* Simulate
* Intrep

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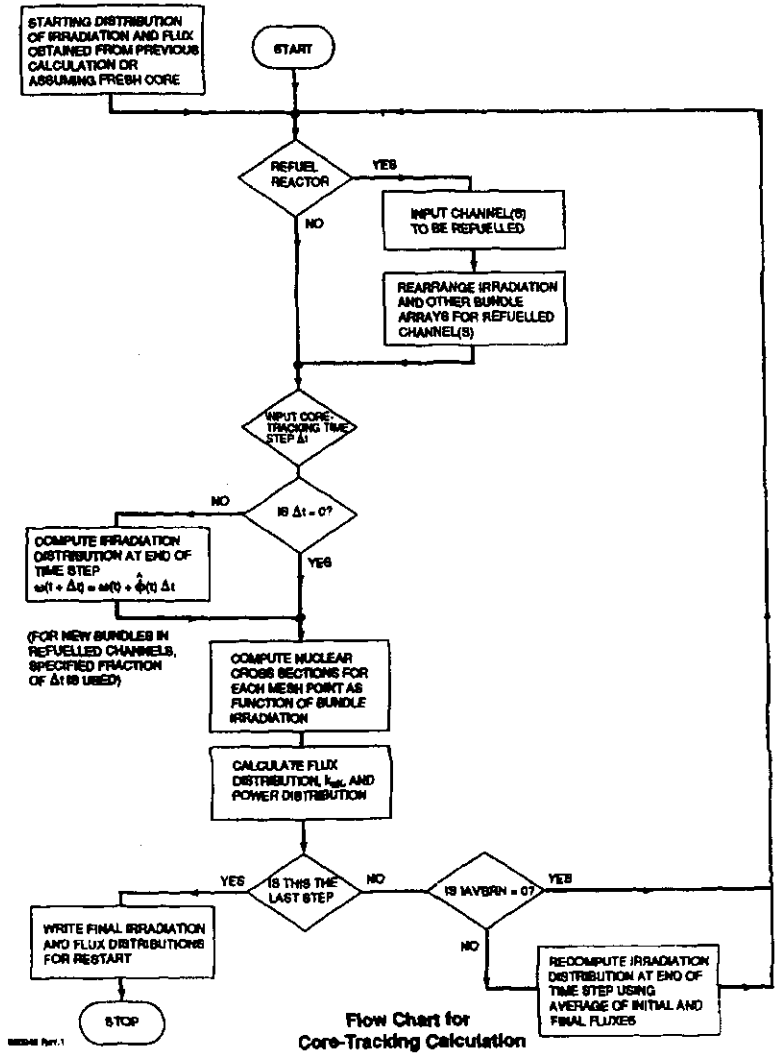


Flow Chart for Core-Tracking Calculation

Lattice Cross-Sections Vary with Position in the Core

Non-uniform core parameters

- **irradiation**
- **fuel temperature (correlated with bundle power)**
- **coolant density (depends on channel and axial position within channel)**
- **absolute flux level (correlated with bundle power)**
- **concentration of saturating fission products (correlated with flux level)**
- **Moderator temperature (to a lesser degree)**

Methodologies for Calculating Lattice Properties for RFSP

1) Uniform Parameters
2) Grid-Based Local Parameters
3) History-Based Local Parameters

Uniform Parameter Method

This was the method used in core design and fuel management calculations for many years

- Only accounts for variation in irradiation (i.e., one fuel table for entire core)
- Other parameters assumed uniform at effective average values
- No history-assumes each bundle at average conditions throughout stay in core

Grid-Based Local-Parameter Method

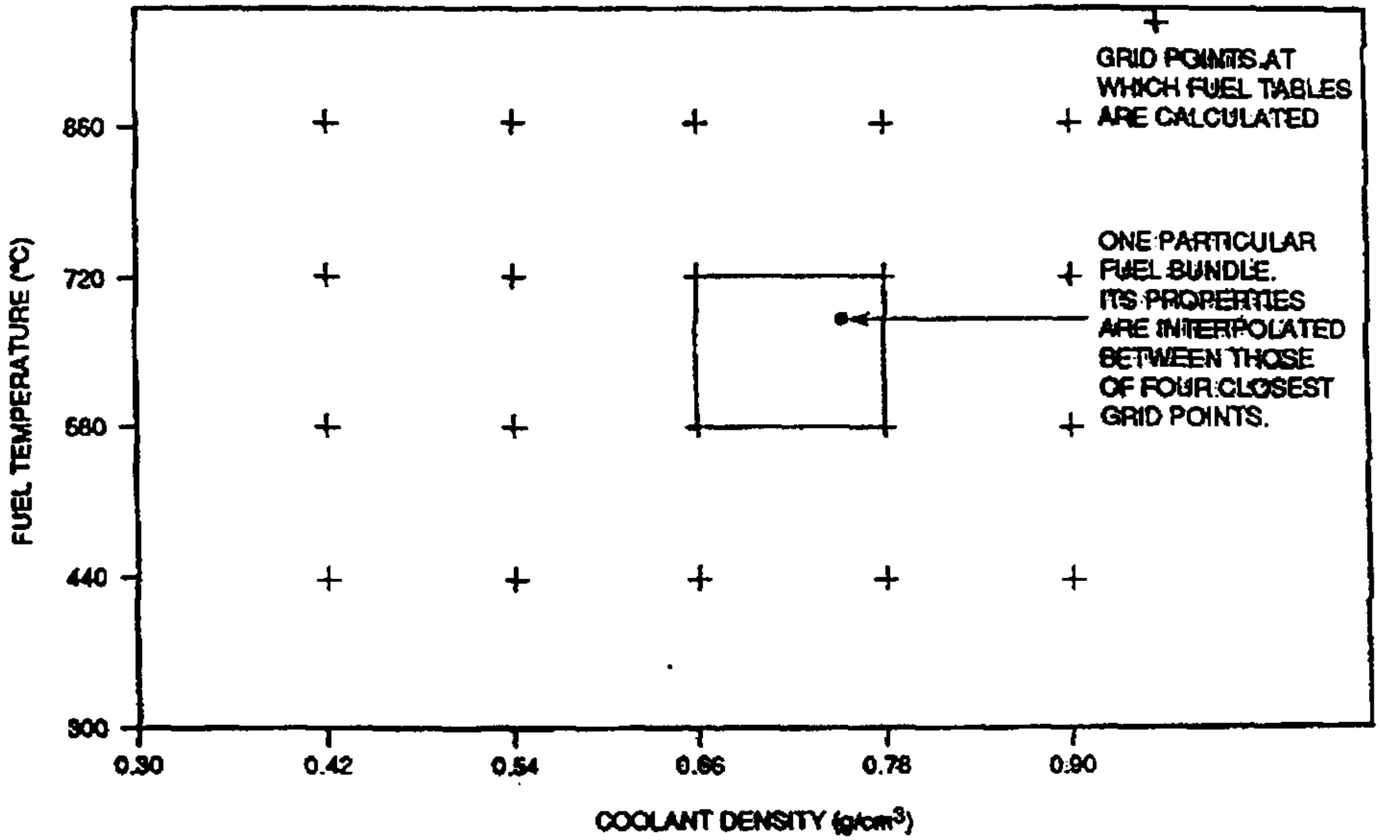
- Takes into account local variation in bundle power

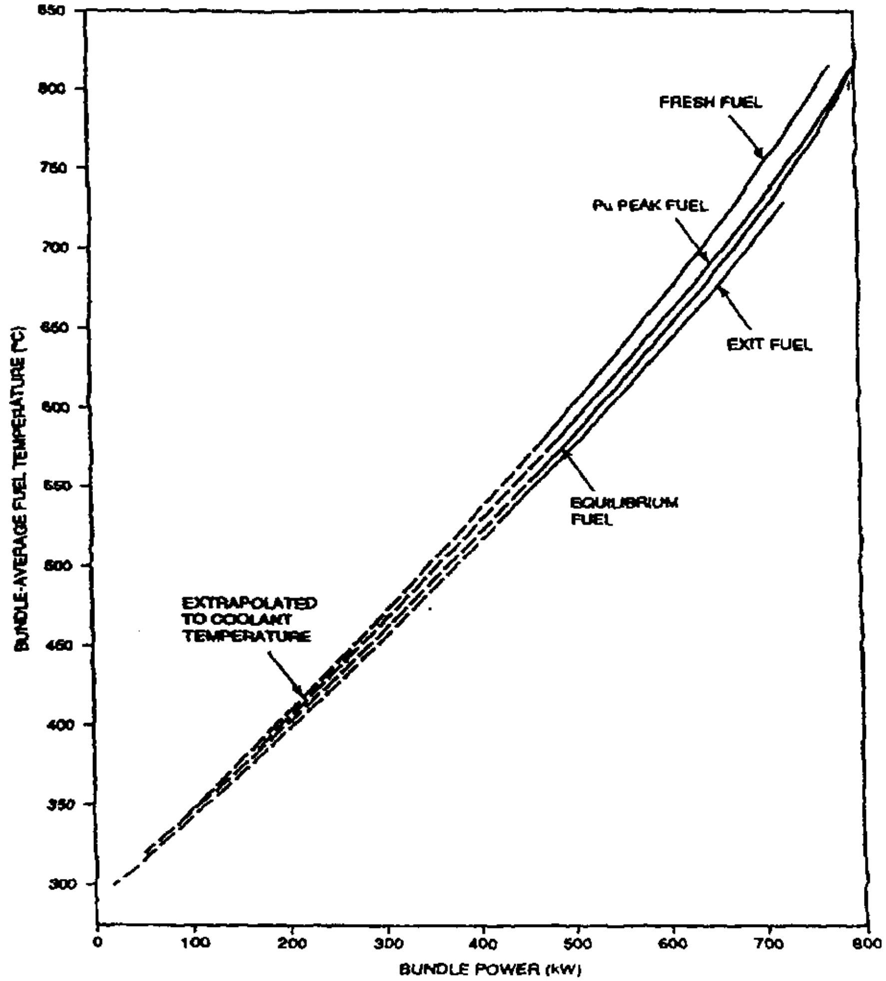
  (fuel temperature)

  (flux level)

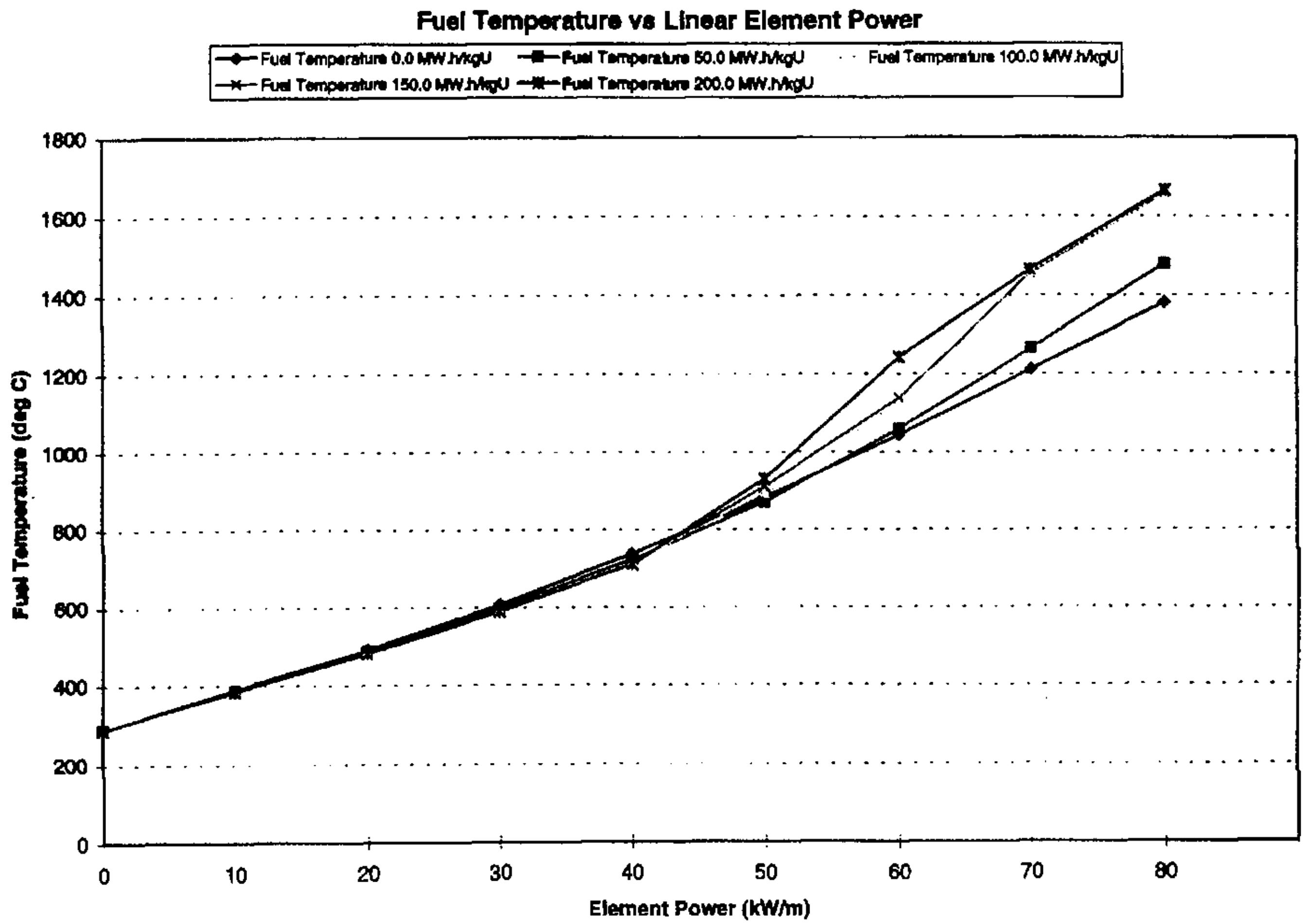
  (xenon)

  and coolant density (from NUCIRC)
- Calculates fuel tables for a grid of bundle power vs. coolant density
- Uses double linear interpolation in grid to obtain each bundle's properties


GRID POINTS AT WHICH FUEL TABLES ARE CALCULATED
ONE PARTICULAR FUEL BUNDLE. ITS PROPERTIES ARE INTERPOLATED BETWEEN THOSE OF FOUR CLOSEST GRID POINTS.
FUEL TEMPERATURE (°C)
860
720
580
440
300
0.30
0.42
0.54
0.66
0.78
0.90
COOLANT DENSITY (g/cm³)



Variation of Fuel Temperature with Bundle Power for 37-Element Fuel, *ELESIM II Calculation*
(Basis of Bundle Power/Fuel Temperature Correlation in RFSP)


Fuel Temperature vs Linear Element Power
Fuel Temperature 0.0 MW.h/kgU
Fuel Temperature 50.0 MW.h/kgU
Fuel Temperature 100.0 MW.h/kgU
Fuel Temperature 150.0 MW.h/kgU
Fuel Temperature 200.0 MW.h/kgU
1800
1600
1400
1200
1000
800
600
400
200
0
Fuel Temperature (deg C)
0
10
20
30
40
50
60
70
80
Element Power (kW/m)

Limitations of the Grid-Based Local-Parameter Method

- Handles only two independent non-uniform parameters
- Cannot easily handle perturbations
- Assumes that each bundle has been irradiated at constant values of its local conditions (no history)

History-Based Local-Parameter Method

- **Trimmed down version of PPV is executed for every bundle in core**
- **Only small irradiation step since last simulation is calculated (typically .01-.05 n/kb)**
- **43 items of data are kept for each bundle (such as nuclide densities) to allow irradiation step to be calculated**
- **For CANDU 6 core all PPVs are calculated in about one minute on an HP735 work station**

History-Based Local-Parameter Method (con't)

- Treats each bundle's history as individual
- Local conditions can be specified for each bundle
- Changes in local conditions can be taken into account
- In principle, any change in any physical parameter of each individual bundle can be modelled
- Important basic simulation refinement

Capabilities of History-Based Local-Parameter Method

In addition to individual tracking of every bundle this method permits new types of calculations:

- Bundle specific perturbations
- Changes in local concentration of saturating fission products:

  xenon

  samarium

  rhodium

  can be simulated by fission-product drivers

General Effects of History-Based Local-Parameter Method

Overall radial and axial flattening of flux and power because:

- Lattice reactivity decreases when fuel temperature and power increase
- Reactivity increases when coolant density drops

Implementation and Use

Fully operational in RFSP, used for:

- Core-tracking simulators (Lepreau)
- Fission-product transients following power changes
- Large-loss-of-coolant accidents
- Startup after long shutdown including Phase B tests

Comparison of Pt. Lepreau RFSP Production Runs with and Without the HISTORY Option

Item	No History	History	Difference (%)
Maximum Channel Power (kW)	6879	6752	-1.8
Maximum Bundle Power (kW)	847	800	-5.5
CPPF	1.088	1.074	-1.4

TABLE 1

Comparison of Pt. Lepreau RFSP Production Runs With and Without the HISTORY Option

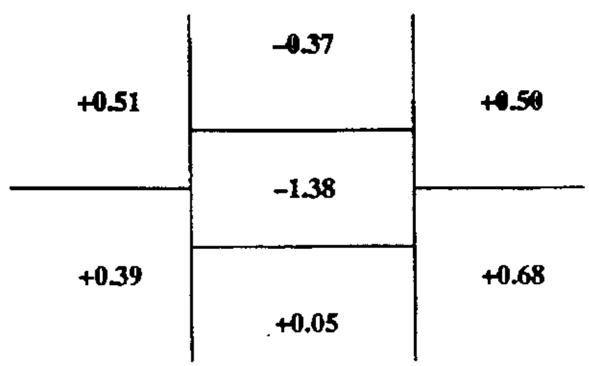
FPD	Maximum Channel Power (kW)			Maximum Bundle Power (kW)			CPPF		
	No HISTORY	HISTORY	Difference (%)	No HISTORY	HISTORY	Difference (%)	No HISTORY	HISTORY	Difference (%)
2683	6852 (P08)	6815 (P08)	−0.5	845 (P06/6)	838 (P06/6)	−0.8	1.079 (P11)	1.073 (P11)	−0.6
2686	6780 (R10)	6681 (R10)	−1.5	846 (S10/6)	809 (S10/6)	−4.4	1.090 (S08)	1.080 (S08)	−1.0
2690	6828 (R10)	6713 (R10)	−1.7	839 (P06/6)	796 (S10/6)	−5.1	1.088 (S08)	1.077 (S08)	−1.1
2693	6774 (O08)	6643 (O08)	−1.9	839 (P06/6)	788 (P06/6)	−6.1	1.072 (S12)	1.064 (H18)	−0.8
2697	6994 (P07)	6813 (P07)	−2.6	871 (P06/6)	812 (P06/6)	−6.8	1.096 (P07)	1.072 (H18)	−2.4
2700	6965 (P07)	6820 (P07)	−2.1	855 (P06/6)	803 (P06/6)	−6.1	1.092 (P06)	1.075 (P05)	−1.7
2704	6919 (P07)	6787 (P07)	−1.9	849 (P06/6)	798 (P06/6)	−6.0	1.098 (Q05)	1.090 (Q05)	-0.8
2707	6947 (G11)	6774 (G11)	−2.5	845 (E11/7)	793 (P06/7)	−6.2	1.090 (P12)	1.076 (Q05)	−1.4
2711	6914 (P07)	6784 (P07)	−1.9	842 (P17/6)	797 (P17/6)	−5.3	1.084 (P07)	1.067 (P17)	−1.7
2714	6871 (P07)	6744 (N18)	−1.8	855 (P06/6)	806 (P06/6)	−5.7	1.077 (P07)	1.068 (S08)	−0.9
2718	6885 (P07)	6769 (P07)	−1.7	846 (P06/6)	800 (P06/6)	−5.4	1.079 (P07)	1.065 (Q05)	−1.4
2721	6934 (P07)	6816 (P07)	−1.7	838 (P06/7)	794 (P06/7)	−5.3	1.093 (P05)	1.088 (Q05)	−0.5
2725	6851 (H13)	6719 (P07)	−1.9	833 (G17/7)	790 (P05/7)	−5.2	1.075 (G15)	1.064 (Q05)	−1.4
2728	6905 (O08)	6759 (O08)	−2.1	848 (O05/7)	795 (O05/7)	−6.3	1.075 (P07)	1.063 (S08)	−1.2
2732	6882 (N18)	6778 (N18)	−1.5	847 (S10/6)	806 (S10/6)	−4.8	1.084 (M13)	1.068 (M19)	−1.6
2734	6878 (N08)	6742 (N08)	−2.0	847 (E12/7)	801 (E12/7)	−5.4	1.075 (M08)	1.067 (Q16)	−0.8
2737	6839 (P07)	6733 (P07)	−1.5	842 (O18/6)	799 (O18/6)	−5.1	1.084 (H16)	1.070 (H16)	−1.4
2742	6827 (H15)	6708 (H15)	−1.7	841 (O18/6)	797 (O18/7)	−5.2	1.086 (H16)	1.067 (Q16)	−1.9
2746	6853 (H15)	6759 (S09)	−1.4	850 (S09/6)	807 (S09/6)	−5.1	1.095 (S09)	1.081 (S09)	−1.4
2749	6850 (S09)	6745 (S09)	−1.5	853 (S09/6)	807 (S09/6)	−5.4	1.096 (S09)	1.079 (S09)	−1.7
2753	6909 (O06)	6754 (O06)	−2.2	852 (S09/6)	807 (O05/6)	−5.3	1.099 (S09)	1.079 (S09)	−2.0
2756	6888 (O06)	6742 (O06)	−2.1	852 (O05/6)	808 (O05/6)	−5.2	1.092 (Q16)	1.078 (Q16)	−1.4
2760	6876 (Q15)	6737 (Q15)	−2.0	840 (O06/6)	797 (O05/6)	−5.1	1.101 (Q16)	1.082 (Q16)	−1.9
2763	6844 (G13)	6717 (G13)	−1.9	844 (J06/7)	804 (J06/7)	−4.7	1.090 (Q16)	1.076 (Q16)	−1.4
2767	6878 (M07)	6743 (M07)	−2.0	847 (O06/6)	801 (O06/6)	−5.4	1.086 (M07)	1.074 (Q17)	−1.2
2770	6905 (O17)	6772 (O17)	−1.9	844 (O17/7)	797 (O17/7)	−5.6	1.098 (Q06)	1.087 (Q06)	−1.1
2774	6834 (Q15)	6742 (Q15)	−1.3	851 (O06/6)	804 (O05/6)	−5.5	1.083 (D11)	1.071 (D11)	−1.2
2777	6832 (O06)	6723 (O06)	−1.6	841 (O06/6)	798 (O06/6)	−5.1	1.092 (D11)	1.082 (D11)	−1.0
2781	6846 (G14)	6759 (Q08)	−1.3	841 (O17/7)	795 (O06/6)	−5.5	1.082 (Q17)	1.073 (Q17)	−0.9
2784	6864 (O06)	6755 (O06)	−1.6	850 (O06/6)	807 (O06/6)	−5.1	1.082 (D11)	1.073 (D11)	−0.9
2788	6895 (G14)	6771 (O06)	−1.8	851 (O05/6)	810 (O05/6)	−4.8	1.098 (O04)	1.084 (O04)	−1.4
2690–2788	6879	6752	−1.8	847	800	−5.5	1.088	1.074	−1.4

TABLE 2

Comparison of Zone Powers With and Without the HISTORY Option

Axial Zone Pair	Percent of Reference Power—Averaged Over the Period FPD 2690 –2788		Difference (%)
	No HISTORY	HISTORY	
1/8	99.74	100.25	+0.51
2/9	101.22	101.61	+0.39
3/10	101.93	101.55	–0.37
4/11	98.82	97.46	–1.38
5/12	99.14	99.19	+0.05
6/13	100.57	101.07	+0.50
7/14	98.34	99.01	+0.68

100 x (History – No History) / No History



Fission Product Representation

Traditional Method

- Only ^{135}I an ^{135}Xe concentrations treated
- Other fission products at stead-steady values from POWDERPUFS-V
- Full effect of xenon in single increment $\Delta\Sigma_{a2(Xe)}$
- Results in deviations in reactivity

Powderpufs-V Saturating Fission Products

1) Xenon group, consists of ^{135}Xe
2) Rhodium group, consisting of ^{105}Rh
3) Samarium (stable) group consisting of: ^{149}Sm, ^{151}Sm, ^{155}Eu, ^{157}Gd, ^{113}Cd

Each of above now has a "driver" to calculate its concentration in each bundle (in history-based local-parameter methodology)

The metastable state of xenon $^{135}Xe^{m}$ (15-minute half life) also included as option

Three Options to Handle Fission Products:

1) Steady-State - fission product concentrations consistent with fuel flux
2) Transient - calculates new concentration based on previous concentration, initial and final fuel fluxes, and time step

Three Options to Handle Fission Products (con't)

3) Long Shutdown

i) sets concentrations of ^{135}Xe, ^{135}I, ^{105}Rh and ^{105}Ru to zero (assumes they have decayed)

ii) assumes all ^{239}Np has decayed to ^{239}Pu

iii) for each stable fission product in the "samarium" group the precursor's concentration is added to the stable isotopes concentration i.e.:

all $^{149}Pm \rightarrow {}^{149}Sm$

all $^{151}Pm \rightarrow {}^{151}Sm$

all $^{155}Sm \rightarrow {}^{155}Eu$

all $^{157}Eu \rightarrow {}^{157}Gd$

all $^{113}Ag \rightarrow {}^{113}Cd$

Test Simulation

- Startup after 1992 Point Lepreau Outage (one month)
- Both methods used
- Power recovery from 0.1% FP to 100% FP
- Starting from Lepreau RFSP production run
- Traditional method:
  - i) no xenon at low power
  - ii) follow xenon build-up to full power
  - iii) include temperature feedback in lattice calculation

Test Simulations

- History-based local-parameter with drivers:
  - i) "long shutdown" option at low power
  - ii) "transient" option to full power
  - iii) temperature feedback automatically included
  - iv) coolant temperature and density from NUCIRC (at higher powers)

Startup After Outage –
Comparison of Reactivity Prediction Resulting From Traditional Xenon Transient Simulation and History Based Local Parameters With All Fission Product Drivers

Case No.	Description	Excess Reactivity of the Core* (milli-k) XE	HBLP	Difference in Reactivity
0	Set-up model from FPD3130 production run	–	–	–
1	Cold shutdown steady-state xenon all adj. out	41.11	44.51	3.40
2	Step power to 1% and hold for 22 hours	33.15	38.67	5.52
3	Nominal, all adjusters in, xenon from case 2	24.87	30.50	5.63
4	Ramp up to 25% FP in 31 hours with SC	13.36	14.68	1.32
5	Hold at 25% for 8 hours	9.88	15.88	6.00
6	Step to 50% Power and take 28 hour time-step	3.11	9.19	6.08
7	Ramp up to 100% FP in 500 s	3.54	9.11	5.57
8	Case 7 + Burn for 1 FPD	0.80	7.68	6.88
9	Case 7 + Burn for 2 FPD	–0.59	5.77	6.36
10	Case 7 + Burn for 3 FPD	–1.02	4.34	5.36
11	Case 7 + Burn for 4 FPD	–1.34	2.92	4.26
12	Case 7 + Burn for 5 FPD	–1.69	1.63	3.32

* Calculated from difference in boron relative to Case 0
  (using a coefficient of 8.3 milli-k / ppm B)
  and difference in average zone fill from Case 0
  (using a coefficient of 0.065 milli-k / % average zone fill).

Results

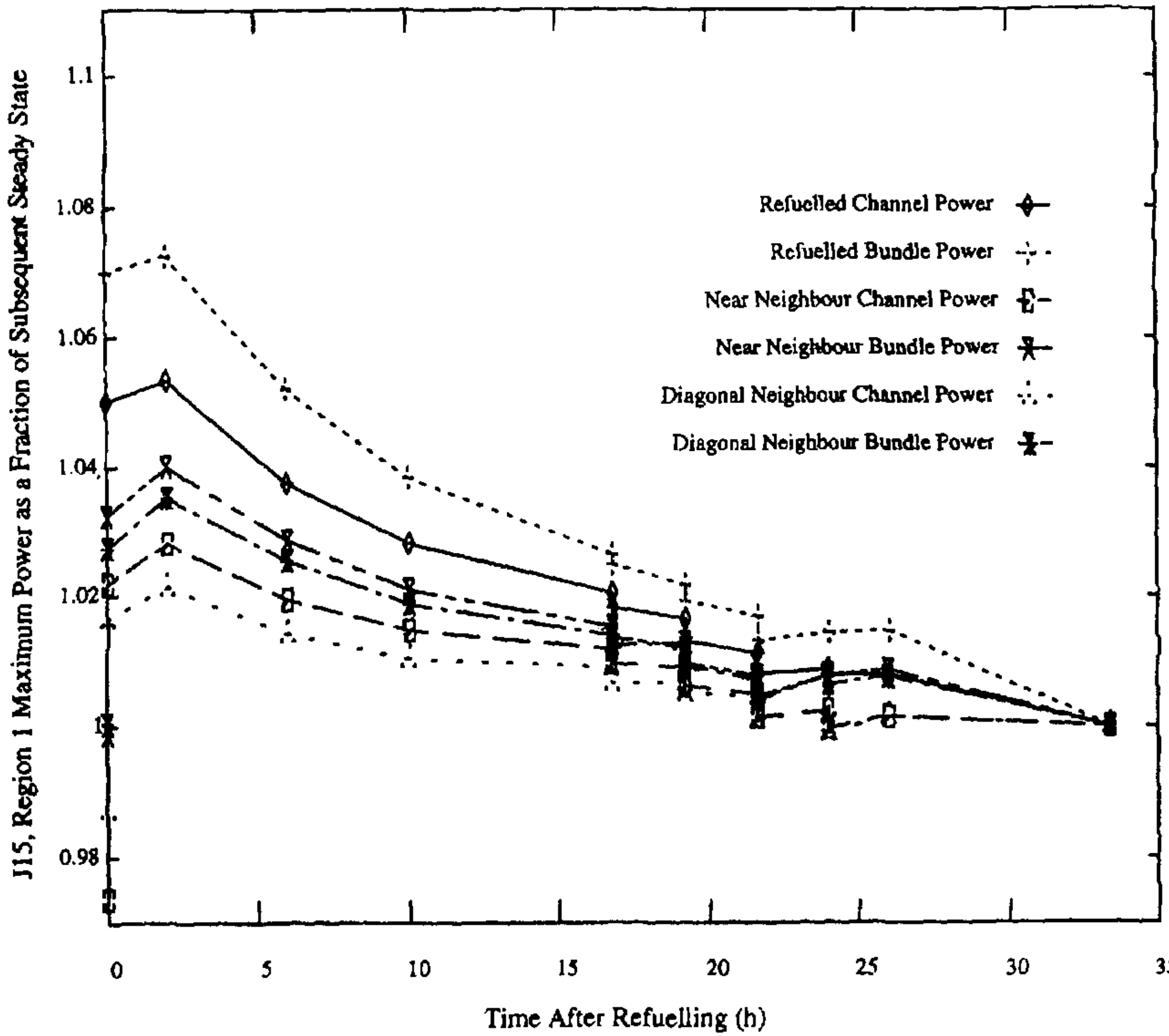
- Reference case 0.3 milli-k higher with new drivers - due to distributed fission products
- New drivers give higher core excesses reactivity throughout. Maximum difference is ~7 milli-k about 2 FPD after startup
- Difference diminishes at about 1 milli-k / FPD after reaching full power

Conclusions

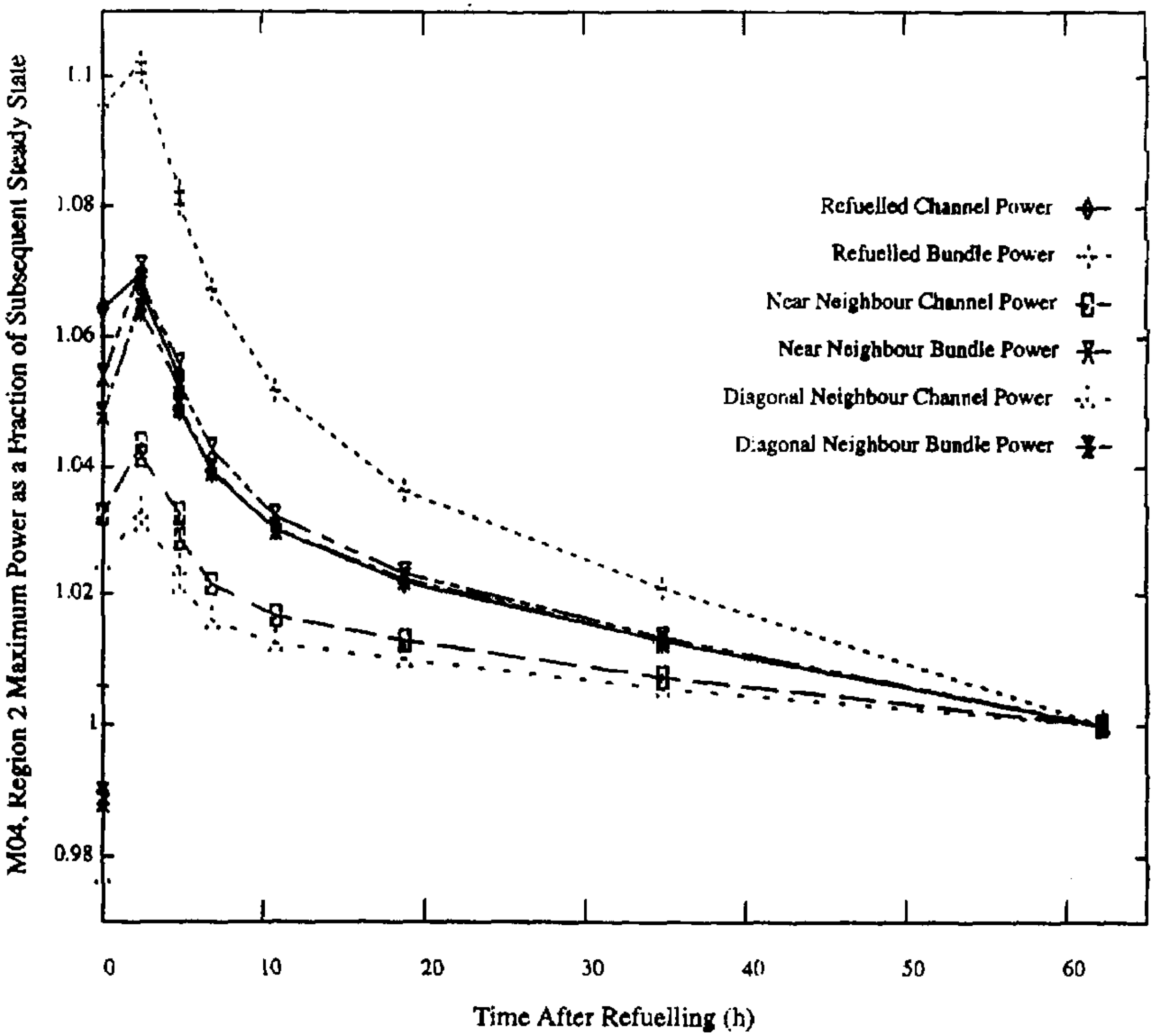
- Gives better estimate of critical boron
- Startup after long outage simulation gives excess core reactivity observed at site

	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22
A											3241											
B											OUTER CORE		3244									
C							3224										3237					
D					3242		3251												3230			
E							3238			3231			**3229**		3248		3238					
F				3228					3250													
G													3255	3237		3252						
H											3235											
J		3229		3238			3248								3241				3245			
K								3230		3242						3228					3235	
L											INNER CORE			3230						3251		
M			3244	**3231**			3237		3237					3250								
N					3255											3244		3238			3231	
O			3252							3245	3231				3229					3249		
P						3238	3249						**3228**	3255		3252					3231	
Q														3241		3237						
R			3230						3242													
S						3245							3248									
T																			3242			
U								3235	3251		3230			3236								
V																						
W														3255								

The numbers represent the FPD of refuelling. The channels in **bold** are ones for which HBAL data is available for comparison.



Refuelled Channel Power
Refuelled Bundle Power
Near Neighbour Channel Power
Near Neighbour Bundle Power
Diagonal Neighbour Channel Power
Diagonal Neighbour Bundle Power
J15, Region 1 Maximum Power as a Fraction of Subsequent Steady State
1.1
1.08
1.06
1.04
1.02
1
0.98
0
5
10
15
20
25
30
35
Time After Refuelling (h)



M04, Region 2 Maximum Power as a Fraction of Subsequent Steady State
1.1
1.08
1.06
1.04
1.02
1
0.98
0
10
20
30
40
50
60
Time After Refuelling (h)
Refuelled Channel Power
Refuelled Bundle Power
Near Neighbour Channel Power
Near Neighbour Bundle Power
Diagonal Neighbour Channel Power
Diagonal Neighbour Bundle Power

TABLE 1

Maximum, Average and Standard Deviation in Fission-Product-Free Correction Factor For One Month of Fuelling at Gentilly-2

Parameter	Inner Core			Outer Core(%)		
	Max. (%)	Ave. (%)	Stan. Dev. (%)	Max. (%)	Ave. (%)	Stan. Dev. (%)
Channel Power of Refuelled Channel	5.58	4.56	0.59	6.98	5.62	0.95
Channel Power of Nearest Neighbours of Refuelled Channel	3.45	2.32	0.67	4.89	3.25	1.01
Channel Power of Diagonal Neighbours of Refuelled Channel	3.13	1.95	0.73	4.63	2.97	0.95
Maximum Bundle Power of Refuelled Channel	9.02	6.79	0.87	10.21	8.00	0.91
Maximum Bundle Power of Nearest Neighbours of Refuelled Channel	5.46	3.72	0.75	7.06	4.91	0.97
Maximum Bundle Power of Diagonal Neighbours of Refuelled Channel	5.15	3.19	0.78	6.61	4.42	1.04

TABLE 2

RFSP-Simulated (Transient) Power Boost, Caused By Refuelling, Compared With Heat Balance Results for 3 Channels at Gentilly-2

Channel	Power Increase On Refuelling (just before to just after)	
	RFSP (%)	Heat Balance (%)
E13	18.99	18.31
M04	23.27	22.19
P13	16.84	15.44

*SIMULATE Methods

History Based Local Parameters:

- Required trailer cards:
  - HI (history-maximum number of outer iterations on power to obtain consistent flux/cross-sections)
  - FI (fission products - STEADY, TRANSIENT, or LONG SHUT)
- Conflicting trailer cards:
  - LO (grid-based local parameters)
  - XE (distributed xenon)
  - Y (xenon time-search option)

*SIMULATE Methods (con't)

- If starting from non history-based file then:
  - run *SIMULATE without history at desired energy
  - run *PPVSWHIST - generates tables of 43 required values for history at 0.1 n/KB intervals (stored under index PPVSORHIST for each fuel type)
  - run *FPDTOHIST - generates starting history point by burning from next lowest 0.1 interval to value in FUEL IRRAD

*SIMULATE Methods (con't)

Uniform Parameters with distributed Xenon:

- Required trailer cards:
  - XE (distributed xenon - steady or transient)
- Conflicting trailer cards:
  - HI (history)
  - FI (fission products)
  - LO (grid-based local parameters)
- Note that XENON PROP block is required
- Note that if the steady option is selected on XE card (i.e., IDEQUIL = 1) then the frequency of xenon calculations must be set on the *Simulate control card (IXENON)
- The xenon time-search option (Y card) can be used to calculate the time at which the change in xenon matches a desired k_{eff} value

*SIMULATE Methods (con't)

Grid-Based Local Parameters:

- Required trailer cards:
  - LO (grid based local parameters - maximum number of outer iterations on power to obtain consistent flux/cross sections and mix of current and previous bundle power for next cycle)
- Conflicting trailer cards:
  - HI (history)
  - FI (fission products)
  - XE (distributed xenon)
  - Y (xenon time-search option)

*SIMULATE Methods (con't)

- If starting from non-grid based file then:
  - run *POWDERPUF module with "LOCAL PARM" option (as ROOFLAG parameter of card type 2) before the grid based *SIMULATE
- Note that GRID values are fixed (hard-coded):
  - Bundle power: 30, 155, 280, 405, 530, 655, 780, 905 kW
  - Coolant Density: 0.45, 0.56, 0.67, 0.78, 0.89 g/cm^3
    If outside grid boundary - error generated

*SIMULATE Methods (con't)

Uniform Parameters:

- Required trailer cards:
  - none
- Conflicting trailer cards:
  - HI (history)
  - FI (fission products)
  - LO (grid-based local parameters
  - XE (distributed xenon)
  - Y (xenon time-search option)

*SIMULATE Methods (con't)

Bulk and Spatial Control:

- Required trailer cards:
  - AA-GG (initialized once and kept in Zone CNTL block)
- Conflicting trailer cards:
  - FINDBORON conflicts with bulk control
- Note that to activate bulk and spatial both ISPCNTL and IBLKCTL on the AA card must be > 0 as well as NSCZCNT on the *SIMULATE control card.
- Can also turn off one or both by setting above selectively to zero
- When defining detector locations on FF cards do not overlap mesh intervals, will result in double counting
- Also, if FF cards are input each time then data will accumulate in ZONE CNTL

New algorithm:

$$Z'(i) = Z(i)\frac{DLIF(i)}{Kt}$$

$$DLIF(i) = Kt\ \beta\iota\left[\frac{\varphi_{\iota}}{\varphi_{\iota ref}} - \left\langle\frac{\varphi}{\varphi_{ref}}\right\rangle\right]$$

$$- Kh\ (1 - \beta\iota)\ [Z(i) - < Z >]$$

$$- K1\ \ [Z(\iota) - < Z >]$$

where:

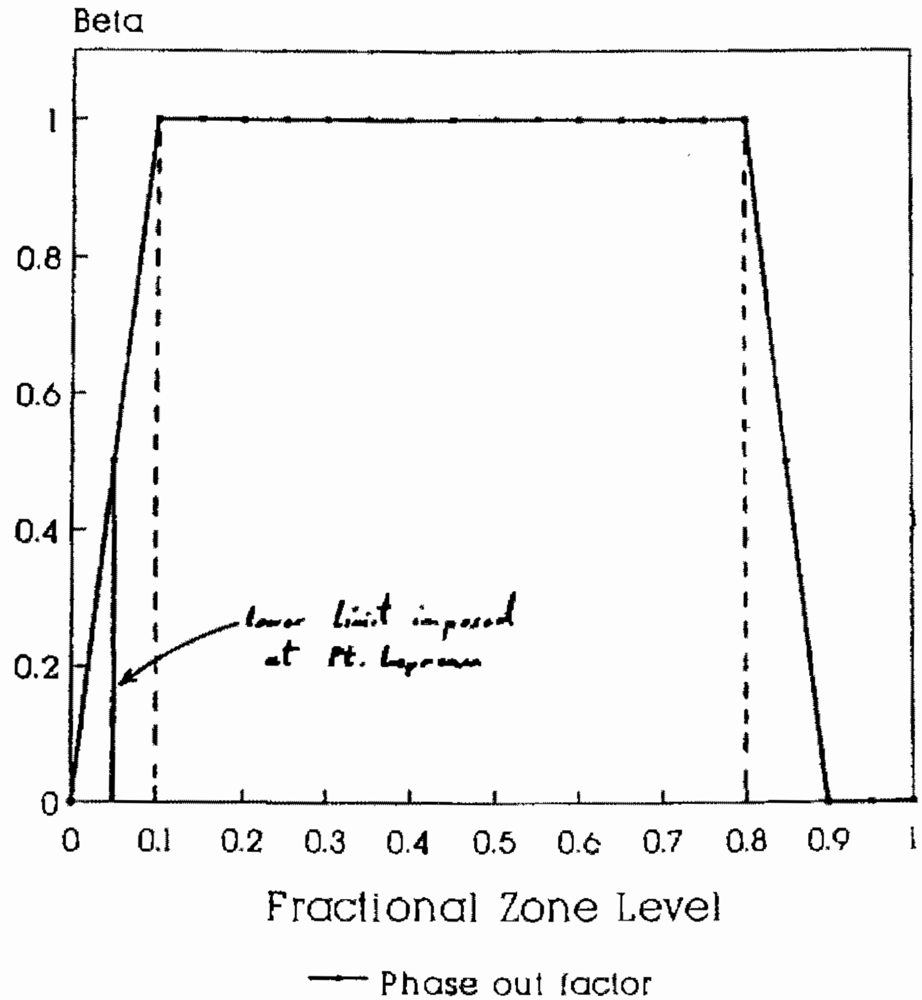
Kt = 3.0% valve lift / % flux tilt error

Kh = 0.6% valve lift / fractional level error

K1 = 0.1% valve lift / fractional level error

$$\beta\iota \begin{cases} = 0 & 0 \quad < Z(i) < 0.5 \\ = Z(i) / 0.1 & 0.5 < Z(i) < .10 \\ = 1 & .10 < Z(i) < .80 \\ = [0.9 - Z(i)] / 0.1 & .80 < Z(i) < .90 \\ = 0 & .90 < Z(i) < 1.0 \end{cases}$$

Phase Out Factor Beta versus Zone Level



*SIMULATE Methods (con't)

Other useful options:

- PPV trailer cards:
  - MODDENSITY — moderator density
  - MODTEMP — moderator temperature
  - COOLDENSIT — coolant density
  - COOLTEMP — coolant temperature
  - MD2OPURITY — moderator D_20 purity
  - CD2OPURITY — coolant D_20 purity
  - BORONINMOD — boron in moderator
  - FINDBORON — find boron value to achieve target k_{eff}

SIMULATE Methods (con't)

- All types of these cards change the input for all PPV fuel types found under the index R000 and generate new tables for fuel and reflector
- For grid-based local parameters they have no effect unless *POWDERPUF module is rerun with "LOCAL PARM" option after the change
- For history based calculations all cards are effective except COOLDENSIT and COOLTEMP which come from NUCIRC and are independent of the PPV input.