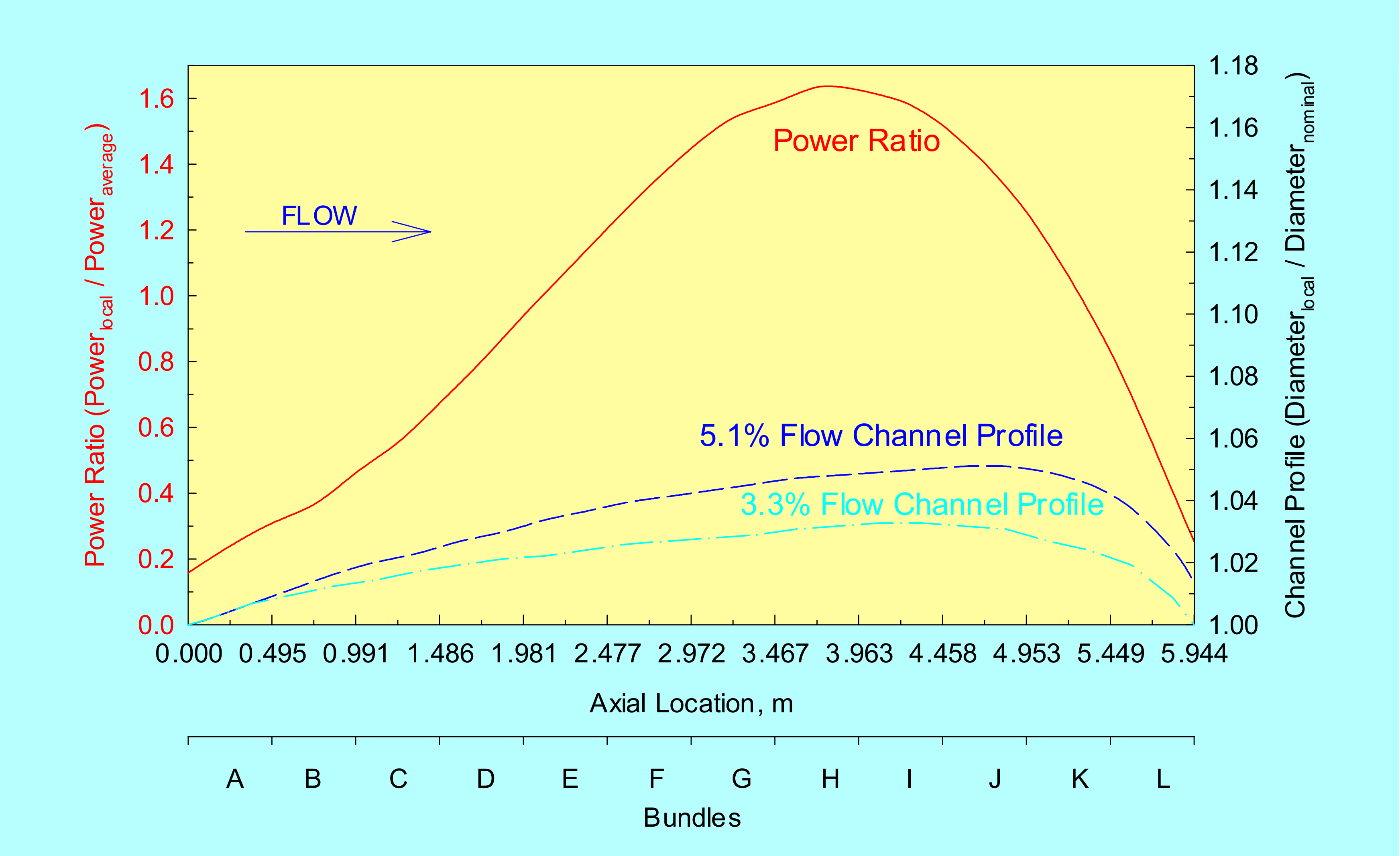
Water CHF Test Station at Stern Labs



Power Connection for Water CHF Test



Thermal Hydraulic Testing



CANFLEX Mk 4 NU Water Test Matrix

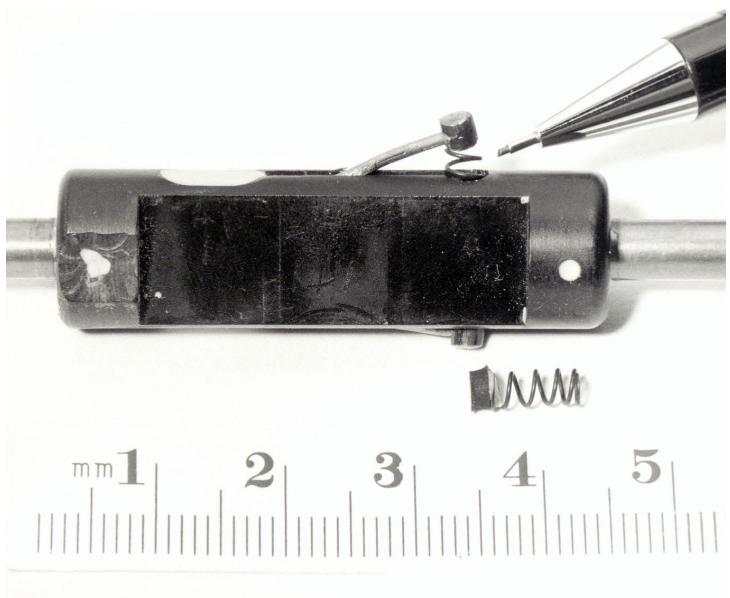
SL CANFLEX water CHF test matrix.

	Uncrept flow tube									3.3 % crept flowtube							5.1% crept flowtube								
Flow kg/s	7	10	14	17	19	21	23	25	27	7	10	14	17	19	21	23	10	14	17	19	21	23	25	27	29
6 MPa																									
265°C		x	x,P	x							x	x	x	x			x	Px	x	x					
245		x	x	x	x						x	x	x	x			x	x	x	x					
225		x	x	x	x					x	x	x	x	x			xx	x	x	x					
212																									
200		x	x	x						x	x	x	x	x			x	x	x	x					
7.5 MPa																									
265°C		x		x		x					x		x		x										
9 MPa																									
284°C			x	x	x	x						x		x		x			xxx		x	x			
273			x		x						x	x	xx	x	x	x		xxx	xxx	xx	xxx	xx	xxxx		
263		xx	xxx	xxx	xxx	xxx	xx				x	x	x	x	x			xP	xxP	x	x	x			
253		x	xxx	xx	x	x					x	x	x	xx	x	x		xx	xx	xx	xx	x	xxxx		
240		x	x	x	x						x	x	x	xx	x			xxx	xxx	xxx	xx	xx			
228			xxx	x	x	x					x		xx		x			x		x		x			
10 MPa																									
265°C		x		x		x					x		x		x										
10.5 MPa																									
265°C		x	x	x	x	x					x		x		xx			xxx	x	xx			x		
11 MPa																									
290°C	x	x	x	xx		xxx	xx					x	x		x		x		x		x				
280		x	x	x	x	x	xx	x			x	x	x	x	x	x		xx	xxx	xx	x	x	xxx	x	
268		xx	x	xx	x	xxx	xx	xx	x		x	x	xx	x	xx	x	Px	Px	Px	xxx	x	x	xxxx	x	x
255		x	x	x	xxxx	xxx	xx	x			x	x	x	x	x	x		x	xx	x	x	xxx	xxx	x	
249																									
243		xxxx	xxxx	xxxx	xxxx	xx	xxx				x	x	x	x	x	x	xx	x	xxx	xx	x	x	x		

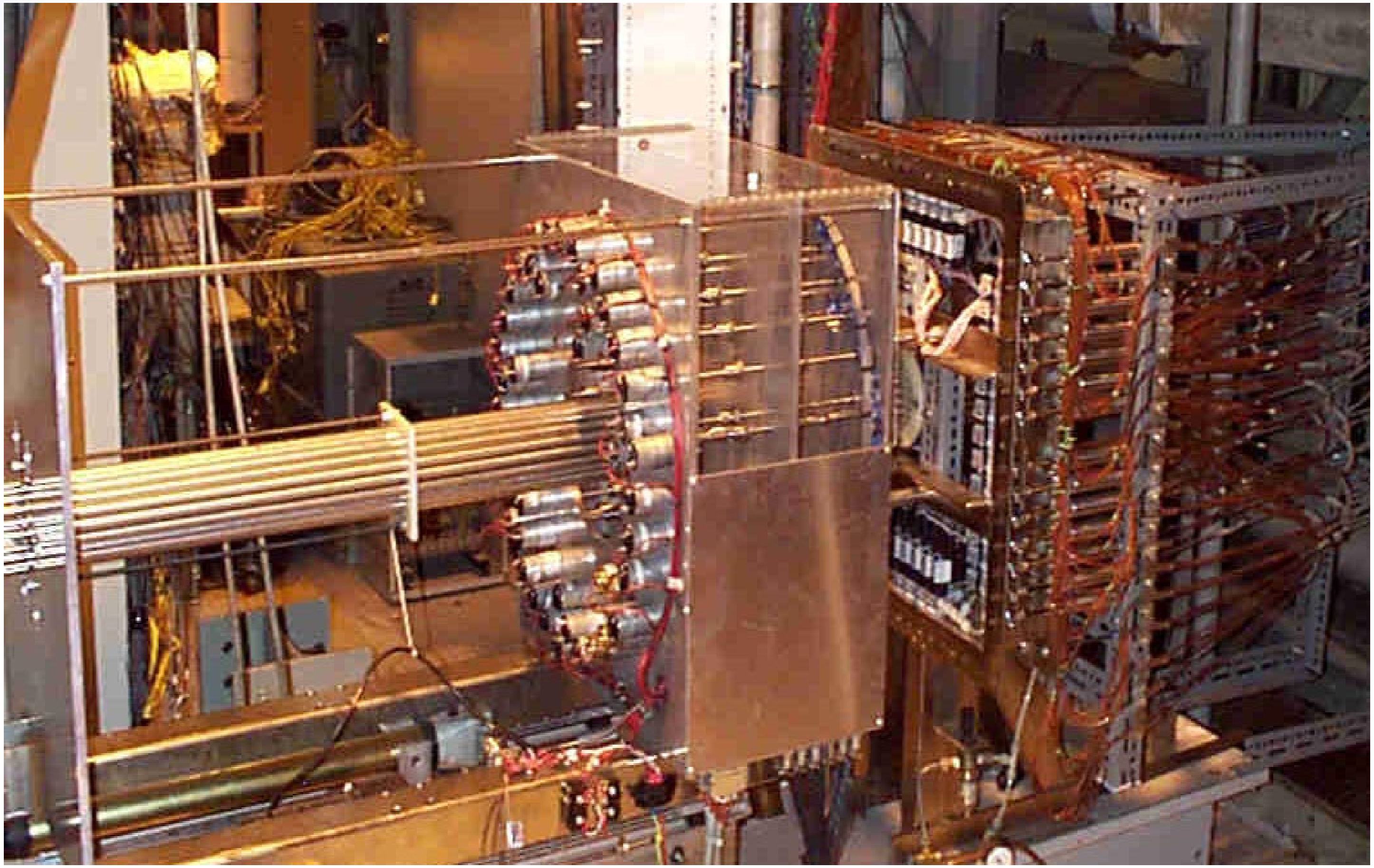
x CHF runs completed. Blue background are 37 element CHF tests.

Sliding Thermocouples

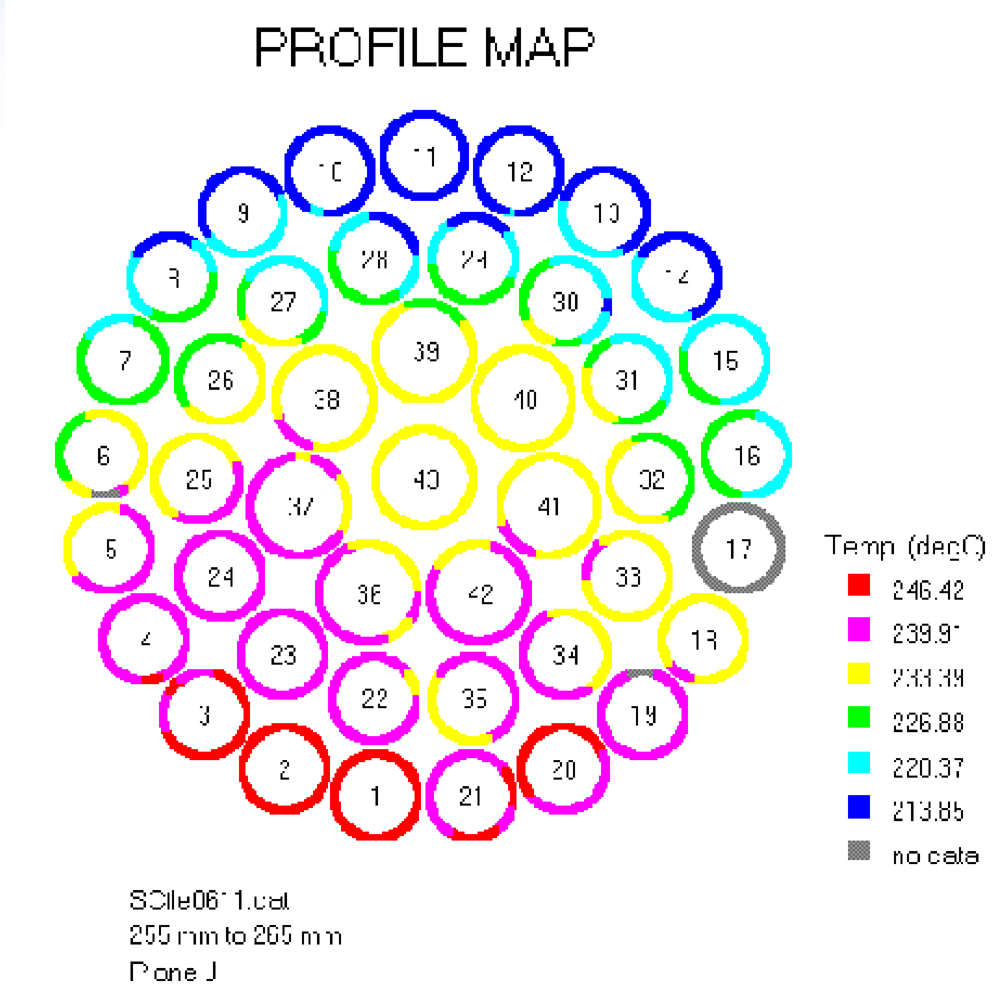
- **Sliding thermocouple assemblies for dryout detection and fuel clad temperature measurements**
  - **cover almost the entire fuel clad area**
  - **detects initial and subsequent dryout locations**
  - **allows 3-D representation of clad temperature**



Sliding Thermocouple Drive Unit



Temperature Profile Map, 5.1% Crept Test



Temperature Map from Profile Scan (#611J)

CANFLEX Demonstration Irradiation (DI)

- In 2 channels in the Point Lepreau Generating Station (PLGS)
  - a high-power and low-power, instrumented channel
- All on-power refueling with CANFLEX was normal
- 24 discharged bundles were inspected visually and in normal condition for irradiated fuel
- Two bundles were examined in the hot cells at Chalk River and all evidence showed excellent fuel performance
- As a result of DI minor changes were made to the CANFLEX design drawing to tightening dimensions on appendages

High Power Channel S08 Fueling Scheme

Prior to first CANFLEX fuelling

1	2	3	4	5	6	7	8	9	10	11	12

After first 8 bundle CANFLEX fuelling (Sept 98)

1	2	3	4	5	6	7	8	9	10	11	12

After second 8 bundle CANFLEX fuelling (Aug 99)

1	2	3	4	5	6	7	8	9	10	11	12

First 4 CANFLEX bundles into bay

After first 8 bundle 37-element bundle fuelling (Feb 00)

1	2	3	4	5	6	7	8	9	10	11	12

8 CANFLEX bundles into bay

After second 8 bundle 37-element fuelling (Aug 00)

1	2	3	4	5	6	7	8	9	10	11	12

Last 4 CANFLEX bundles into bay

#	37-element bundle
#	1st fuelling of 8 CANFLEX bundles
#	2nd fuelling of 8 CANFLEX bundles

A total of 16 CANFLEX bundles fuelled into the high power channel

Low Power Channel Q20 Fueling Scheme

Prior to first CANFLEX fuelling

1	2	3	4	5	6	7	8	9	10	11	12

After first 8 bundle CANFLEX fuelling (Sept 98)

1	2	3	4	5	6	7	8	9	10	11	12

After first 8 bundle 37-element bundle fuelling (Mar 99)

1	2	3	4	5	6	7	8	9	10	11	12

First 4 CANFLEX bundles into bay

After second 8 bundle 37-element fuelling (Jan 00)

1	2	3	4	5	6	7	8	9	10	11	12

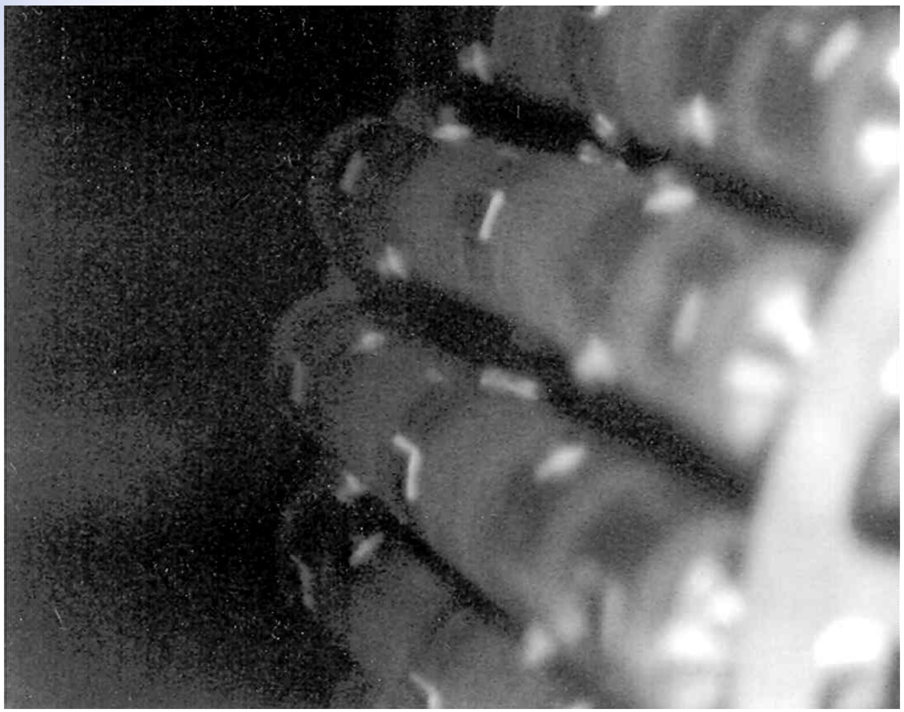
Last 4 CANFLEX bundles into bay

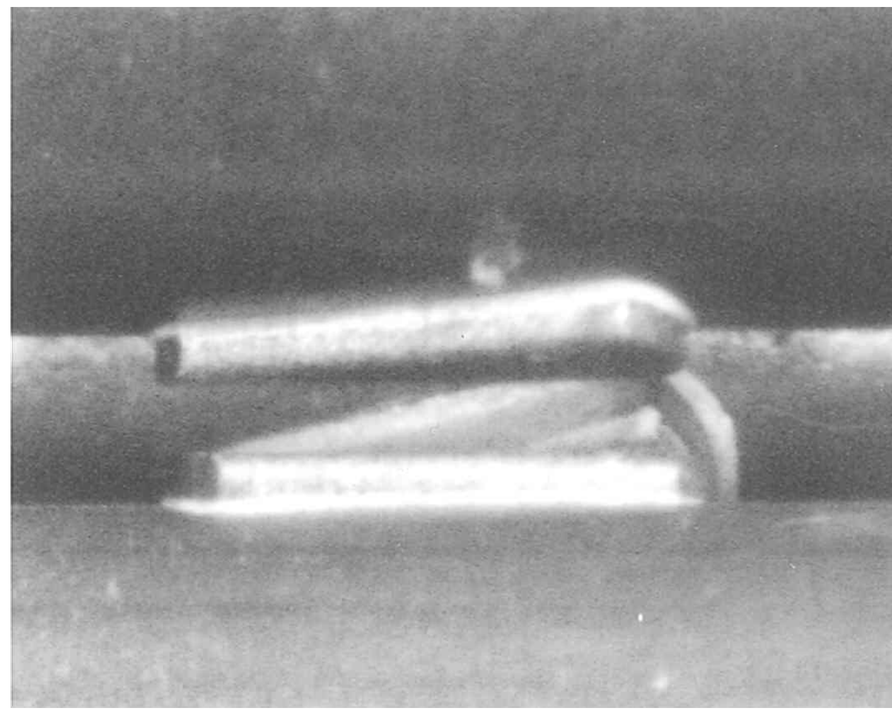
#	37-element bundle
#	1st fuelling of 8 CANFLEX bundles

A total of 8 CANFLEX bundles fuelled into the low power channel

Loading CANFLEX at PLGS Fuel Room

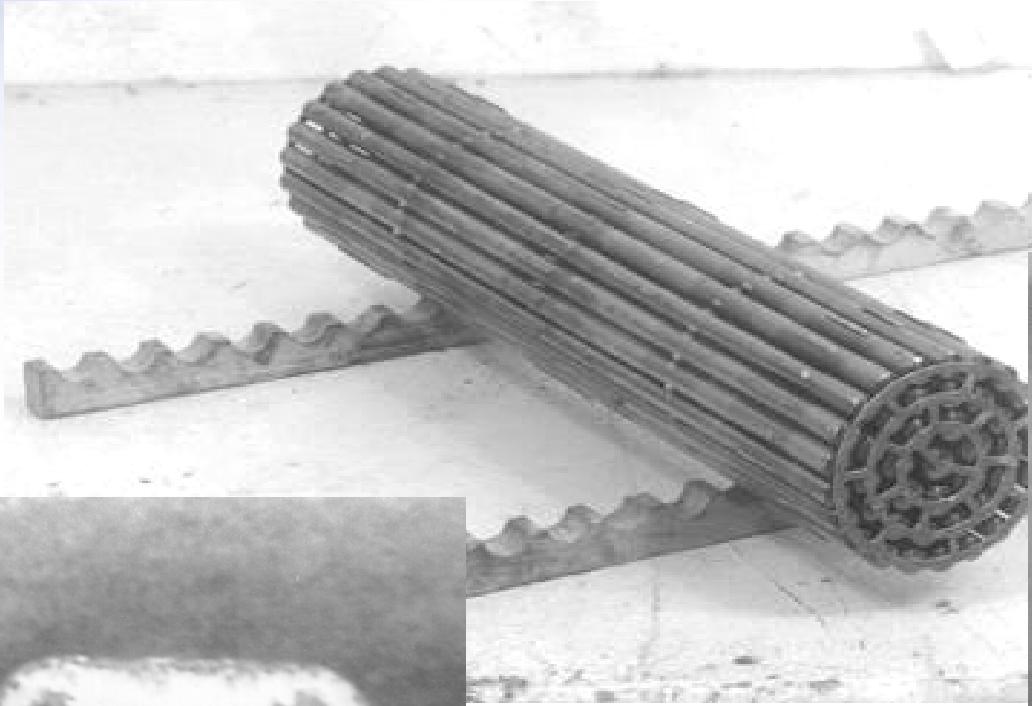
In-bay Inspection at PLGS

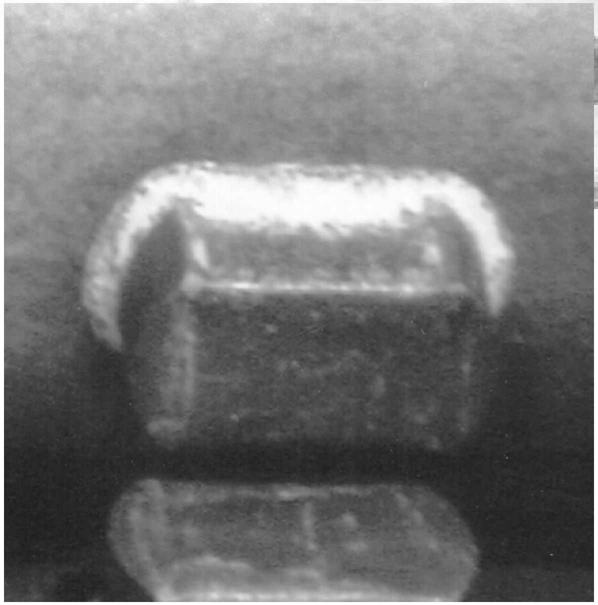


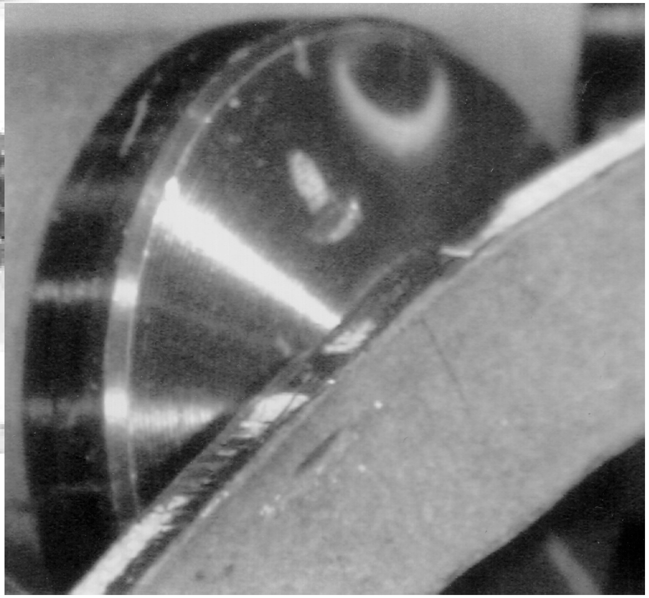


Element Straightness Normal For Irradiated Fuel

PIE of CANFLEX Bundle from PLGS

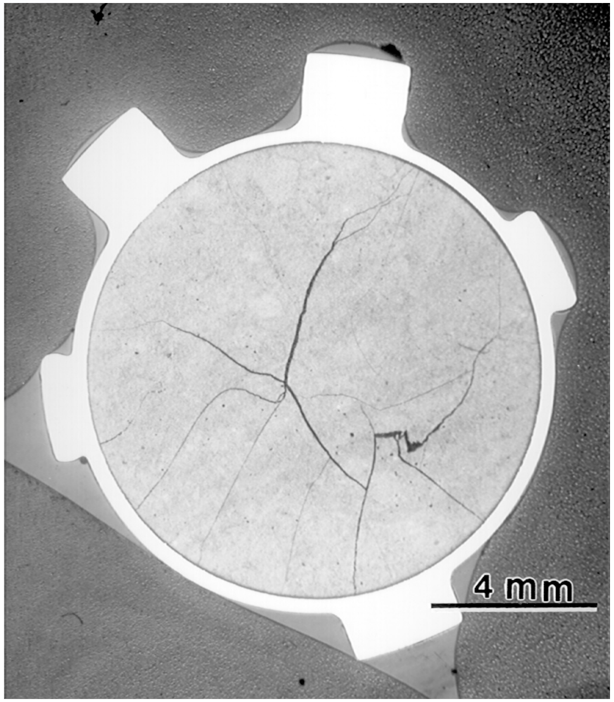




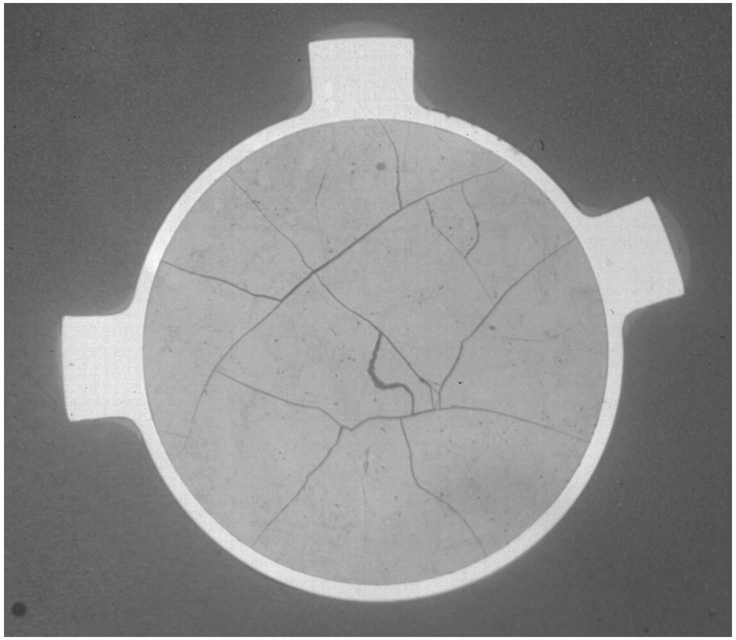


Element Fuel Microstructure Profile

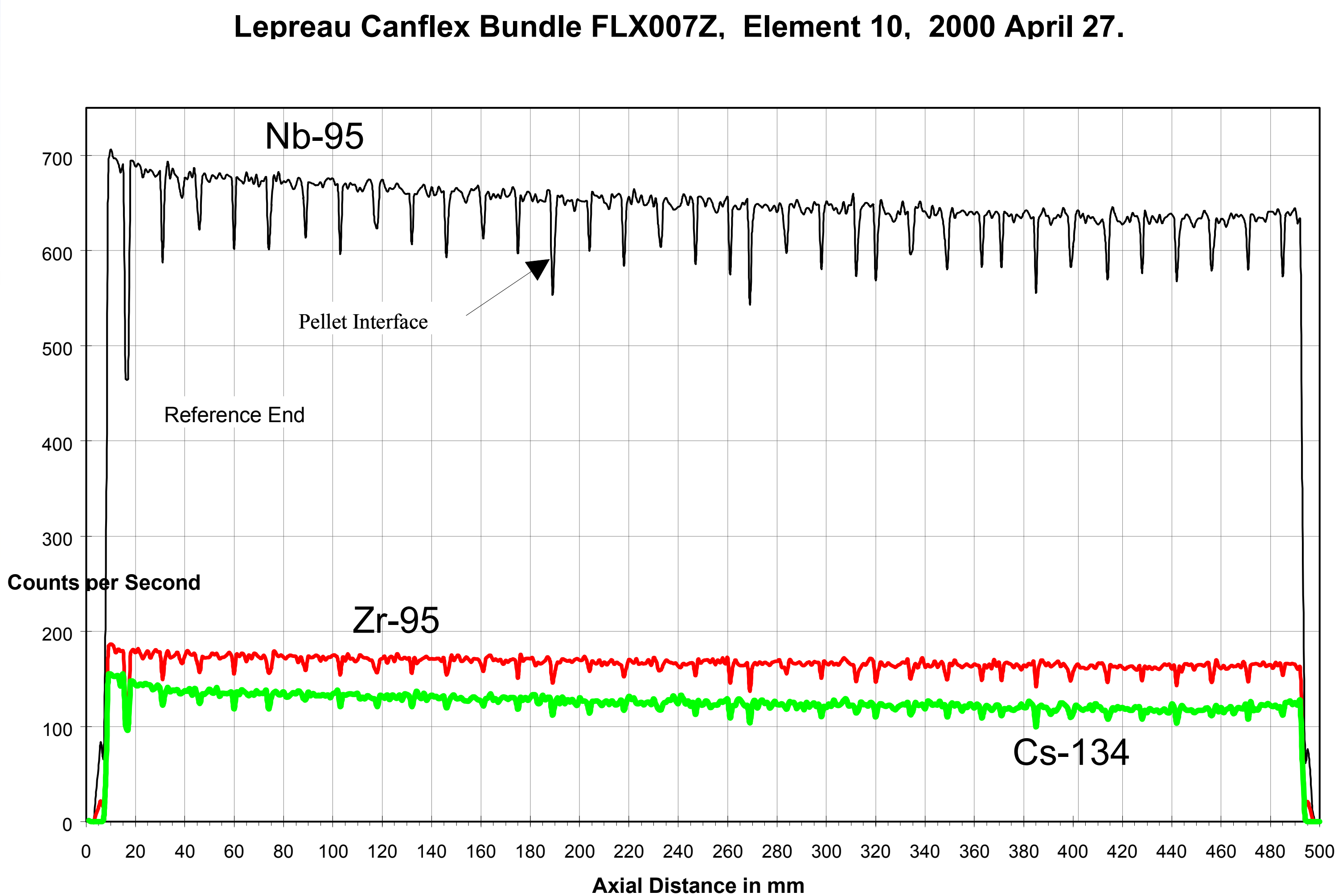
FLX0019Z



FLX007Z



Typical CANFLEX Gamma Scan Results



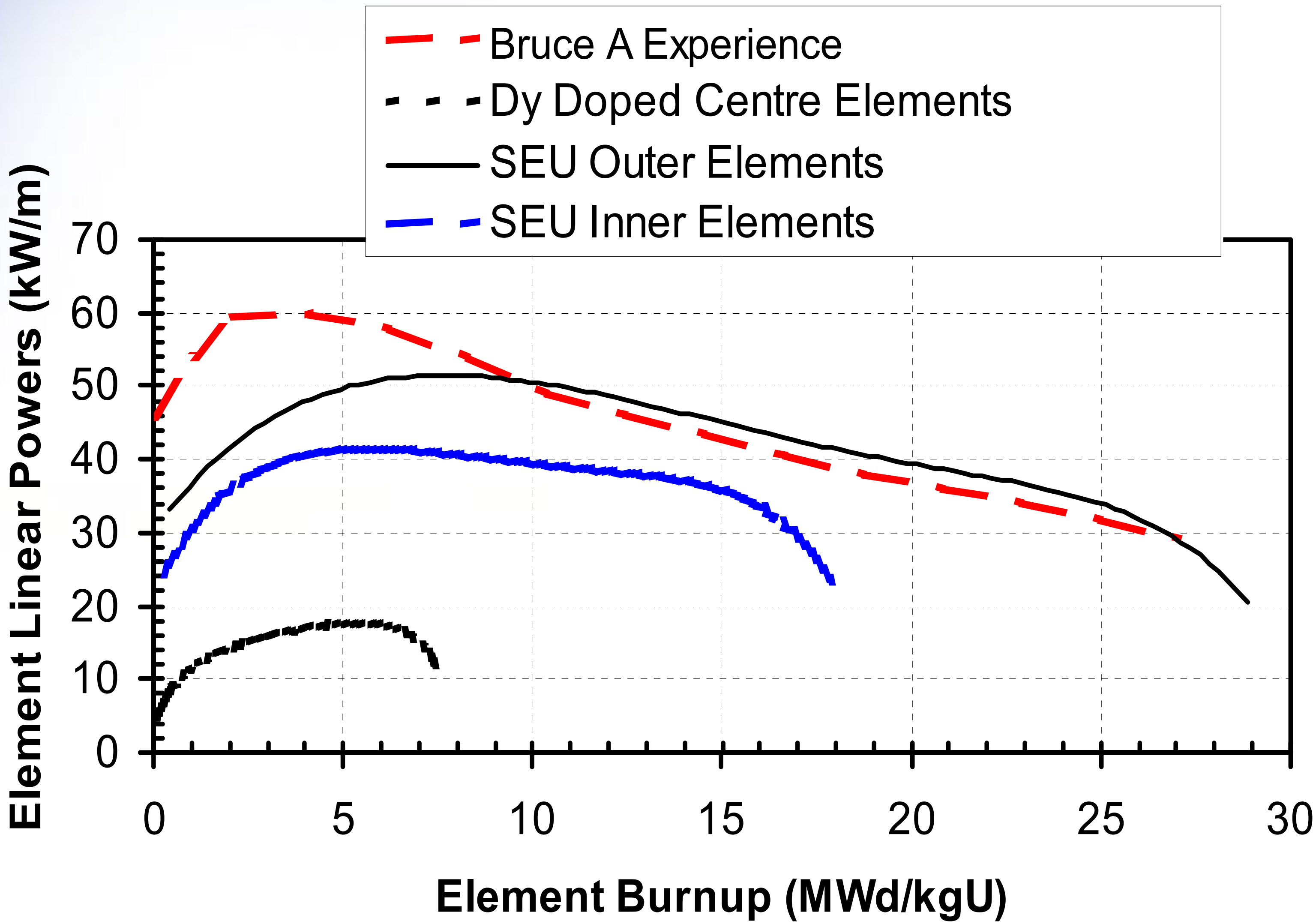
Summary for CANFLEX Mk 4 NU

- Design Qualification process completed in accordance with CAN/CSA-N286.2 to meet the interface requirements of existing CANDU 6 stations
- CANFLEX is ready for full commercial implementation
  - business case for full core implementation of CANFLEX into Gentilly 2 and Wolsong 1 being assessed
- Conversion to full core of CANFLEX NU in Canada will require regulatory approval
  - proponent to demonstrate that change in fuel does not compromise safe operation of reactor, based on existing safety report and supporting documentation
  - must also consider transition between an all-37-element-bundle core, and an all-CANFLEX core
  - AECL is working with CANDU utilities in Canada to establish the licensing program requirements and the various roles and responsibilities

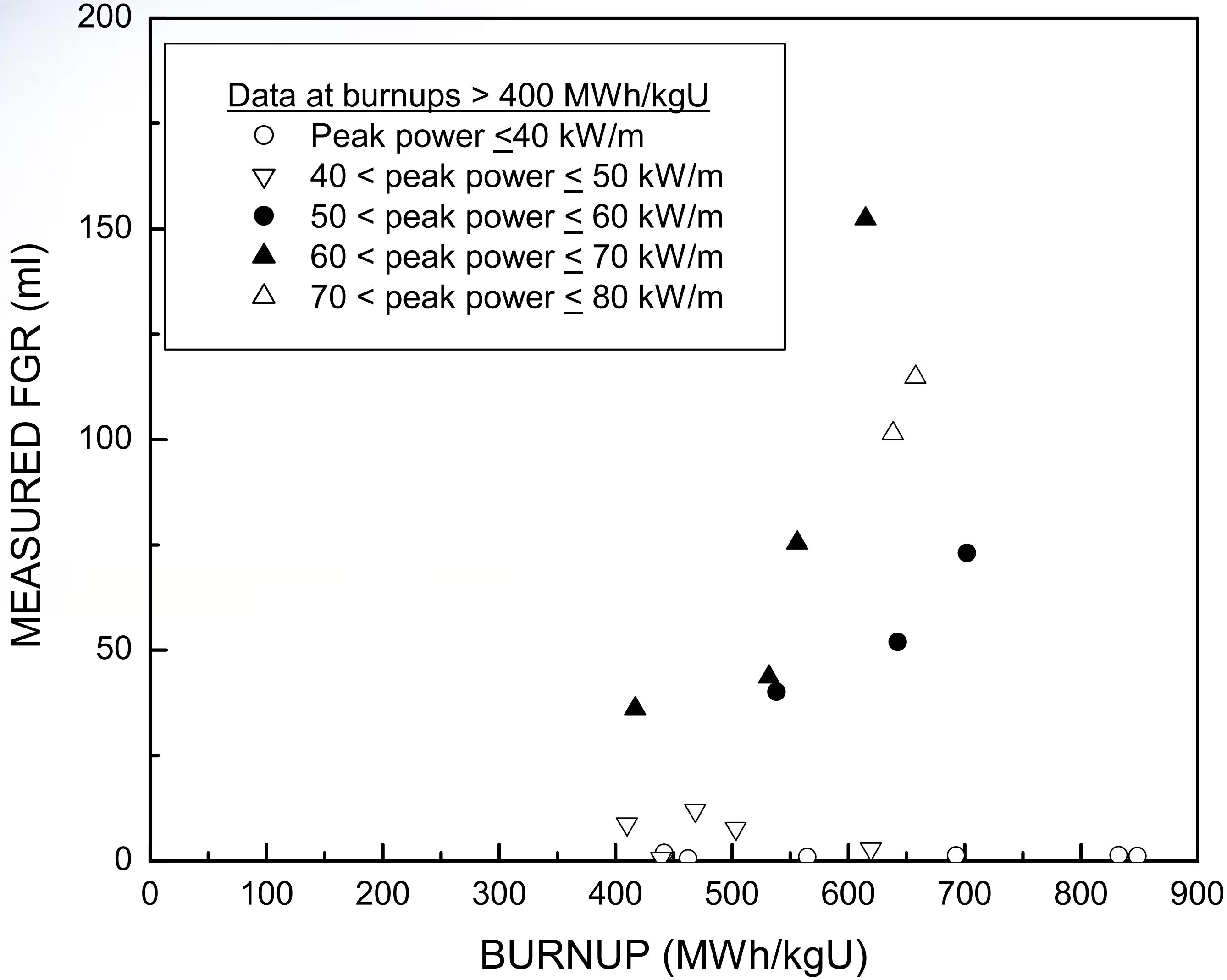
Extended Burnup Irradiation Experience

- Power reactor experience
  - >230 37-element bundles achieved burnups > 17 MWd/kg in Bruce A
- Research reactor experience
  - >24 bundle and element irradiations in NRU > 17 MWd/kg
  - 15 irradiations with burnups greater than 21 MWd/kg
  - 10 of 24 irradiations also experienced power ramps
  - several irradiations ongoing
- Qualified irradiated fuel databases
  - 28, 37-element and CANFLEX
- Good confidence in ACR fuel performance based on our experience
  - ACR power envelope is below the high power envelope for which we have experience
  - ACR fuel pellet design is optimized for extended burnup, based on our experience base and assessments

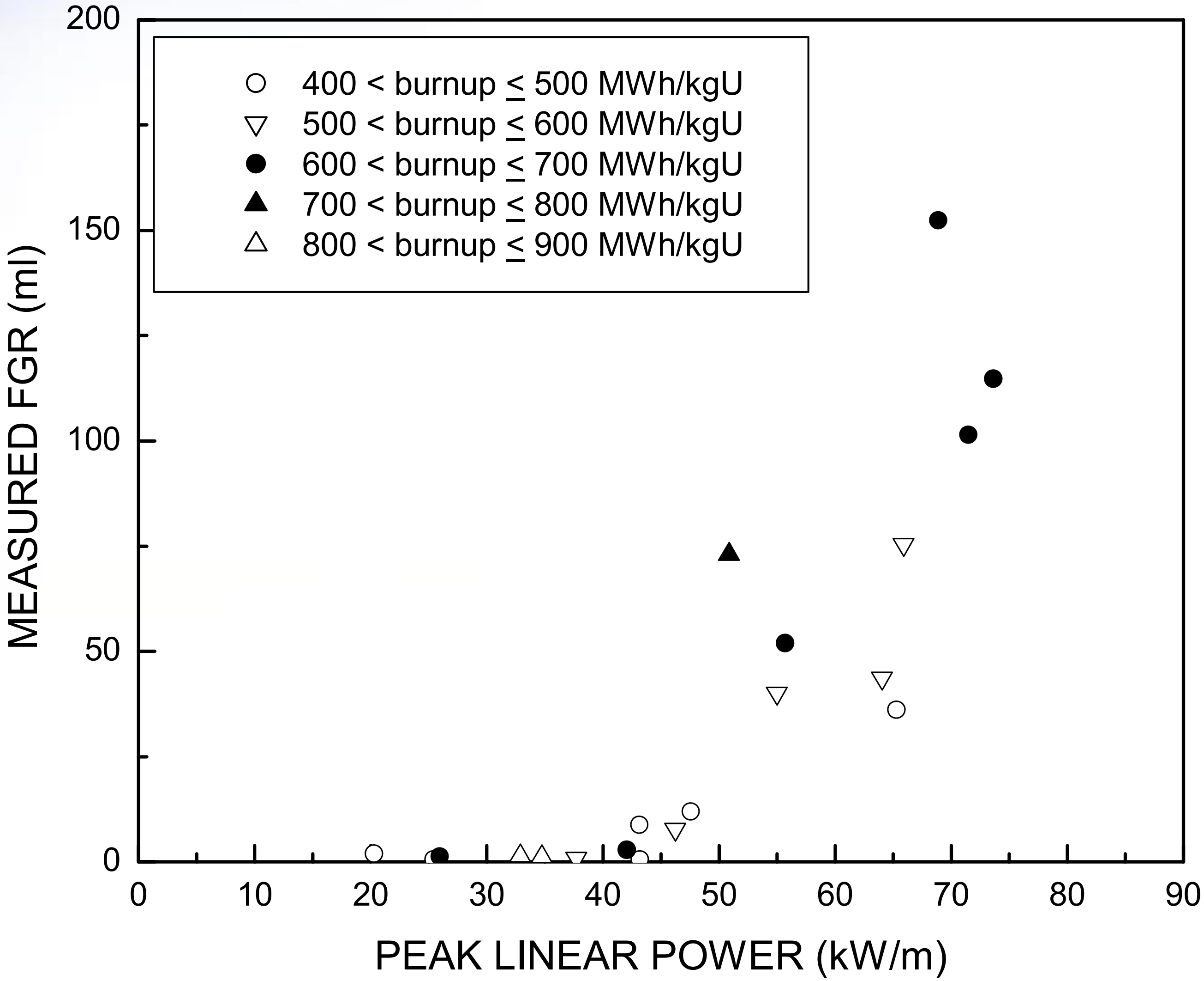
ACR Power Envelope vs. Bruce A Experience



Measured Fission Gas Release vs. Burnup

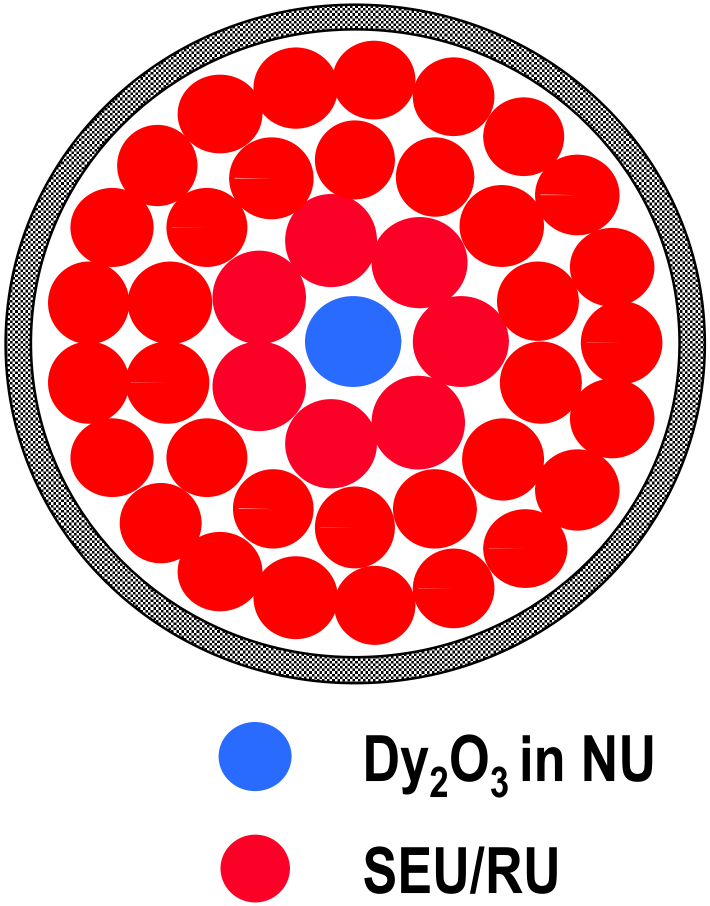


Measured Fission Gas Release vs. Element Rating



LVRF Concept

- CANFLEX (or 37-element bundle)
- Dy_2O_3 (neutron absorber) in central element(s), mixed with NU
- Enrichment in outer elements
- Dy content, and enrichment can be independently varied to give desired value of void reactivity reduction and burnup

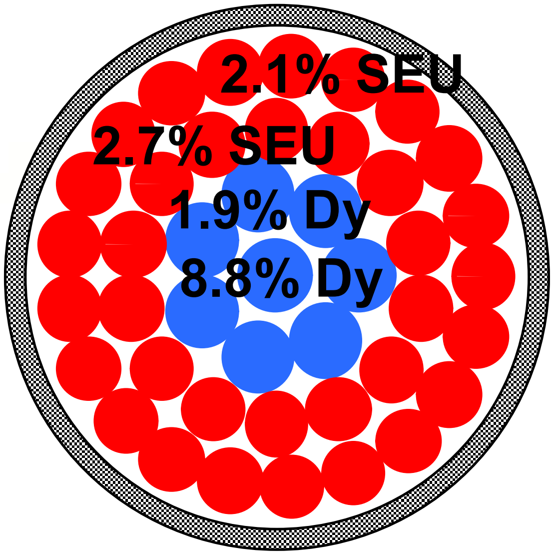


Overview of AECL Studies

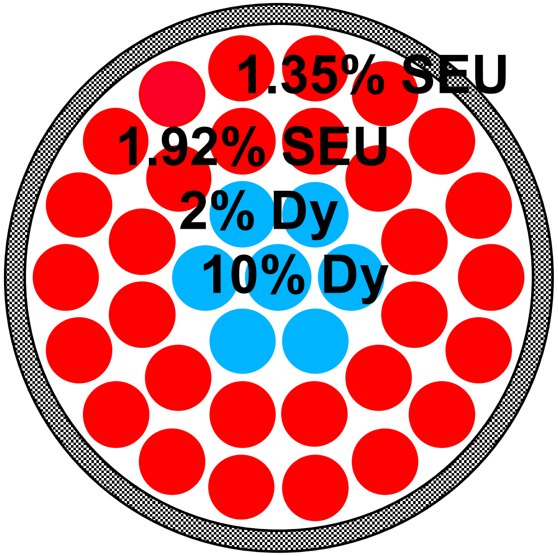
- Over past decade, AECL has undertaken many studies on fuel options for reducing void reactivity in CANDU
- Negative void reactivity fuel (NVRF)
  - 37-element NVRF, NU burnup
  - CANFLEX NVRF, 3x NU burnup
  - developed as “insurance” for international CANDU markets
  - extensive testing done
  - provides high confidence for ACR
  - MOX fuel for Pu-dispositioning an application
- Low void reactivity fuel (LVRF)
  - developed as “insurance” for domestic markets
  - basis for current qualification program for Bruce Power

Negative Void Reactivity Fuel (NVRF)

- Considered limiting case for void reactivity reduction in current reactors
- Bundle designs chosen had negative void reactivity at mid-burnup for current reactors
- Dy mixed with DU in central elements, graded enrichment
- 37-element: NU discharge burnup; CANFLEX: 3x NU burnup



CANFLEX NVRF



37-element NVRF

Overview of Generic NVRF Testing

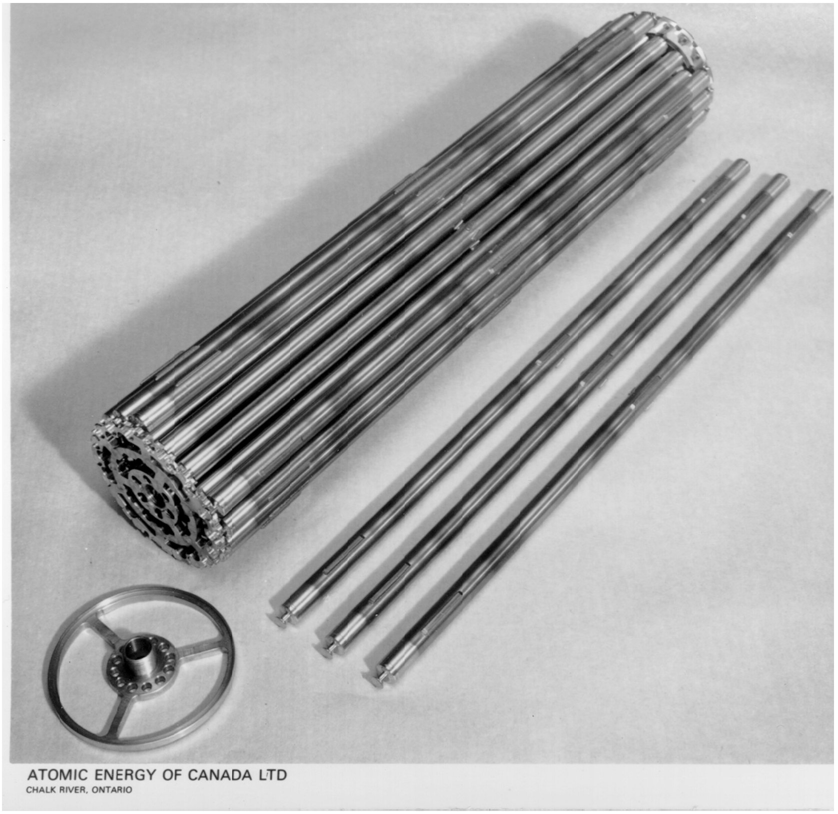
- Dy_2O_3 -UO_2 Pellet Fabrication
  - generic
- Bundle Fabrication
- Irradiation Testing and PIE
  - Dy demountable elements
  - prototype bundles
- Reactor Physics
  - ZED-2 measurements
    - void reactivity
    - fine structure
  - WIMS validation
- Thermalhydraulics
  - measurements, modelling
- Safety Expts
  - interactions with Zircaloy
  - grain-boundary inventory

Dy-UO_2 Pellet Fabrication

- Investigated methods of blending Dy_2O_3 & UO_2
- Developed process capable of
  - high production rate in laboratory
  - scaleable to production levels
  - uniform (relatively) microstructure
- Produced demountable elements to evaluate Dy-poisoned fuel under CANDU conditions
  - Dy levels of 1, 2, 5, 10 and 15%, mixed with either depleted or NU (to look at effect of power level under irradiation)

Dy Elements Irradiation Testing and Pie

- Demountable element bundle irradiation in NRU
- 21 elements fabricated and irradiated (bundle holds 18 at a time)
- Discharged over a range of burnups
- PIE Summary:
  - no changes in microstructure as a result of the irradiation
  - build-up of Ho occurred because of transmutatation of Dy
  - low fission gas release, typical of that in UO_2 under similar power histories



Safety

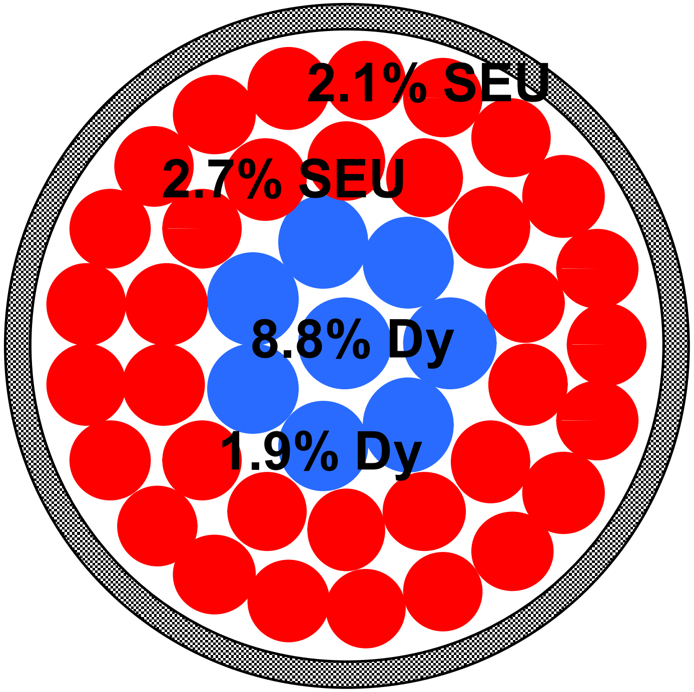
- Interactions with Zircaloy
  - UO_2 pellets containing 2% and 10% Dy_2O_3 were crushed and sieved to produce powder of size less than 45 mm
  - mixed with zirconia powder
  - submitted to DTA / TGA to 1500ºC, subsequent x-ray
  - no evidence of interaction
  - no evidence of liquid formation
- Grain Boundary Inventory
  - in accident analysis, the distribution of fission products within the element (free, grain boundary inventory, matrix) needs to be estimated
  - three elements (containing 2%, 5% Dy and 10% Dy) removed from demountable bundle after 150 full power days for assessment
  - average grain boundary inventory was consistent with prior measurements on low-powered UO_2 fuel

37-element NVRF: Bundle Fabrication, Irradiation and PIE

- Produced 35 bundles for ZED-2 physics tests
- Produced two prototype bundles for NRU irradiation
  - irradiated in positions 2 or 4 of the U1 and U2 loops of NRU between 1994 and 1996, to ~10 MWd/kg
- PIE Summary
  - overall fuel performance as expected based on NU experience
  - large flux gradient in NVRF causes larger burnup in outer elements than NU, but performance comparable to NU at these higher powers and burnups

CANFLEX <u>Negative</u> Void Reactivity Fuel

- 3x NU burnup
- Testing performed
  - ZED-2 measurements on single channel
  - CHF freon testing
  - 2 prototype bundles in NRU



Bruce Power LVRF

- AECL and Bruce Power currently qualifying CANFLEX-LVRF for specific application to Bruce Power
- Details commercially proprietary
- Program will complement ACR fuel qualification
  - measurements of thermal properties of Dy-doped fuel
    - heat capacity, thermal diffusivity (from which thermal conductivity can be derived)
  - reactor physics substitution experiments in ZED-2 with 36 bundles (5 channels) and qualification of physics codes
  - thermal hydraulics measurements in freon
  - computer code validation (fuel, safety)

Summary: Testing Supporting LVRF

- Generic qualification for LVRF through
  - reactor physics, thermal hydraulics, fabrication development, NRU irradiation, and safety tests
- Small amount of additional work is being undertaken to qualify LVRF bundle for Bruce application
- Complementary to ACR fuel qualification

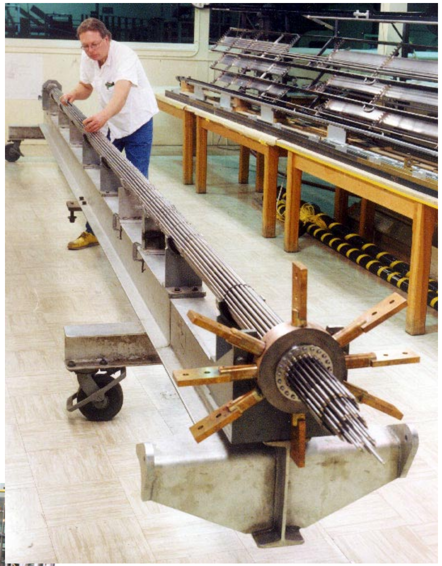
Generic Advanced Fuel Development Supporting ACR Fuel

- NRU irradiations at high power, and power ramp
  - of optimized internal element design
  - of advanced CANLUB coatings
- Improved SCC (power ramp) defect prediction capability
  - both for single power ramp, and for multiple power ramps
- Fuel chemistry studies
  - particularly at the fuel/clad interface
- Fundamental fuel properties (including Dy-doped fuel)
  - measurement of oxygen-to-uranium ratio; intrinsic fission product diffusion coefficients; thermal conductivity
- International collaboration
  - fundamental properties
  - IAEA FUMEX II
  - load-following test with Pitesti in Romania
  - CANFLEX SEU/RU collaboration with BNFL, KAERI, NASA (Argentina)

Facilities Supporting Fuel Development

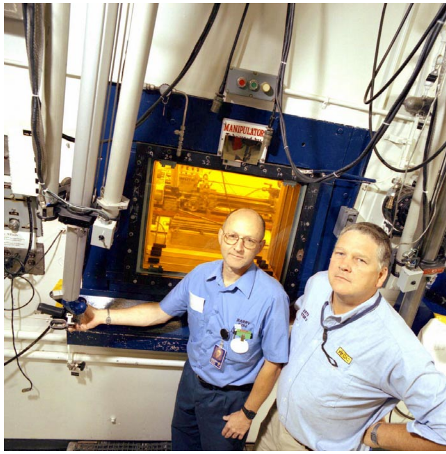
Fuel Fab Lab

Thermal hydraulics Lab



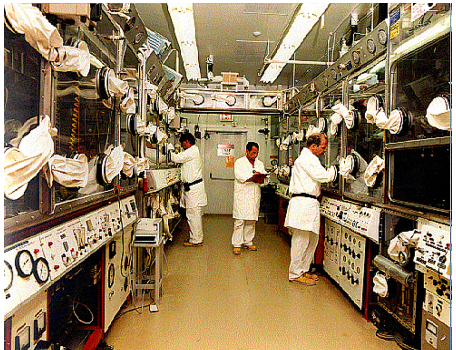
Surface Science Lab

Hot-cells

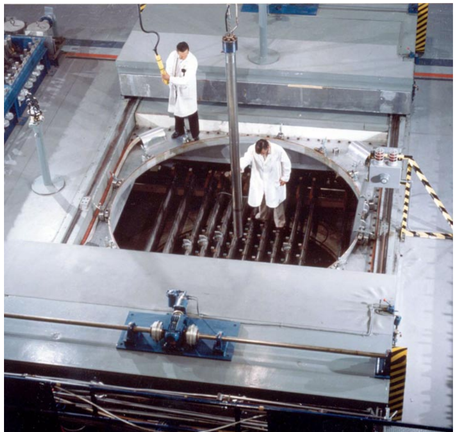


NRU

RFFL



ZED-2



Summary

- **ACR fuel is based on 3 underlying, well established fuel technologies**
  - **CANFLEX**
    - **fully qualified, ready for commercial implementation**
  - **enriched uranium with extended burnup**
    - **extensive experience both in power reactors (Bruce A) and in NRU irradiation tests**
  - **Low Void Reactivity Fuel (LVRF)**
    - **generic qualification is applicable to ACR**
    - **Bruce LVRF fuel currently undergoing qualification**

- **AECL maintains a strong fuel development capability, encompassing fundamental studies, support for operating stations, and advanced fuels and fuel cycles**
  - **includes qualified staff, computer codes, and facilities**

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