Looking Through the Glass Clearly:
Reviewing 30 years of Reactor Physics at Pickering

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1 Introduction

The central problem in reactor physics is the determination of the neutron flux. The purpose of this paper is to summarize the experimental basis of reactor physics at Pickering. We will review experimental data obtained over 30 years of operation and examine the extent to which such data and reactor testing can be used to confirm the adequacy of our theoretical understanding of Reactor Physics.

1.1 Importance and Limitations of Experiments

Karl Popper (and others) have argued that scientific theories are those which can be shown to be incorrect by experiment or observation[1]. The corollary of this assertion is that accuracy of a theory is directly tied to the accuracy of the measurements and *that the accuracy of a theory can never exceed that of the experimental basis*. A familiar example is that of the electron neutrino: The standard theory holds that the neutrino has a rest mass of zero, whereas the experimental results can only confirm that the rest mass is less than 3 eV [2]. Similarly, experimental evidence can only state that the photon rest mass is less than 2×10^{-16} eV.

It should be noted that this view enhances (rather than diminishes) the power of the scientific method, in that it permits the development of theories which predict new phenomena, while maintaining consistency with both the existing experimental basis and the theoretical underpinnings. In the examples above, novel theories involving massive photons and neutrinos already exist. Furthermore, when a theory is shown to be at odds with experiment, we are forced to develop a new theory (e.g. the discovery of magnetic monopoles would certainly require a modification to electromagnetic theory).

2 Background

2.1 Station Description

Pickering Nuclear is an 8 unit station located east of Toronto on Lake Ontario.

The first four units (Pickering NGS A) were placed in service over the period of 1971-1973, and were retubed over the period of 1985-1990. These units were shutdown and placed in a "layed-up" condition in 1996. They are currently being returned to service.

The second four units (Pickering B) were commissioned and placed in service over 1983-85 and have been in-service since that time.

Table 1 lists the In-service dates for each unit. Table 2 lists key reactor unit information. For comparison purposes data pertaining to Darlington are included.

3 Methodology and Technical Issues

3.1 Reactor Physics and Measurements

In general, Reactor Physics measurements have been conducted to confirm design functionality or operational capability during commissioning and related testing. The types of Reactor Physics measurements fall into the following categories:

- Criticality measurements
- Reactivity device worth measurements
- Reactivity coefficient measurements
- SDS Rundown tests
- Flux mapping measurements
- Neutron flux detector response measurements
- Channel power measurements

3.2 Simulation and Theoretical Tools

With the exception of the initial commissioning for Pickering A units (1972-73), the reactor physics measurements at Pickering have been verified and/or compared against predictions from the historical toolset (PPV/MULTICELL/OHRFSP/SMOKIN). These predictions and simulations form the design basis for the Pickering reactors.

For the most part, comparisons of the Pickering B experimental data against predications by the Industry Standard Toolset (IST) have not been conducted. These will be performed as part of the IST program in the coming years.

3.3 Measurement Techniques and Limitations

Measurements of reactivity involve either laboratory analysis of moderator poison samples, or changes in LZCS, both with inherent uncertainties and limitations. In the case of the former, lab analysis uncertainty is at least 5%. Furthermore, “burnout” (isotopic depletion) will systematically affect the results of chemical analysis, making this technique of limited use under high power conditions. In the case of the latter, indicated zone level is strongly influenced by the LZCS compressor cycle and can vary by as much as 5%. While various techniques can be used to minimize the impact of process uncertainties, the level of “irresolvable measurement error” is in the order of 5% for a given measurement.

3.4 Acceptance criteria

The acceptance criteria in place at Pickering for reactor physics Testing and Commissioning[3] has been developed based on practical experience which reflects instrumentation capability and other operational uncertainty. Table 3 summarizes the criteria.

4 Overview of Reactor Physics Measurement and Testing

Tables 4a and 4b present the major testing programs which have been conducted at Pickering over the past thirty years and the results are presented in the sections which follow.

4.1 Pickering A

Table 5 presents selected commissioning results following Retube/Rehab. The data presented is typical and it can be seen that there is good agreement between the predicted results and the measurements.

4.2 Pickering B

Table 6(a) presents the summary of results from the commissioning tests for Units 5,6,7,8. The data presented is typical and it can be seen that there is good agreement between the predicted results and the measurements.

Table 6(b) presents FDRP results. As can be seen, the measurements of detector response to various reactivity device movements is in excellent agreement with predictions.

Table 6(c) presents the summary of results from adjuster rod changes that have been performed in support of the cobalt program over the years. The data presented is typical and it can be seen that there is good agreement between the predicted results and the measurements.

4.3 Other Reactor Physics Measurements

Accurate estimates of neutron source strength are essential to safe and efficient unit start-ups after outages. Figures 1(a) and 1(b) present ATC results over the past 6 years. The trends lines shown, which were derived from the historical data, are now used to predict unit condition at criticality. Excellent agreement exists, as is demonstrated by recent ATC events.

Rundown tests are performed per the commissioning specifications. Typical results are shown in Figures 2(a) and 2(b) from the Unit 8 commissioning reports.

Flux scans using both activation and fission chamber techniques have been employed at Pickering over the years. Figure 3 presents typical results from Unit 8 using a manually operated fission chamber system.

5 Discussion and Conclusions

As noted in the introduction, experimental results are the only means by which the accuracy of theoretical models can be calculated. This paper has reviewed the measurement and test data related to reactor physics accumulated over 30 years of operation at Pickering. We can draw the following conclusions:

- In general, the measurements are in good agreement with prediction, and accuracies of ~10% can be supported.
- Systematic errors in adjuster rod worths have been observed in a variety of AA rod designs (both cobalt and stainless steel). These errors have been attributed to (in part) inherent weaknesses in the use of MULTICELL to generate incremental cross-sections.
- The verification of small reactivity changes (such as those associated with reactivity coefficients) is difficult given the uncertainties associated with LZCS measurements.
- Rundown tests have demonstrated that the Shutdown Systems meet the Safety Report assumptions regarding reactivity insertion rate and effectiveness.
- Flux detector response tests demonstrate excellent agreement with prediction. This is an interesting result, in view of the aforementioned issues with moveable devices.
- Flux mapping measurements are consistent with general predictions regarding flux profiles in the reactor core.
- A reliable model of shutdown source term has been developed which facilitates accurate predictions for ATC evaluation.

The results also establish that the historical toolset (OHRFSP/PPV/MULTICELL/SMOKIN) is capable of modeling reactor physics with accuracies approaching the limits of normal reactor instrumentation. Having said that, it is hoped that the IST will address some known deficiencies, particularly those around the calculation of incremental cross-sections for moveable devices.

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Table 1 Unit In-Service Dates

UNIT	MCR	MCR	First	FIRST	IN-SERVICE
	Gross	Net	Critical	ELECTRIC	DATE
P1	542	515	Feb 25/71	Apr 4/71	Jul 29/71
P2	542	515	Sep 15/71	Oct 6/71	Dec 30/71
P3	542	515	Apr 24/72	May 3/72	Jun 1/72
P4	542	515	May 16/73	May 21/73	Jun 17/73
P5	540	516	Oct 23/82	Dec 19/82	May 10/83
P6	540	516	Oct 15/83	Nov 8/83	Feb 1/84
P7	540	516	Oct 22/84	Nov 17/84	Jan 1/85
P8	540	516	Dec 17/85	Jan 21/86	Feb 28/86

Table 2: Comparison of Nuclear Generating Stations (from Pickering B Safety Report)

ITEM	PICKERING A	PICKERING B	DARLINGTON
Unit electrical output MV(e) (net)	515	516	881
Number of Units	4	4	4
Core and fuel data			
Maximum licence 100% reactor power MW(th)	1744	1744	2776
No. of channels	390	380	480
Maximum licenced 100% channel power MW(th)	6.1	6.1	7.2
No. of bundles/channels	12	12	13 (12 in core)
Maximum licenced bundle power kW(th)	750	750	1035
No. of elements/bundle	28	28	37
Average fuel element power kW(th) (based on licenced bundle power)	26.8	26.8	28.0
Direction of refuelling	With flow	With flow	Against flow
Minimum pressure tube wall thickness, mm	4.06	4.06	4.2
Reactivity Mechanisms in Service			
Adjuster rods (absorbers)	6 (SS)	21 (SS/Co) [a]	18 (SS)
Reactivity Control	LZCS, plus Moderator Level Control	LZCS, plus 4 Control Absorbers	LZCS, plus 4 Control Absorbers
Vertical flux detector assemblies	6	14 (Units 5,6,7) 20 (Unit 8)	23
Horizontal flux detector assemblies	-	7	14
Primary shutdown mechanism	23 shutoff rods augmented by moderator dump [b]	28 shutoff rods	32 shutoff rods
Secondary shutdown mechanism		6 Poison injection nozzles	8 Poison injection nozzles
Heat Transport System			
Reactor inlet header temperature °C	249	249	267
Reactor outlet header temperature °C	293	293	310
Quality in reactor outlet header at 100% FP	5°C subcooled	7°C subcooled	2.0 wt%
Reactor outlet header pressure MPa(a)	8.83	8.83	10.0
Main system volume, m^3	139	139	217
Heavy Water inventory at 38°C m^3/MW(e) [c]	0.317	0.317	0.25
No. of steam generators	12	12	4
No. of pumps	12 + 4 spare	12 + 4 spare	4
Pressure control	Feed and bleed	Feed and bleed	Pressurizer

NOTES

(a) Provision has been made to use Cobalt in Units 6, 7 and 8, Unit 5 retains SS AA rods.
(b) Since Pickering A has a moderator dump system, a spray cooling system is provided to cool the calandria tubes.
(c) Excluding requirements for pressurizer and auxiliary systems.

Table 3 Acceptance Criteria

Measurement Category	Criteria
Liquid Zone Control System Reactivity Worth (mk)	+/- 15%
Adjuster Rod Reactivity Worth (mk)	+/- 15%
Control Absorber Reactivity Worth (mk)	+/- 15%
SOR Reactivity Worth (mk)	+/- 10%
SDS Rundown	Meet Safety Report assumptions

Table 4(a) Summary of Major Reactor Physics M&T Programs: Pickering A

Program Description	Time Period	Summary of Testing
RP testing per original commissioning specifications	Sept 1971 to Sept 1973	Criticality measurements Reactivity device worths Reactivity coefficients SDS Rundown tests Flux mapping
RP testing per post retube commissioning specifications	Sept 1987 to Sept 1990	Criticality measurements Reactivity device worths Reactivity coefficients SDS Rundown tests Flux mapping
Cobalt Adjuster Rod changes	1987 to present	Adjuster rod worths
SDSE commissioning	Sept 1993 to Sept 1995	Fission chamber tests ICFD response testing
PARTS	Jan 2003 to Dec 2004	Criticality measurements SDS Rundown tests SDSE commissioning

Table 4(b) Summary of Major Reactor Physics M&T Programs: Pickering B

Program Description	Time Period	Summary of Testing
RP testing per original commissioning specifications	Sept 1971 to Sept 1973	Criticality measurements Reactivity device worths Reactivity coefficients SDS Rundown tests Flux mapping
RP testing for FDRP program retube commissioning specifications	Sept 1987 to Sept 1990	Neutron flux detector response Channel power measurements
Cobalt Adjuster Rod changes	1987 to present	Adjuster rod worths

Table 5 Selected Pickering "A" T&C Results

Post Retube/Rehab Commissioning (Unit 4)

Measurement	Predicted	Measured
Critical Poison Concentration (ppm B)	10.4	10.9
LZCS Worth (mk)	4.92	4.45
Adjuster Rod Worth - Total (mk)	9.5	9.9
Individual SOR worth (%)	-	Predicted value +15%

<u>Table 6(a) Selected Pickering "B" T&C Results</u>

Initial Commissioning (Unit 8)

Measurement	Predicted	Measured
Critical Poison Concentration (ppm Gd)	2.6	2.62
LZCS Worth (mk/%)	0.079	0.069
Adjuster Rod Worth - Total (mk)	17.5	17.6
Control Absorber – average (mk)	1.78	1.9
Individual SOR worth (%)	-	Predicted value +/- 3.9%

<u>Table 6(b) Selected FDRP T&C Results</u>

Predicted vs. Measured Detector Response to Device Movement (Unit 7)

Measurement	Mean	Std. Dev.
Adjuster Rod AA5	0.96	1.85
LZCS	0.61	0.71
Control Absorber CA1	-0.91	1.61
Shutoff Rod SA8	-0.80	1.24
Safety Report (NOP) assumptions	0.0	3.5

Table 6(c) Cobalt AA Rod Commissioning Results

Measurement	Predicted	Measured
Adjuster Rod Worth U6- Total (mk)	19.5	16.3
Adjuster Rod Worth U8- Total (mk)	19.5	16.6

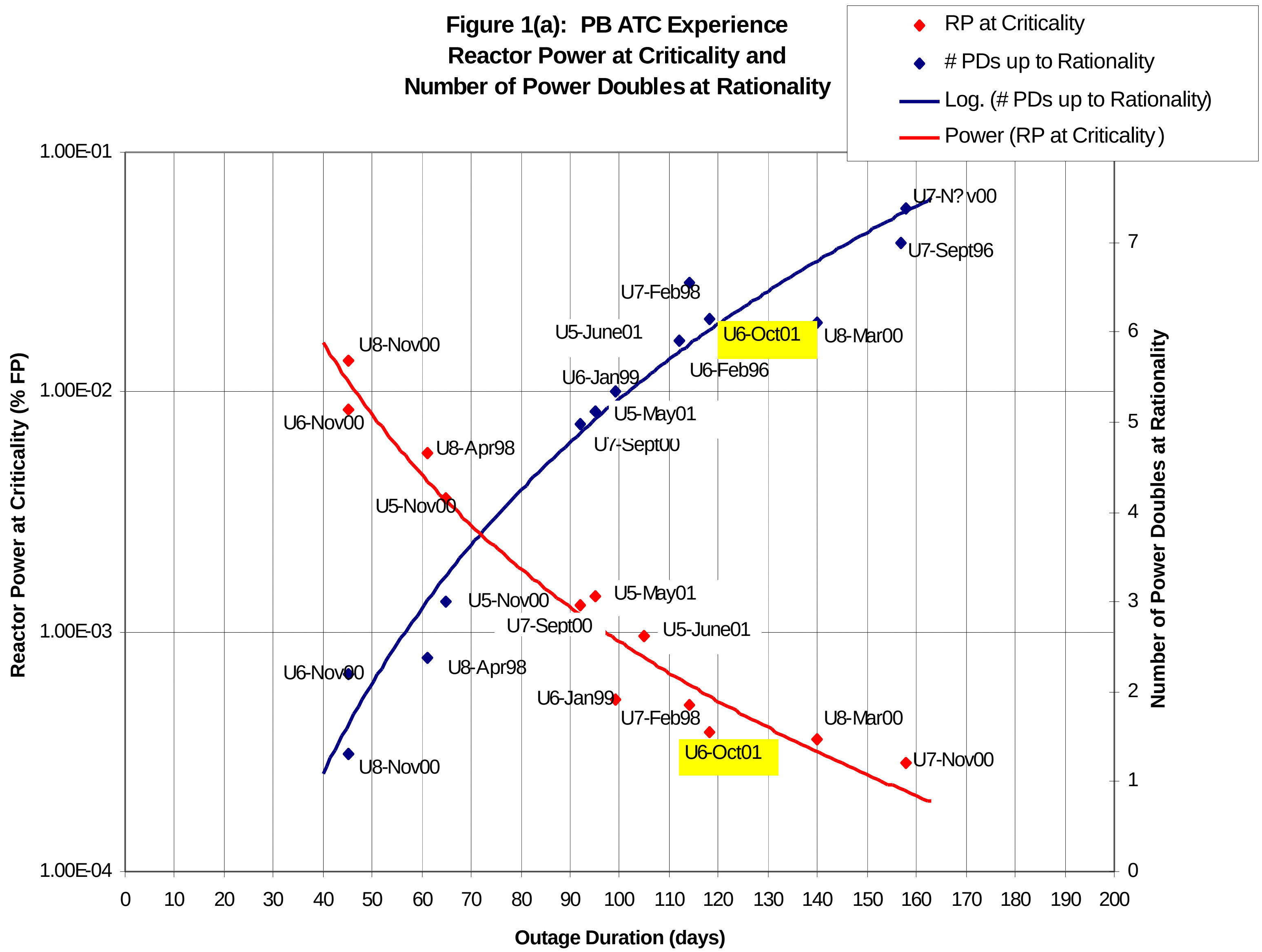


Figure 1(a): PB ATC Experience
Reactor Power at Criticality and
Number of Power Doubles at Rationality

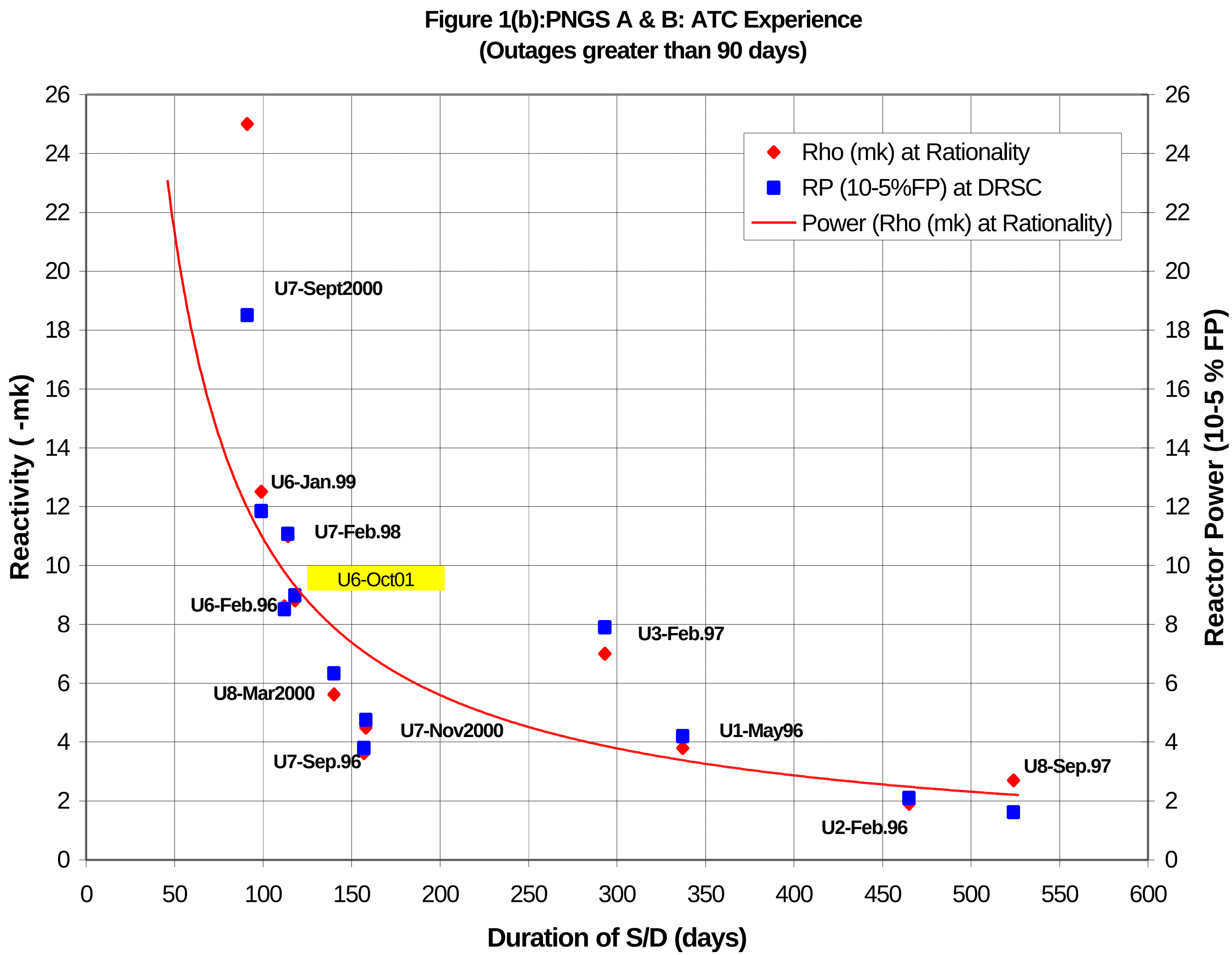


Figure 1(b):PNGS A & B: ATC Experience
(Outages greater than 90 days)
Reactivity (-mk)
Reactor Power (10-5 % FP)
Duration of S/D (days)
Rho (mk) at Rationality
RP (10-5%FP) at DRSC
Power (Rho (mk) at Rationality)
U7-Sept2000
U6-Jan.99
U7-Feb.98
U6-Oct01
U6-Feb.96
U3-Feb.97
U8-Mar2000
U7-Nov2000
U1-May96
U7-Sep.96
U8-Sep.97
U2-Feb.96
0
2
4
6
8
10
12
14
16
18
20
22
24
26
0
50
100
150
200
250
300
350
400
450
500
550
600

Figure 2(a): Typical SDS1 Rundown Data from Unit 8 Commissioning Report

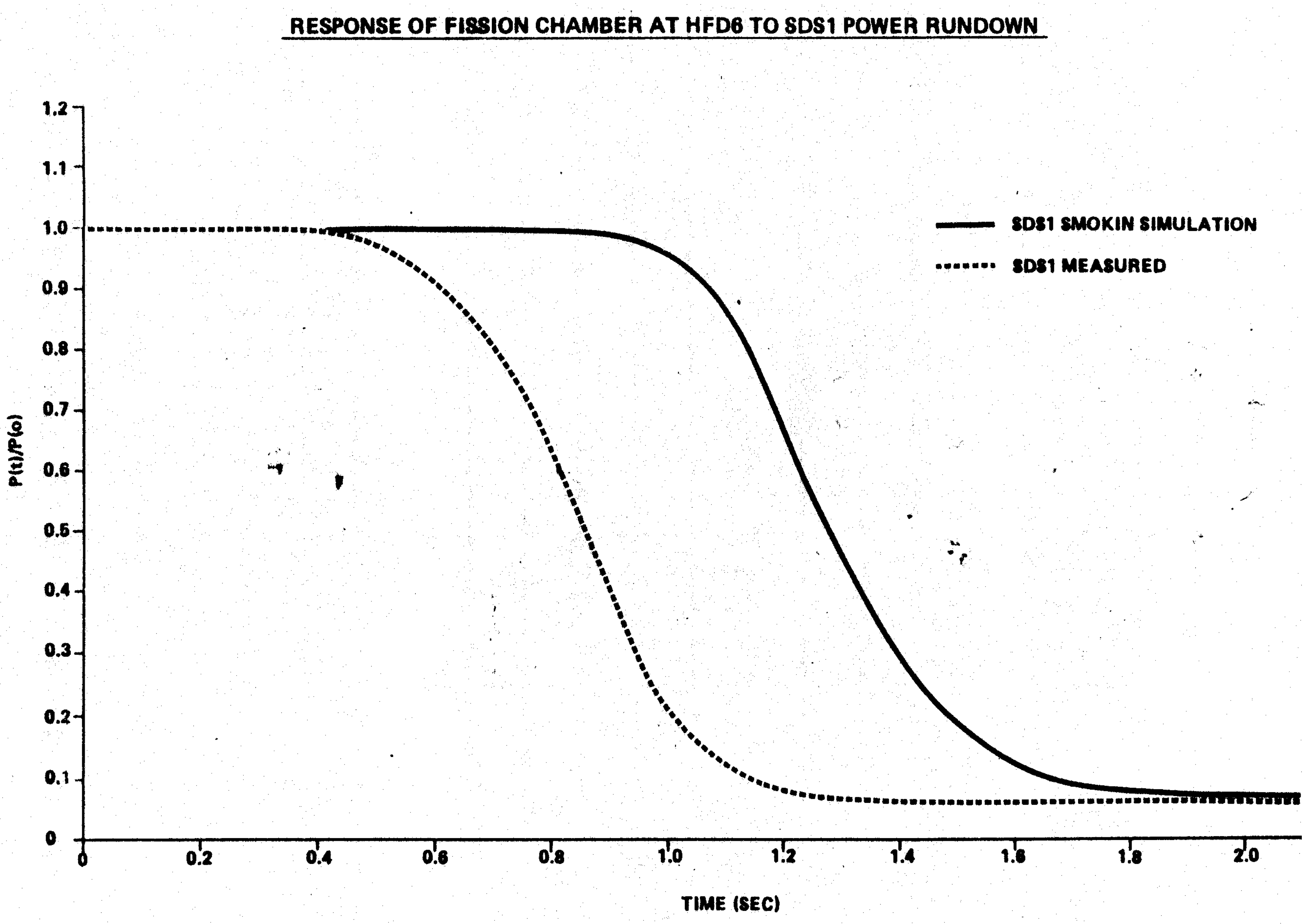


Figure 2(b): Typical SDS2 Rundown Data from Unit 8 Commissioning Report

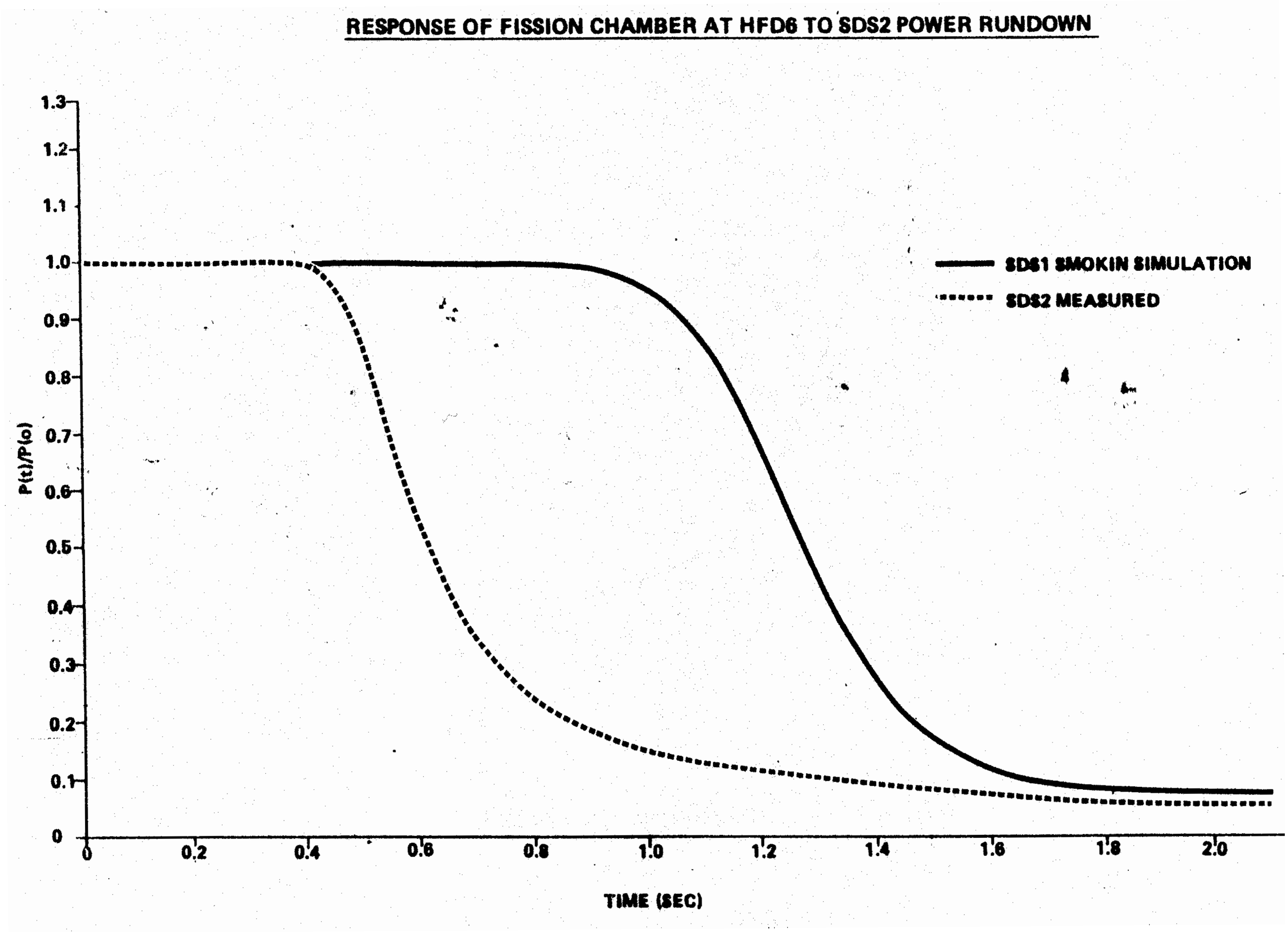
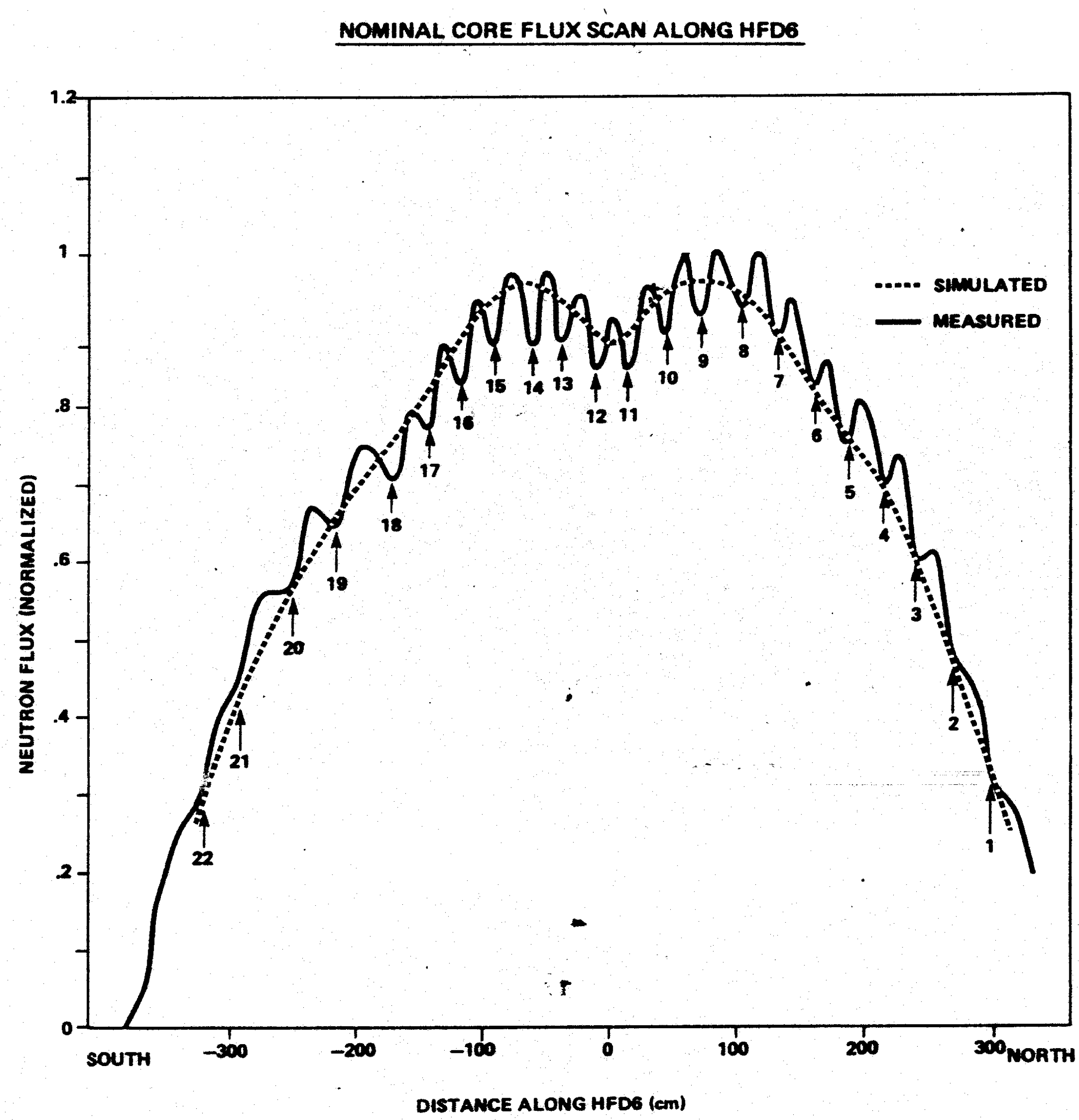


Figure 3: Typical Flux Scan Data from Unit 8 Commissioning Report



[1] Karl H. Popper, "Conjectures and Refutations", 1962
[2] K.Hagiwara et al, "Review of Particle Physics", Physical Review D 66, 2002
[3] M.K. O'Neill, "Acceptance Criteria for Reactor Physics Tests at PND", Pickering Nuclear Safety Department Report 96003, September 1996