Photoneutron Source Strength Studies in Pickering Reactors

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Abstract

Reactor power measurements and reactivity change measurements taken during the execution of approach to critical procedures following long outages (> 100 days) on Pickering reactors revealed the presence of a neutron source of greater strength than predicted by the 15 group delayed and photoneutron precursor model. The apparent additional neutron source has been characterized by modelling it as a sixteenth group in the Ontario Hydro code SPARK (Simulation of Photoneutrons and Reactor Kinetics). Data are available from three Pickering-A outages and two Pickering-B outages. The duration of each Pickering-A outage was greater than 250 days. The Pickering-B outages were of 117 days and 154 days duration. Two interpretations of the available data are possible: (i) after about 150 days, neutron source power is relatively constant, or; (ii) owing to differences in reactor structural materials, the source power is quite different on PNGS-A from PNGS-B. Characterization of the source for the stations is of practical benefit because it allows engineering staff to predict when to expect significant milestones in the approach to critical procedure. Examples of such milestones are: (i) the core reactivity at which regulating system ion chamber signals come on scale, and (ii) the critical power level.

Introduction

The Pickering Nuclear Generating Station

The Pickering Nuclear Generating Station (NGS) is an 8-unit CANDU facility with a nominal gross power rating of approximately 540 MW(e) for each unit. The facility contains units of two separate designs, called Pickering NGS-A and Pickering NGS-B. The Pickering NGS-A units (Units 1 to 4) were commissioned from 1971 to 1974 and the Pickering NGS-B units (Units 5 to 8) were commissioned from 1983 to 1986.

Reactor Power and Reactivity in Subcritical Reactors

Reactor power and reactivity in subcritical reactors are related to delayed and photoneutron power per the subcritical multiplication equation:

$$P = Po/(1-k_{eff})$$

where: P is reactor power
Po is the source power

k_{eff} is the multiplication factor

Following a reactor shutdown, the delayed neutron precursors decay away rapidly while the longer lived photoneutron precursors continue to contribute to the neutron density. Although these long-lived photoneutron precursors were produced from the induced fission process prior to shutdown, they represent an extraneous neutron source as far as the induced fission process after shutdown is concerned. They therefore contribute to Po.

As the length of an outage increases, Po gets smaller due to decay of the delayed and photoneutron precursors. Currently, Po is modelled by a 15 group precursor model (see Table 1)[1].

The decaying source power causes the reactor power at a given k_{eff} to be smaller for longer outages. The signal from the reactor regulating system (RRS) neutron detectors (ion chambers) will therefore decay off scale (at about -7 decades) after a unit has been shut down for a few months. Reactor power must then be monitored with startup instrumentation (SUI). This instrumentation is installed during the outage before the ion chamber signal decays off scale. The startup instrumentation cannot be calibrated to absolute reactor power, however it can be used to monitor the relative change in reactor power, and it can also be used for neutronic trips. Reactor power is essentially under manual control after the ion chamber signal has decayed off scale. Special procedures are used for reactor control during such a time. The shutdown trip setpoint is set to a count rate not exceeding 1 decade above the current count rate.

The decay of the source power is an important consideration for the execution of approach to critical (ATC) procedures. Operationally it is desirable to execute the entire procedure with the ion chambers on scale because the reactor would be under automatic RRS control of reactor power. Often however, the ATC procedure must be started with SUI in service. Typically the ion chamber signal comes on scale before the ATC procedure is complete. Knowledge of the source power is important for very long outages in order for operating staff to be prepared for the unit operating conditions when criticality is achieved. ATC procedures under SUI are more difficult than ATC procedures under automatic RRS control.

The only time in Pickering's operating history that reactors have gone critical with the ion chamber signals off scale has been during commissioning or recommissioning with fresh cores. There has not yet been an outage on an equilibrium core long enough that criticality has been achieved before the ion chamber signal has come on scale.

Observed Reactor Power and Reactivity Following Long Outages:

Reactor power and reactivity change measurements taken during the execution of approach to critical procedures following long outages (>100 days) has revealed the presence of a neutron source of greater strength than predicted by the 15 group delayed and photoneutron precursor model. An attempt to characterize the neutron source was done by modelling it as a sixteenth group in the Ontario Hydro code SPARK (Simulation of Photoneutrons and Reactor Kinetics). This code uses the point kinetics equations along with a Reactor Regulating System and a poison effects model to simulate low power operation[2]. Data are available from three Pickering-A outages and two Pickering-B outages. The duration of each Pickering-A outage was greater than 250 days. The Pickering-B outages were of 111 days and 157 days duration.

Observations:

Unit 1 Restart, May 1995

Unit 1 was restarted in May of 1995 following a maintenance outage of 337 days duration. A source power greater than that predicted by the 15 group model was observed (see Table 2).

Unit 6 Restart, February 1996

Unit 6 was restarted in February of 1996 following a maintenance outage of 117 days duration. No significant deviation from expected behaviour was noted during the approach to critical. The source power was found to be reasonably close to, albeit slightly above, the values predicted by the 15 group model (see Table 2).

Unit 2 Restart, February 1996

Unit 2 was restarted in February of 1996 following a maintenance outage of 437 days duration. Before executing the approach to critical, the possibility of criticality occurring before the rationality limit of the Regulating System ion chambers (-6.94 decades) was anticipated. However criticality was declared at a reactor power significantly greater than that predicted by the 15 group model. The source power was therefore also significantly greater than predicted (see Table 2).

Unit 2 Operating History, Summer 1996

The ability to predict the neutron source power was put to the test in the spring and summer of 1996 when, because of significant operational difficulties, Unit 2 operated for only 1.5 full power days (FPD) after the February restart and was then shut down again for 127 days. Because of the very short operating period, there was uncertainty regarding whether or not the ion chamber signals would be on scale prior to criticality. Olive and Shanes[3] modelled the extra source neutrons as a postulated "sixteenth group" (although no speculation was made that these neutrons were actually photoneutrons) and, using data obtained from the previous approaches to critical on Units 1 and 2, modelled the "sixteenth group" as having a yield fraction (β) of 0.478×10^{-8} and a decay constant (λ)of 0.852×10^{-7} s^{-1}. Ion chamber rationality before criticality was predicted and this was actually observed. The predicted values for the approach to critical were very close to the observed values (see Table 2).

Unit 2 was restarted, then shut down again after only 3 FPD of operation, again due to operational difficulties. This time the outage duration was only 4 days. The 3 FPD of operation had a significant effect on the source power (see Table 2).

The operating history of Unit 2 for the summer of 1996 is shown in Figure 1.

Unit 7 Restart, September 1996

Unit 7 was restarted in September of 1996 following a maintenance outage of 154 days duration. Following the experience with Units 1 and 2 earlier in the year, it was confidently predicted that the ion chambers would be rational before criticality. This in fact was observed but the reactor power was lower than expected based on predicted values using the "sixteenth group", although higher than predicted by the 15 group model (see Table 2) .

Unit 3 Restart, February 1997

Unit 3 was restarted in February of 1997 following a maintenance outage of 293 days duration. Again, based on the experience with the Unit 1 and 2 approaches to critical in 1996, ion chamber rationality was predicted well before criticality. This was observed and the values were quite close to those predicted by the "sixteenth group" postulated from the previous Unit 1 and 2 data (see Table 2).

Discussion and Conclusions:

The data from Table 1 are shown graphically in Figure 2. Since the neutron source power for Pickering reactors has been found to be higher than predicted by the 15 group model, a neutron source other than the modelled photoneutrons is present. This postulate is supported by the observed neutron signal in Pickering-A reactors following retube outages prior to fuel loading[4].

The source power for all restarts shown in Figure 2 was between -9 and -10 decades. This suggests that the source power after a long outage is relatively constant. However, since the two PNGS-B data points are grouped together at the beginning of the curve and the three PNGS-A data points are grouped together at the end of the curve, a second interpretation of the data is possible: that the decay rate of the source on PNGS-A is different and significantly slower than the source on PNGS-B. If the former interpretation is correct, then the neutron source may originate from within the fuel. If the latter interpretation is correct, then since the fuel properties (and hence the point kinetics) of PNGS-A and PNGS-B reactors are not significantly different, the neutron source likely does not originate from within the fuel. Rather it may originate from the irradiation of impurities in reactor structural materials. For example, uranium impurities (present initially at 1 ppm in PNGS-A calandria tubes) may be transmuted to higher actinides which undergo spontaneous fission. The Unit 8 approach to critical (>450 day outage) which is scheduled for late August of 1997 will provide an important data point in determining the correct interpretation of the data.

Some confidence in the latter interpretation is provided by the source power prediction for the 127 day outage on Unit 2 which followed the initial 437 day outage. The predictions for both this outage and the 293 day Unit 3 outage based on the 16 group model were quite accurate, while the predictions for the PNGS-B outages were less so, thus suggesting a difference between the two reactor types.

References

1. E.V. Carruthers and N. Roy; Ontario Hydro Nuclear Safety Department Report No. 90129 Rev. 1 "Generic Methodology for Reactor Physics Analyses of Small Loss of Coolant Accidents"; October 1991; Ontario Hydro File No. 906-N-03500-P.

2. S.W. Teare; "The Influence of Photoneutrons on Low Power Operation"; Ontario Hydro Information Report, N-IR-03100-007; April 16, 1993.

3. C. Olive and F. Shanes to K.F. So and M. Hersey; "Pickering Neutron Source and Approach to Critical Calculations"; Jun 12, 1997.

4. S.W. Teare, F.C. Shanes and M.G. Siegele; "Evidence of Neutron Production in Defuelled PNGSA Unit 3"; CPS-03100-006; February 12, 1991.

Table 1

Fifteen Group Delayed Neutron Data for Equilibrium Fuel

Group	Yield Fraction	Decay Constant (s^{-1})
1	1.8060E-04	1.2776E-02
2	1.1665E-03	3.1553E-02
3	1.0372E-03	1.2202E-01
4	2.1513E-03	3.2260E-01
5	7.8960E-04	1.3894E+00
6	2.0070E-04	3.7881E+00
7	1.62E-07	6.26E-07
8	3.23E-07	3.63E-06
9	1.03E-06	4.37E-05
10	7.50E-06	1.17E-04
11	6.63E-06	4.28E-04
12	1.08E-05	1.50E-03
13	2.25E-05	4.81E-03
14	6.55E-05	1.69E-02
15	2.09E-04	2.77E-01

Note: Groups 1 through 6 are the delayed neutron groups.
Groups 7 through 15 are the photoneutron groups

Table 2

Summary of Observed Data

Unit	Date of Criticality	Outage Duration (Days)	Po from Measurement (Decades)	Po from 15 Group Model (Decades)	Po from "16 Group Model" (Decades)
1	May 13, 1995	337	-9.397*	-13.859	-9.379
6	Feb. 16, 1996	117	-9.067+	-9.393	-8.599
2	Feb. 20, 1996	437	-9.688*	-13.998	-9.663
2	Jul. 28, 1996	437 days followed by 1.2 FPD at 60% FP max followed by 127 days shut down	-9.4+	–	-9.536
2	Aug. 20, 1996	437 days followed by 1.2 FPD at 60% FP max followed by 127 days shut down, then followed by 3.0 FPD at 60% FP max followed by 4 days shut down.	-7.33+	–	-7.25
7	Sep. 22, 1996	154	-9.44+	-10.473	-8.813
3	Feb. 1, 1997	293	-9.11+	-13.452	-9.247

* Data used to define "sixteenth group"

\+ Data not used to define "sixteenth group"

Figure 1

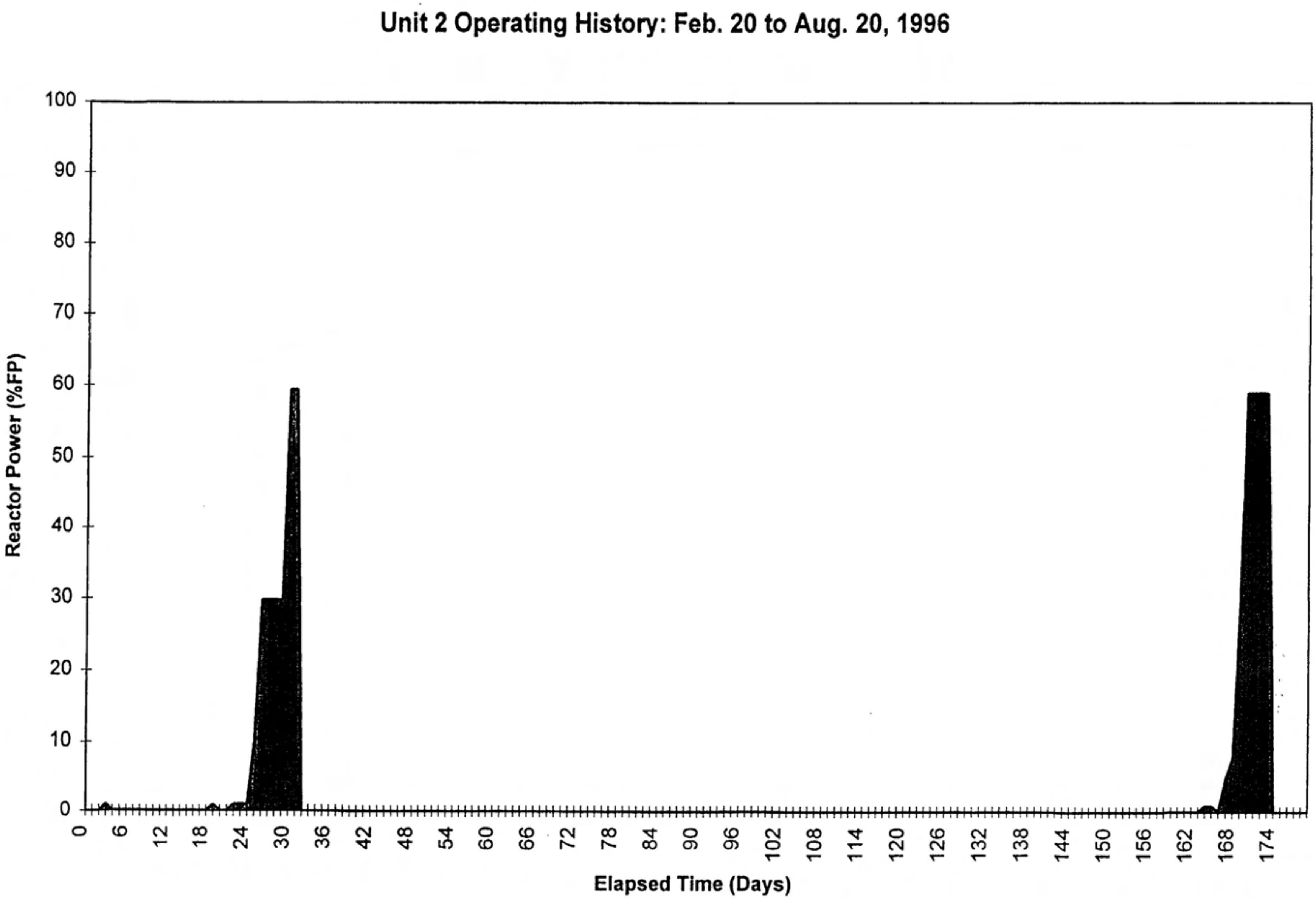
Unit 2 Operating History: Feb. 20 to Aug. 20, 1996
Reactor Power (%FP)
0
10
20
30
40
50
60
70
80
90
100
0
6
12
18
24
30
36
42
48
54
60
66
72
78
84
90
96
102
108
114
120
126
132
138
144
150
156
162
168
174
Elapsed Time (Days)

Figure 2

SOURCE POWER FOR PICKERING SHUTDOWNS - SPARK vs MEASUREMENT