7. PROTEUS EXPERIMENTAL RESULTS

7.1. INTRODUCTION

In this chapter, the results of the HTR-PROTEUS measurement program are presented. A summary of all the parameters investigated in each of the configurations can be found in section 5, table 5.2.

The measurements presented in this chapter are the following:

- **Critical loading**: The measurement of the critical height of the core and/or the number of fuel and moderator pebbles loaded for all the configurations (section 7.2).
- **Component Worths**: The measurement of the reactivity worth of the various components which represent perturbations to the clean system (section 7.2).
- **Control rods**: The measurement of the integral and differential worth of the individual control rods using the stable period technique (section 7.3).
- **Shutdown rods:** The measurement of the integral worth of 1, 2, 3 or 4 bulk absorber rods using either PNS or IK (section 7.4).
- **β/Λ**: The measurement of the kinetic parameter, β/Λ, at critical (section 7.5).

For the most part, the data are presented in the form of tables containing the measured values of a particular parameter in a range of configurations. Where possible, experimental uncertainties are included and unless otherwise stated are 1σ values. The evaluation of uncertainties is described in detail in Section 6 for each measurement technique, but to summarize:

For the reactivity and kinetics measurements, the uncertainties are associated mainly with the statistical uncertainties inherent in the measurement itself.

Uncertainties are not applied to the calculated delayed neutron parameters β_i, λ_i but their values are normally presented with the results of each analysis.

In general, the delayed neutron data have been based upon the JEF-1 evaluation (≅ ENDF/B-V) [7.1]. The slight energy dependence of the total yield has been ignored, but of course the energy dependence of the delayed neutron spectra has not.

The characteristics of even the undermoderated configurations are such that the contribution of delayed precursors from ^{238}U is only some 0.5% of the total (see table 6.1 in Chapter 6).

As far as the calculated correction factors (e.g. K_d in equation (6.15)) and the generation time Λ are concerned, for which the uncertainties are very difficult to estimate, the level of agreement between a set of measurements of the same parameter, using different (complementary) techniques, after correction, is taken as a measure of the uncertainties inherent in the procedure.

7.2. CRITICAL BALANCE

To simplify the modelling of the system, some components are not taken into account in the calculations, for instance the partially inserted fine control rods, the autorod, the nuclear instrumentation, and the start-up sources. Hence, the calculated k_{eff} of the critical core has to be corrected for the reactivity effects of these components. Where possible these effects have been measured directly in the various configurations, but in many cases the values had to be calculated, estimated or scaled from other configurations. Tables 7.1 to 7.19 summarize the results of the critical balances in Cores 1 to 10. Each table is a self-contained report of a measured state and includes a breakdown of the various components of the reactivity excess. This enables the user to choose which correction factors he/she wishes to calculate and which he/she wishes to apply as correction factors to his calculation. The characters **M, S, C, E** which appear in the tables indicate whether the effect has been **M**easured in this core, **S**caled from another core, **C**alculated or simply **E**stimated.

The measured worths of the individual components are normally evaluated against the worths of the ZEBRA/CONTROL rods, which were carefully calibrated using the stable period technique, or against the autorod worth which has been subsequently inter calibrated with the ZEBRA/CONTROL rods.

A small degree of inhomogeneity in the radial graphite reflector is inevitable. Axial holes are required for control and shutdown rod insertion and radial and axial holes for nuclear instrumentation. Over 300 so-called C-Driver holes in the inner radial reflector, left from the previous experiments, have had to be filled with graphite rods for the current series of experiments (R2, R3 indicate the second and third rings of C-Driver channels respectively). These rods can be relatively easily removed and are therefore useful in estimating the effect of missing graphite. Correction for the air gaps between the 27.5mm i.d. C-Driver channels and the 26.5mm o.d. graphite filler rods were calculated by V.D. Davidenko of the Kurchatov Institute using the Cristall code system.

No explicit measurements have been made to determine the worth of the 4 empty ZEBRA/CONTROL rod channels. The values reported in the tables have therefore had to be made on the basis of the results of the C-driver hole measurements. For safety reasons the worth of the 8 safety and shutdown rod channels cannot be measured and the value here was calculated at PSI using the TWODANT code. It is reasonable to remove them from the reactivity excess list and to include them in the calculational model.

In order to enable air-cooling of the core, the upper and lower axial reflectors are each furnished with 33 "ventilation holes". Because the axial thermal flux peak is strongly shifted downwards, graphite density variations below the fuelled region are of greater significance than those above. Unfortunately, for practical reasons, it is difficult to measure the effect in the lower reflector and satisfactory measurements could only be made in the upper axial reflector. In the upper reflector, measurements were made with 11 of the 33 holes plugged with graphite. Because full access to the ventilation holes in the lower axial reflector is impeded from below, it is not possible to measure their worth in the usual manner. At best it was possible to partially fill some of the channels with graphite and to linearly scale the effect to 33 filled channels. In some of the cores all of the coolant channels in the lower axial reflector were filled with graphite plugs.

In all the deterministic cores, some 12 pebbles lie directly over one of the 33 cooling channels in the lower axial reflector. In order to avoid pebble displacement in these cases, special aluminium plugs were developed to support the pebbles in Core 1. In later cores, simple graphite rods were used.

The reactor start-up sources are normally in their "IN" position during reactor operation. At low fluxes their reactivity effect is positive by virtue of the apparent enhanced neutron multiplication, but at the normal operating fluxes of PROTEUS (>10^7 n.cm^{-2}s^{-1}) their effect is a negative one due to the parasitic neutron absorption in the source and casing. The start-up sources pass through horizontal aluminium guide tubes situated in the radial reflector at about the level of the cavity floor. The worth of these penetrations was also measured and the results reported in the tables.

The pulsed neutron source, when used for subcriticality measurements, is partially inserted into the lower axial reflector. Its reactivity worth was measured by replacing it with a plug of graphite of dimensions 250mm x 120mm∅.

There are, in total, 8 detection channels used for nuclear instrumentation: 3 safety channels, 2 impulse channels, 1 logarithmic channel, 1 linear channel and 1 deviation channel. Apart from the 2 impulse channels, which are fission chambers, all the instrumentation consists of large ionisation chambers (220x90mm∅) situated in horizontal channels in the reflector at a radius of ~1000mm. The worth of one of these ionisation chambers compared with a graphite plug was measured by opening a plugged channel and inserting a spare ionisation chamber. The worth of one of the two impulse channels in the outer radial reflector has also been measured, by means of filling a similar channel first with a replacement detector and then with a graphite plug.

There are 4 separate temperature sensors in the system, 2 in the core and 2 in the radial reflector. These sensors were systematically removed from the system in order to assess their reactivity worths.

Finally, it should be noted that the reactivity corrections specified in the G2 Core have no physical meaning but can be used indirectly to calculate corresponding correction factors on α and that some cores have more than one critical balance corresponding to states with slightly different conditions.

The value of β_{eff} , with which the reactivity excess has been converted to k_{eff} , was calculated, for each core and is also presented in the tables.

7.2.1. Core 1 (reference state #1)

1ST CRITICALITY	07.07.92	
UNLOADED	07.06.93	Only partially
NOMINAL M:F	1:2	
PEBBLE COUNT M,F	2585,5181	
PACKING	Hexagonal Close ABABAB...	see [7.2]
WATER LOADING	None	
NOTES	First core and only core with ZEBRA Rods	

REFERENCE STATE #1

DATE	18.05.93		
CRITICAL LOADING	22 layers	**M**	
CRITICAL HEIGHT	1.0888m	**M**	2x(3)+21x(4.898)cm
ROD POSNS (CONT/AUTO)	148/418mm	**M**	200/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^{7}$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	21°C	**M**	
CORE TEMPS (Zentrum/Rand)	19.4/19.9°C	**M**	
REFL. TEMPS (Wald/Aare)	20.2/20.1°C	**M**	
AIR PRESSURE	975.6 mbar	**M**	
HUMIDITY	50%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADING	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Zebra Rest Worths	4	**M**	-264±1	see [7.3]
Zebra Insertion (148mm)	4	**M**	-39±0.2	^
Zebra Rod Channels	4	**M**	-2±0.6	|
Autorod Rest Worth	1	**M**	-7.7±0.1	|
Autorod Insertion (418mm)	1	**M**	-3.7±0.3	|
Autorod Channel	1	**M**	-0.5±0.15	|
Safety+Shutdown Rod Channels	8	**C**	-24±4	|
Empty Channels R2	2	**M**	-2.7±0.3	|
Empty Channels R3	4	**M**	-3.8±0.6	see [7.4]
Air gaps in C-Driver Holes	320	**C**	-8.1	
Channels in Upper Reflector	33	**M**	-3.6±0.9	|
Channels in Lower Reflector	33	**M**	-23±6	|
Aluminum Plugs in Lower Reflector	12	**M**	-15.3±0.2	|
Start-up Sources	2	**M**	-3.3±0.01	|
Start-up Source Penetrations	2	**M**	-1±0.1	|
Pulsed Neutron Source	1	**M**	-4.3±0.1	|
Nuclear Instrumentation (Ionization)	6	**M**	-8.4±1.8	|
Nuclear Instrumentation (Fission)	2	**M**	-0.8±0.6	|
Temp. Instrumentation Reflector	2	**M**	-10.6±0.3	|
Temp. Instrumentation Core	0			v
Total Correction			**426±8¢**	
Corrected k_{eff} (β_{eff} = 0.00723)			**1.0318±0.0006**	

Table 7.1: Critical Balance for Reference State #1 of Core 1

7.2.2. Core 1A (reference state #1)

1ST CRITICALITY	08.06.93
UNLOADED	17.08.93
NOMINAL M:F	1:2
PEBBLE COUNT M,F	2470,4951
PACKING	Hexagonal Close ABABAB... see [7.2]
WATER LOADING	None
NOTES	Core1 with Zebra rods replaced by withdrawable control rods in ring 5. Rods are hollow (i.e. no B_4C pellets)

REFERENCE STATE #1

DATE	14.06.93		
CRITICAL LOADING	21 layers	**M**	
CRITICAL HEIGHT	1.0398m	**M**	2x(3)+20x(4.898)cm
ROD POSNS (CONT/AUTO)	2183/482	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$		**M**
HALL TEMP	20.2°C	**M**	
CORE TEMPS (Zentrum/Rand)	20.7/21.1°C	**M**	
REFL. TEMPS (Wald/Aare)	21.2/21.2°C	**M**	
AIR PRESSURE	980mbar	**E**	
HUMIDITY	50%	**E**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (2183)	4	**M**	-77.9±0.1	see [7.5]
Control Rod Channels in Core 1	4	**E**	-2±1	≡ Zebra rod channels
Old Zebra Rod Channels	4	**M**	-2±0.6	≡ Core 1 value
Autorod Rest Worth	1	**M**	-7.7±0.1	≡ Core 1 value
Autorod Insertion (482)	1	**M**	-3.2±0.3	scaled from Core 1
Autorod Channel	1	**M**	-0.5±0.15	≡ Core 1 value
Safety+Shutdown Rod Channels	8	**C**	-24±4	≡ Core 1 value
Empty Channels R2	2	**M**	-2.7±0.3	≡ Core 1 value
Air gaps in C-Driver Holes	320	**C**	-8.3	
Channels in Upper Reflector	34	**M**	-3.6±0.9	≡ Core 1 value
Channels in Lower Reflector	33	**M**	-23±6	≡ Core 1 value
Aluminium in Lower Reflector	12	**M**	-15.3±0.2	≡ Core 1 value
Start-up Sources	2	**M**	-3.3±0.01	≡ Core 1 value
Start-up Source Penetrations	2	**M**	-1±0.1	≡ Core 1 value
Nuclear Instrumentation (Ion.)	6	**M**	-8.4±1.8	≡ Core 1 value
Nuclear Instrumentation (Fiss.)	2	**M**	-0.8±0.6	≡ Core 1 value
Temp. Instrumentation Reflector	2	**M**	-10.6±0.3	≡ Core 1 value
Temp. Instrumentation Core	2	**M**	-0.9±0.3	≡ Core 1 value
Total			**195±8¢**	
Corrected k_{eff} (β_{eff} = 0.00723)			**1.0143±0.0006**	

Table 7.2: Critical Balance for Reference State #1 of Core 1A

7.2.3. Core 1A (reference state #2)

1ST CRITICALITY (2nd load)	21.02.94
UNLOADED	22.03.94
NOMINAL M:F	1:2
PEBBLE COUNT M,F	2470,4951
PACKING	Hexagonal Close ABABAB... see [7.2]
WATER LOADING	None
NOTES	Repeat of Core 1A to check consistency

REFERENCE STATE #2

DATE	22.02.94		
CRITICAL LOADING	21 layers	**M**	
CRITICAL HEIGHT	1.0398m	**M**	2x(3)+20x(4.898)cm
ROD POSNS (CONT/AUTO)	2350/130	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^{7}$ $n.cm^{-2}s^{-1}$		**M**
HALL TEMP	20°C	**M**	
CORE TEMPS (Zentrum/Rand)	-/19.4°C	**M**	
REF. TEMPS (Wald/Aare/Brugg)	19.0/18.9/18.8°C	**M**	
AIR PRESSURE	980mbar	**E**	just a guess
HUMIDITY	50%	**E**	just a guess

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (2350)	4	**M**	-94.3±0.5	
Control Rod Channels in Core 1	4	**E**	-2±1	≡ Zebra rod channels
Autorod Rest Worth	1	**M**	-7.7±0.1	≡ Core 1 value
Autorod Insertion (130)	1	**M**	-5.4±0.3	scaled from Core 1
Autorod Channel	1	**S**	-0.5±0.15	≡ Core 1 value
Safety+Shutdown Rod Channels	8	**C**	-24±4	≡ Core 1 value
Empty Channels R2	2	**M**	-2.7±0.3	≡ Core 1 value
Air gaps in C-Driver Holes	320	**C**	-8.3	
Channels in Upper Reflector	34	**M**	-3.6±0.9	≡ Core 1 value
Channels in Lower Reflector	29	**S**	-20±6	scaled from Core 1
Start-up Sources	2	**S**	-3.3±0.01	≡ Core 1 value
Start-up Source Penetrations	2	**S**	-1±0.1	≡ Core 1 value
Nuclear Instrumentation (Ion.)	7	**S**	-9.8±2.0	≡ Core 1 value
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	≡ Core 1 value
Temp. Instrumentation Reflector	3	**S**	-15.9±0.9	scaled from Core 1
Temp. Instrumentation Core	1	**S**	-0.5±0.3	scaled from Core 1
Total			**199.8±8¢**	
Corrected k_{eff} (β_{eff} = 0.00723)			**1.0147±0.0006**	

Table 7.3: Critical Balance for Reference State #2 of Core 1A

7.2.4. Core 2 (reference state #1)

1ST CRITICALITY	20.08.93
UNLOADED	04.10.93
NOMINAL M:F	1:2
PEBBLE COUNT M, F	Fueled region: 1880,3768 Moderator region: 6009,0
PACKING	Hexagonal Close ABABAB.... see [7.2]
WATER LOADING	None
NOTES	16 layers like core 1A, then 17 layers moderator pebble then upper reflector in place

REFERENCE STATE #1

DATE	20.08.93		
CRITICAL LOADING	16 layers with fuel, 17 layers moderator	**M**	
CRITICAL HEIGHT	162.736	**M**	2x(3)+32x(4.898)cm
ROD POSNS (CONT/AUTO)	1936/316	**M**	0/1000mm=fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	20°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A		
REFL. TEMPS (Wald/Aare)	22.5/22.4°C	**M**	
AIR PRESSURE	988.1mbar	**M**	
HUMIDITY	55%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	NUMBER PRESENT		TOTAL ¢	COMMENTS
Control Rod Insertion (1936)	4	**M**	-43.6±0.2	
Control Rod Channels	4	**M**	-2±1	≡ Zebra in Core 1
Autorod Rest Worth	1	**S**	-6.7±0.5	scaled from Core 1A
Autorod Insertion (316)	1	**S**	-3.7±0.3	scaled from Core 1A
Autorod Channel	1	**M**	-0.5±0.15	≡ Core 1A value
Safety+Shutdown Rod Channels	8	**C**	-21±4	≡ Core 1A value
Empty Channels R2	2	**M**	-2.3±0.3	scaled from Core 1A
Air gaps in C-Driver Holes	320	**C**	-8.7	
Channels in Upper Reflector	34		0.0	reflector no worth
Channels in Lower Reflector	33	**M**	-23±6	≡ Core 1A value
Aluminium in Lower Reflector	12	**M**	-15.3±0.2	≡ Core 1A value
Start-up Source Penetrations	2	**M**	-1±0.1	≡ Core 1A value
Nuclear Instrumentation (Ion.)	6	**S**	-7.3±1.8	scaled from Core 1A
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	≡ Core 1 value
Temp. Instrumentation Reflector	2	**S**	-9.2±0.3	scaled from Core 1A
Total			**145±8¢**	
Corrected k_{eff} (β_{eff} = 0.00723)			**1.0106±0.0006**	

Table 7.4: Critical Balance for Reference State #1 of Core 2

7.2.5. Core G2 (reference state #1)

BEGINNING	08.10.93
END	15.10.93
NOMINAL M:F	N/A
PEBBLE COUNT M,F	0,0
PACKING	N/A
WATER LOADING	N/A
NOTES	Empty core for PNS measurement of absorption cross section of reactor graphite

REFERENCE STATE #1 - NO UPPER REFLECTOR

DATE	14.10.93		
CRITICAL LOADING	Empty cavity, no upper reflector, cavity covered with B plastic		
CRITICAL HEIGHT	N/A		
ROD POSNS (CONT/AUTO)	0/1000	**M**	fully out
NOMINAL FLUX (DESK)	N/A		
HALL TEMP	20°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A		
REFL. TEMPS (Wald/Aare)	20.2/20.3	**M**	
AIR PRESSURE	968.1mbar	**M**	
HUMIDITY	45%	**M**	

CORRECTIONS PERTURBATIONS	**NUMBER PRESENT**		**TOTAL ¢ IN CORE 1**	**COMMENTS**
Control Rod Insertion (0)	0			
Control Rod Channels	4	**S**	-2±1	≡ Zebra in core 1
Autorod Rest Worth	1	**S**	-7.7±0.1	≡ core 1 value
Autorod Insertion (1000)	0			
Autorod Channel	1	**S**	-0.5±0.15	≡ core 1 value
Safety+Shutdown Rod Channels	8	**S**	-24±4	≡ core 1 value
Empty Channels R2	2	**S**	-2.7±0.3	≡ core 1 value
Channels in Upper Reflector	0			no reflector
Channels in Lower Reflector	0			graphite filled
Start-up Sources	0			
Start-up Source Penetrations	2	**S**	-1±0.1	≡ core 1 value
Pulsed Neutron Source	1	**S**	-4.3±0.3	≡ core 1 value
Nuclear Instrumentation (Ion.)	6	**S**	-8.4±1.8	≡ core 1 value
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	≡ core 1 value
Temp. Instrumentation Reflector	0			
Temp. Instrumentation Core	0			
Measurement Detectors in R2	2	**E**	-6±2	≡ core 1 value(R3)
Measurement Detectors in Cavity	1	**E**	-2±1	pure guess

Table 7.5: Critical Balance for Reference State #1 of Core G2 (upper reflector absent)

7.2.6. Core G2 (reference state #2)

BEGINNING	08.10.93
END	15.10.93
NOMINAL M:F	N/A
PEBBLE COUNT M,F	0,0
PACKING	N/A
WATER LOADING	N/A
NOTES	Empty core for PNS measurement of absorption cross section of reactor graphite

REFERENCE STATE #2 - WITH UPPER REFLECTOR

DATE	13.10.93		
CRITICAL LOADING	Empty cavity, with upper reflector		
CRITICAL HEIGHT	N/A		
ROD POSNS (CONT/AUTO)	0/1000	**M**	fully out
NOMINAL FLUX (DESK)	N/A		
HALL TEMP	20°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A		
REFL. TEMPS (Wald/Aare)	20.2/20.3	**M**	
AIR PRESSURE	968.1mbar	**M**	
HUMIDITY	45%	**M**	

CORRECTIONS PERTURBATIONS	**NUMBER PRESENT**		**TOTAL ¢ IN CORE 1**	**COMMENTS**
Control Rod Insertion (0	0			
Control Rod Channels	4	**S**	-2±1	≡ Zebra in core 1
Autorod Rest Worth	1	**S**	-7.7±0.1	≡ core 1 value
Autorod Insertion (1000)	0			
Autorod Channel	1	**S**	-0.5±0.15	≡ core 1 value
Safety+Shutdown Rod Channels	8	**S**	-24±4	≡ core 1 value
Empty Channels R2	2	**S**	-2.7±0.3	≡ core 1 value
Channels in Upper Reflector	33	**S**	-3.6±0.9	≡ core 1 value
Channels in Lower Reflector	0			graphite filled
Start-up Sources	0			
Start-up Source Penetrations	2	**S**	-1±0.1	≡ core 1 value
Pulsed Neutron Source	1	**S**	-4.3±0.3	≡ core 1 value
Nuclear Instrumentation (Ion.)	6	**S**	-8.4±1.8	≡ core 1 value
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	≡ core 1 value
Temp. Instrumentation Reflector	0			
Temp. Instrumentation Core	0			
Measurement Detectors in R2	2	**E**	-6±2	≡ core 1 value(R3)
Measurement Detectors in Cavity	1	**E**	-2±1	pure guess

Table 7.6: Critical Balance for Reference State #2 of Core G2 (upper reflector present)

7.2.7. Core 3 (reference state #1)

1ST CRITICALITY	20.10.93
UNLOADED	17.02.93
NOMINAL M:F	1:2
PEBBLE COUNT M, F	2000/4009
PACKING	Hexagonal Close ABABAB.... see [7.2]

WATER LOADING 327, 8.9mm polyethylene rods, one in every available channel and each one cut to slightly more than core height

NOTES This is not the operational loading. After this balance, 25 fuel and 12 moderator pebbles were added to provide more reasonable control rod positions

REFERENCE STATE #1

DATE	20.10.93		
CRITICAL LOADING	17 layers	**M**	
CRITICAL HEIGHT	0.843m	**M**	2x(3)+16x(4.898)cm
ROD POSNS (CONT/AUTO)	0/685	**M**	0/1000mm=fully out
NOMINAL FLUX (DESK)	$1x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	20°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A		
REFL. TEMPS (Wald/Aare)	N/A		
AIR PRESSURE	986.7mbar	**M**	
HUMIDITY	40%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (0)	0			
Control Rod Channels	4	**S**	-1.3±1	scaled from Core 1A
Autorod Rest Worth	1	**S**	-5.0±0.5	scaled from Core 1A
Autorod Insertion (685)	1	**S**	-2.0±0.5	scaled from Core 1A
Autorod Channel	1	**S**	-0.5±0.15	≡ Core 1A value
Safety+Shutdown Rod Channels	8	**C**	-16±4	scaled from Core 1A
Empty Channels R2	2	**S**	-1.8±0.3	scaled from Core 1A
Air gaps in C-Driver Holes	320	**C**	-6.8	
Channels in Upper Reflector	33	**S**	-3.6±2.0	≡ Core 1A value
Channels in Lower Reflector	1	**S**	-0.7±0.2	graphite filled
Start-up Source Penetrations	2	**S**	-1±0.1	≡ Core 1A value
Nuclear Instrumentation (Ion.)	6	**S**	-5.6±1.8	scaled from Core 1A
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	≡ Core 1A value
Total			**45.1±5¢**	
Corrected k_{eff} (β_{eff} = 0.00727)			**1.0033±0.0004**	

Table 7.7: Critical Balance for Reference State #1 of Core 3

7.2.8. Core 4.1 (reference state #1)

1ST CRITICALITY	31.03.94
UNLOADED	07.04.94
NOMINAL M:F	1:1
PEBBLE COUNT M,F	5020,5020
PACKING	Random
WATER LOADING	None
NOTES	First random loading - separate pipes used for loading of fuel and moderator pebbles. Some doubts about true randomness

REFERENCE STATE #1

DATE	31.03.94		
CRITICAL LOADING	5020,5020	**M**	
CRITICAL HEIGHT	1.58±0.01m	**M**	core surface 'flattened'
ROD POSNS (CONT/AUTO)	1530/660	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^{7}$ $n.cm^{-2}s^{-1}$		**M**
HALL TEMP	20°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	19.8/19.8/19.7°C	**M**	
AIR PRESSURE	975mbar	**M**	
HUMIDITY	44%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (1530)	4	**M,S**	-44.9±5	scaled from Core 5
Control Rod Channels	4	**S**	-2.4±1	scaled from Core 5
Autorod Rest Worth	1	**S**	-9.8±0.3	scaled from Core 1A
Autorod Insertion (660)	1	**S**	-2.1±0.3	scaled from Core 1A
Autorod Channel	1	**S**	-0.7±0.2	scaled from Core 1A
Safety+Shutdown Rod Channels	8	**C,S**	-30±10	scaled from Core 1A
Empty Channels R2	2	**S**	-3.0±0.3	scaled from Core 5
Air gaps in C-Driver Holes	320	**C**	-10.3	
Channels in Upper Reflector	34	**M**	-3.6±2.0	≡ Core 1A value
Channels in Lower Reflector	33	**M**	-23±10	≡ Core 1A value
Aluminium in Lower Reflector	12	**M**	-15.3±5	≡ Core 1A value
Start-up Sources	2	**S**	-3.6±0.1	scaled from Core 1A
Start-up Source Penetrations	2	**M**	-1±0.1	≡ Core 1A value
Pulsed Neutron Source +Missing Graphite	1	**S**	-4.7±0.3	scaled from Core 1[a]
Nuclear Instrumentation (Ion.)	7	**S**	-10.7±2.0	scaled from Core 1A
Nuclear Instrumentation (Fiss.)	2	**S**	-0.9±0.6	scaled from Core 1A
Temp. Instrumentation Reflector	3	**S**	-17.4±2.0	scaled from Core 1A
Total			**183±16¢**	
Corrected k_{eff} (β_{eff} = 0.00723)			**1.0134±0.0011**	

Table 7.8: Critical Balance for Reference State #1 of Core 4.1

7.2.9. Core 4.2 (reference state #1)

1ST CRITICALITY	15.04.94
UNLOADED	30.05.94
NOMINAL M:F	1:1
PEBBLE COUNT M,F	4940,4940
PACKING	Random
WATER LOADING	None
NOTES	Presumed better mixing of pebbles - only one pipe used

REFERENCE STATE #1

DATE	15.04.94		
CRITICAL LOADING	1940,1940	**M**	
CRITICAL HEIGHT	1.52±0.01m	**M**	core surface 'flattened'
ROD POSNS (CONT/AUTO)	1600/470	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	19.2°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	19.7/19.6/19.5°C	**M**	
AIR PRESSURE	980mbar	**E**	pure guess
HUMIDITY	50%	**E**	pure guess

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (1600)	4	**M,S**	-51.5±5	scaled from Core 5
Control Rod Channels	4	**S**	-2.4±1	scaled from Core 5
Autorod Rest Worth	1	**S**	-9.8±0.3	scaled from Core 1A
Autorod Insertion (470)	1	**S**	-3.3±0.3	scaled from Core 1A
Autorod Channel	1	**S**	-0.7±0.2	scaled from Core 1A
Safety+Shutdown Rod Channels	8	**C,S**	-30±10	scaled from Core 1A
Empty Channels R2	2	**S**	-3.0±0.3	scaled from Core 5
Air gaps in C-Driver Holes	320	**C**	-10.2	
Channels in Upper Reflector	34	**M**	-3.6±2.0	≡ Core 1A value
Channels in Lower Reflector	33	**M**	-23±10	≡ Core 1A value
Start-up Sources	2	**S**	-3.6±0.01	scaled from Core 1A
Start-up Source Penetrations	2	**M**	-1±0.1	≡ Core 1A value
Pulsed Neutron Source +Missing Graphite	1	**S**	-4.7±0.3	scaled from Core 1A
Nuclear Instrumentation (Ion.)	7	**S**	-10.7±2.0	scaled from Core 1A
Nuclear Instrumentation (Fiss.)	2	**S**	-0.9±0.6	scaled from Core 1A
Temp. Instrumentation Reflector[a]	3	**S**	-17.4±10	scaled from Core 1[a]
Total			**175.8±14¢**	
Corrected k_{eff} (β_{eff} = 0.00723)			**1.0129±0.001**	

[a] the temperature sensors in channels R2/47 and R2/15 had been pulled down to be 420mm above the lower reactor support plate but there is no measurement for this position and so the uncertainty has been increased.

Table 7.9: Critical Balance for Reference State #1 of Core 4.2

7.2.10. Core 4.3 (reference state #1)

1ST CRITICALITY	01.06.94
UNLOADED	22.06.94
NOMINAL M:F	1:1
PEBBLE COUNT M,F	4900,4900
PACKING	Random
WATER LOADING	None
NOTES	

REFERENCE STATE #1

DATE	01.06.94		
CRITICAL LOADING	4900,4900	**M**	
CRITICAL HEIGHT	1.50±0.01m	**M**	core surface 'flattened'
ROD POSNS (CONT/AUTO)	1620/500	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	21°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	21.3/21.2/21.2°C	**M**	
AIR PRESSURE	980mbar	**E**	pure guess
HUMIDITY	50%	**E**	pure guess

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (1620)	4	**M,S**	-56±5	scaled from Core 5
Control Rod Channels	4	**S**	-2.4±1	scaled from Core 5
Autorod Rest Worth	1	**S**	-9.8±0.3	scaled from Core 1A
Autorod Insertion (500)	1	**S**	-3.1±0.3	scaled from Core 1A
Autorod Channel	1	**S**	-0.7±0.2	scaled from Core 1A
Safety+Shutdown Rod Channels	8	**C,S**	-30±10	scaled from Core 1A
Empty Channels R2	2	**S**	-3.0±0.3	scaled from Core 5
Air gaps in C-Driver Holes	320	**C**	-10.3	
Channels in Upper Reflector	34	**M**	-3.6±2.0	≡ Core 1A value
Channels in Lower Reflector	33	**M**	-23±10	≡ Core 1A value
Start-up Sources	2	**S**	-3.6±0.01	scaled from Core 1A
Start-up Source Penetrations	2	**M**	-1±0.1	≡ Core 1A value
Pulsed Neutron Source +Missing graphite	1	**S**	-4.7±0.3	scaled from Core 1[a]
Nuclear Instrumentation (Ion.)	7	**S**	-10.7±2.0	scaled from Core 1A
Nuclear Instrumentation (Fiss.)	2	**S**	-0.9±0.6	scaled from Core 1A
Temp. Instrumentation Reflector[a]	3	**S**	-17.4±10	scaled from Core 1A
Total			**180±14¢**	
Corrected k_{eff} (β_{eff} = 0.00723)			**1.0132±0.001**	

[a] Same comment applies as for Core 4.2

Table 7.10: Critical Balance for Reference State #1 of Core 4.3

7.2.11. Core 5 (reference state #1)

1ST CRITICALITY	15.07.94
UNLOADED	19.04.95
NOMINAL M:F	1:2
PEBBLE COUNT M,F	2870, 5433
PACKING	Columnar Hexagonal (point-on-point)
WATER LOADING	None
NOTES	22 layers 1:2 (ABCAB.. [7.2]) , 23rd layer with F=138 and M= 223

REFERENCE STATE #1 (channels in bottom reflector open)

DATE	03.02.95		
CRITICAL LOADING	see NOTES above	**M**	
CRITICAL HEIGHT	1.38m	**M**	23x6cm
ROD POSNS (CONT/AUTO)	1815/880	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{1}$	**M**	
HALL TEMP	18°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	18.3°C	**M**	
AIR PRESSURE	995.4mbar	**M**	
HUMIDITY	37%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (1815)	4	**M**	-68.8±1	
Control Rod Channels	4	**M**	-2.2±0.2	
Autorod Rest Worth	1	**S**	-10.9±0.3	scaled from total a/rod worth
Autorod Insertion (880	1	**M**	-1.3±0.2	
Autorod Channel	1	**S**	-0.6±0.2	scaled from Core 1A
Safety+Shutdown Rod Channels	8	**C**	-28±6	scaled from Core 1A
Empty Channels R2	3	**M**	-4±1	
Air gaps in C-Driver Holes	320	**C**	-9.2	
Channels in Upper Reflector	34	**S**	-3.6±2.0	≡ Core 1 value
Channels in Lower Reflector	34	**M**	-14.8±0.2	
Start-up Source Penetrations	2	**S**	-1±0.1	≡ Core 1 value
Nuclear Instrumentation (Ion.)	6	**M**	-8.0±1.2	
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	scaled from Core 1A
Total			**153±7¢**	
Corrected k_{eff} (β_{eff} = 0.00720)			**1.0111±0.0005**	

Table 7.11: Critical Balance for Reference State #1 of Core 5

7.2.12. Core 5 (reference state #2)

1ST CRITICALITY	15.07.94		
UNLOADED	19.04.95		
NOMINAL M:F	1:2		
PEBBLE COUNT M,F	2870, 5433		
PACKING	Columnar Hexagonal (point-on-point)		
WATER LOADING	None		
NOTES	22 layers 1:2 (ABCAB.. [7.2]) , 23rd layer with F=138 and M= 223		
REFERENCE STATE #2 (channels in bottom reflector filled)			
DATE	03.02.95		
CRITICAL LOADING	see NOTES above	**M**	
CRITICAL HEIGHT	1.38m	**M**	23x6cm
ROD POSNS (CONT/AUTO)	1945/944	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	5×10^{7} $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	18°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	18.3°C	**M**	
AIR PRESSURE	995,4mbar	**M**	
HUMIDITY	37%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (1945)	4	**M**	-84.2±1	
Control Rod Channels	4	**M**	-2.2±0.2	
Autorod Rest Worth	1	**S**	-10.9±0.3	scaled from total a/rod worth
Autorod Insertion (944)	1	**M**	-0.6±0.2	
Autorod Channel	1	**S**	-0.6±0.2	scaled from Core 1A
Safety+Shutdown Rod Channels	8	**C**	-28±6	scaled from Core 1A
Empty Channels R2	3	**M**	-4±1	
Air gaps in C-Driver Holes	320	**C**	-9.2	
Channels in Upper Reflector	34	**S**	-3.6±2.0	≡ Core 1A value
Start-up Source Penetrations	2	**S**	-1±0.1	≡ Core 1A value
Nuclear Instrumentation (Ion.)	6	**M**	-8.0±1.2	
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	scaled from Core 1[a]
Total			**153±7¢**	
Corrected k_{eff} (β_{eff} = 0.00720)			**1.0111±0.0005**	

Table 7.12: Critical Balance for Reference State #2 of Core 5

7.2.13. Core 5 (reference state #3)

1ST CRITICALITY	16.11.95
UNLOADED	25.01.96
NOMINAL M:F	1:2
PEBBLE COUNT M,F	2870, 5433
PACKING	Columnar Hexagonal (point-on-point)
WATER LOADING	None
NOTES	22 layers 1:2 (ABCAB.. [7.2]) , 23rd layer with F=138 and M= 223

REFERENCE STATE #3 (channels in bottom reflector filled)

DATE	16.11.95		
CRITICAL LOADING	see NOTES above	**M**	
CRITICAL HEIGHT	1.38m	**M**	23x6cm
ROD POSNS (CONT/AUTO)	1945/830	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	19.7°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	N/A	**M**	
AIR PRESSURE	965mbar	**M**	
HUMIDITY	57%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (1945)	4	**M**	-84.2±1	
Control Rod Channels	4	**M**	-2.2±0.2	
Autorod Rest Worth	1	**S**	-10.9±0.3	scaled from total a/rod worth
Autorod Insertion (830)	1	**M**	-1.7±0.2	
Autorod Channel	1	**S**	-0.6±0.2	scaled from Core 1A
Safety+Shutdown Rod Channels	8	**C**	-28±6	scaled from Core 1A
Empty Channels R2	3	**M**	-4±1	
Air gaps in C-Driver Holes	320	**C**	-9.2	
Channels in Upper Reflector	34	**S**	-3.6±2.0	≡ Core 1A value
Start-up Source Penetrations	2	**S**	-1±0.1	≡ Core 1A value
Nuclear Instrumentation (Ion.)	6	**M**	-8.0±1.2	
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	scaled from Core 1A
Total			**154±7¢**	
Corrected k_{eff} (β_{eff} = 0.00720)			**1.0112±0.0005**	

Table 7.13: Critical Balance for Reference State #3 of Core 5

7.2.14. Core 6 (reference state #1)

1ST CRITICALITY	28.04.95
UNLOADED	15.05.95
NOMINAL M:F	1:2
PEBBLE COUNT M,F	2758, 5184
PACKING	Columnar Hexagonal (point-on-point)
WATER LOADING	654 hollow triangular CH_2 rods containing Cu wire
NOTES	An attempt was made in this core to balance the positive

reactivity effect of polyethylene by the absorbing effect of copper wire, and thus to create a configuration having the same dimensions as Core 5, but with a significant amount of simulated water ingress. 21 layers 1:2 (ABCABC.. [7.2]) , 22nd layer with F=130 and M=231

REFERENCE STATE #1

DATE	05.05.95		
CRITICAL LOADING	see NOTES above	**M**	
CRITICAL HEIGHT	1.32m	**M**	22x6cm
ROD POSNS (CONT/AUTO)	2000/225	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	20.7°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	N/A	**M**	
AIR PRESSURE	986mbar	**M**	
HUMIDITY	35%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (2000)	4	**M**	-51.7±1	
Control Rod Channels	4	**M**	-1.3±1	scaled from Core 1A
Autorod Rest Worth	1	**S**	-5.0±0.5	scaled from Core 1A
Autorod Insertion (225)	1	**S**	-4.9±0.5	scaled from Core 1A
Autorod Channel	1	**S**	-0.5±0.15	scaled from Core 1A
Safety+Shutdown Rod Channels	8	**C,S**	-16±4	scaled from Core 1A
Empty Channels R2	3	**S**	-2.7±1	scaled from Core 1A
Air gaps in C-Driver Holes	320	**C**	-6.8	
Channels in Upper Reflector	34	**S**	-3.6±2	≡ Core 1A value
Start-up Source Penetrations	2	**S**	-1±1	≡ Core 1A value
Nuclear Instrumentation (Ion.)	6	**S**	-5.6±1.8	scaled from Core 1A
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	≡ Core 1A value

Total	**100±5 ¢**
Corrected k_{eff} (β_{eff} = 0.00720)	**1.0075±0.0004**

Table 7.14: Critical Balance for Reference State #1 of Core 6

7.2.15. Core 7 (reference state #1)

1ST CRITICALITY	29.05.95
UNLOADED	23.10.95
NOMINAL M:F	1:2
PEBBLE COUNT M,F	2277, 4221
PACKING	Columnar Hexagonal (point-on-point)
WATER LOADING	654 8.3mm Polyethylene rods
NOTES	17 layers of 1:2 (ABCABC.. [7.2]), and 18th layer with F=130 and M= 231

REFERENCE STATE #1

DATE	12.10.95		
CRITICAL LOADING	see NOTES above	**M**	
CRITICAL HEIGHT	1.08m	**M**	18x6cm
ROD POSNS (CONT/AUTO)	1960/170	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	19.8°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	N/A	**M**	
AIR PRESSURE	987.6mbar	**M**	
HUMIDITY	74%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**	**TOTAL ¢**		**COMMENTS**
Control Rod Insertion (1960)	4	**M**	-48±1	
Control Rod Channels	4	**S**	-1.3±1	scaled from Core 1A
Autorod Rest Worth	1	**M,S**	-5.8±1	scaled from total
Autorod Insertion (170)	1	**M**	-0.8±0.1	measured in Core 7
Autorod Channel	1	**S**	-0.5±0.5	scaled from total
Safety+Shutdown Rod Channels	8	**C**	-16±4	≡ Core 3 value
Empty Channels R2	3	**S**	-2.7±1	scaled from Core 1A
Air gaps in C-Driver Holes	320	**C**	-6.8	≡ Core 3 value
Channels in Upper Reflector	34	**S**	-3.6±2	≡ Core 1A value
Start-up Source Penetrations	2	**S**	-1±1	≡ Core 1A value
Nuclear Instrumentation (Ion.)	6	**M**	-5.6±1.8	≡ Core 3 value
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	≡ Core 1A value
Total			**93±5 ¢**	
Corrected k_{eff} (β_{eff} = 0.00720)			**1.0067±0.0004**	

Table 7.15: Critical Balance for Reference State #1 of Core 7

7.2.16. Core 8 (reference state #1)

1ST CRITICALITY	30.01.96		
UNLOADED	14.02.96		
NOMINAL M:F	1:2		
PEBBLE COUNT M,F	2647+223, 5295+138		
PACKING	Columnar Hexagonal (point-on-point)		
WATER LOADING	every channel (654) contains a 15cm long hollow triangular rod		
NOTES	The aim of Core 8 was to produce a configuration with the same pebble loading as Core 5 but containing a substantial amount of polyethylene in the lower region of the core. 22 layers 1:2 (ABCAB.. [7.2]) , 23rd layer with F=138 and M= 223		

REFERENCE STATE #1

DATE	05.02.96		
CRITICAL LOADING	see NOTES above	**M**	
CRITICAL HEIGHT	1.38m	**M**	23x6cm
ROD POSNS (CONT/AUTO)	2500/506	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	19.2°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	19.5, 19.7	**M**	
AIR PRESSURE	976mbar	**M**	
HUMIDITY	24%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (2500)	4	**S**	-134±1	using Core 5 calibration
Control Rod Channels	4	**S**	-2.2±0.2	Core 5 value
Autorod Rest Worth	1	**S**	-10.9±0.3	Core 5 value
Autorod Insertion (506)	1	**S**	-4.0-±0.2	using Core 5 calibration
Autorod Channel	1	**S**	-0.6±0.2	Core 5 value
Safety+Shutdown Rod Channels	8	**S**	-28±6	Core 5 value
Empty Channels R2	3	**S**	-4±1	Core 5 value
BF_3 Detectors in R2	3	**M**	-8.6±0.5	to reduce reactivity
Air gaps in C-Driver Holes	320	**S**	-9.2	Core 5 value
Channels in Upper Reflector	34	**S**	-3.6±2	Core 5 value
Start-up Source Penetrations	2	**S**	-1±0.1	Core 5 value
Nuclear Instrumentation (Ion.)	6	**S**	-8.0±1.2	Core 5 value
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	Core 5 value
Total			**218±7¢**	
Corrected k_{eff} (β_{eff} = 0.00722)			**1.0160±0.0005¢**	

Table 7.16: Critical Balance for Reference State #1 of Core 8

7.2.17. Core 9 (reference state #1)

1ST CRITICALITY	22.02.96
UNLOADED	08.05.96
NOMINAL M:F	1:1
PACKING	Columnar Hexagonal (point-on-point)
WATER LOADING	None
NOTES	with 27 layers loaded the system was just critical with all control rods fully withdrawn and the channels in the lower axial reflector filled

REFERENCE STATE #1

DATE	22.02.96		
CRITICAL LOADING	27 layers	**M**	
CRITICAL HEIGHT	1.62m	**M**	27x6cm
ROD POSNS (CONT/AUTO)	0/258	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	$5x10^7$ $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	19.6°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	N/A	**M**	
AIR PRESSURE	980mbar	**M**	
HUMIDITY	25%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**	**TOTAL ¢**		**COMMENTS**
Control Rod Insertion (0)	4	**M**	0	no control rod insertion
Control Rod Channels	4	**S**	-2.5±0.3	scaled from Core 5
Autorod Rest Worth	1	**S**	-12.5±0.5	scaled from Core 5
Autorod Insertion (258)	1	**S**	-7.5±0.5	scaled from Core 5
Autorod Channel	1	**S**	-0.7±0.3	scaled from Core 5
Safety+Shutdown Rod Channels	8	**S**	-32±8	scaled from Core 5
Empty Channels R2	3	**S**	-5±1	scaled from Core 5
Air gaps in C-Driver Holes	320	**S**	-10.5	scaled from Core 5
Channels in Upper Reflector	34			no estimate
Start-up Sources	2	**M**	-4±1	
Start-up Source Penetrations	2	**S**	-1±0.2	Core 5 value
Nuclear Instrumentation (Ion.)	6	**S**	-9.0±1.5	scaled from Core 5
Nuclear Instrumentation (Fiss.)	2	**S**	-1.0±0.7	scaled from Core 5
Channels in Lower Axial Reflector	0			channels filled
Total			**86±9¢**	
Corrected k_{eff} (β_{eff} = 0.00720)			**1.0062±0.0007**	

Table 7.17: Critical Balance for Reference State #1 of Core 9

7.2.18. Core 9 (reference state #2)

1ST CRITICALITY	22.02.96
UNLOADED	08.05.96
NOMINAL M:F	1:1
PACKING	Columnar Hexagonal (point-on-point)
WATER LOADING	None
NOTES	27 layers + 1 pure moderator

REFERENCE STATE #2

DATE	23.02.96		
CRITICAL LOADING	27 + 1 layers	**M**	
CRITICAL HEIGHT	1.68m	**M**	28x6cm
ROD POSNS (CONT/AUTO)	1620/25	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	5×10^{7} $n.cm^{-2}s^{-1}$	**M**	
HALL TEMP	19.2°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	N/A	**M**	
AIR PRESSURE	981mbar	**M**	
HUMIDITY	25%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**		**TOTAL ¢**	**COMMENTS**
Control Rod Insertion (1620)	4	**M**	-70.4±1.0	calibrated via stable period
Control Rod Channels	4	**S**	-2.5±0.3	scaled from Core 5
Autorod Rest Worth	1	**S**	-12.5±0.5	scaled from Core 5
Autorod Insertion (25)	1	**S**	-10.0±0.5	scaled from Core 5
Autorod Channel	1	**S**	-0.7±0.3	scaled from Core 5
Safety+Shutdown Rod Channels	8	**S**	-32±8	scaled from Core 5
Empty Channels R2	3	**S**	-5±1	scaled from Core 5
Air gaps in C-Driver Holes	320	**S**	-10.5	scaled from Core 5
Channels in Upper Reflector	34			no estimate
Start-up Sources	2	**M**	-4±1	
Start-up Source Penetrations	2	**S**	-1±0.2	Core 5 value
Nuclear Instrumentation (Ion.)	6	**S**	-9.0±1.5	scaled from Core 5
Nuclear Instrumentation (Fiss.)	2	**S**	-1.0±0.7	scaled from Core 5
Channels in Lower Axial Reflector	0			channels filled
Total			**159±10¢**	
Corrected k_{eff} (β_{eff} = 0.00720)			**1.0142±0.0007**	

Table 7.18: Critical Balance for Reference State #2 of Core 9

7.2.19. Core 10 (reference state #1)

1ST CRITICALITY	10.05.96
UNLOADED	10.96
NOMINAL M:F	1:1
PACKING	Columnar Hexagonal (point-on-point)
WATER LOADING	654 6.5mm rods having a length of 1450mm
NOTES	Core 10 is a repeat of the Core 9 geometry with the addition of 654, 6.5mm diameter polyethylene rods and a correspondingly reduced core height

REFERENCE STATE #1

DATE	5.07.96		
CRITICAL LOADING	24 layers	**M**	
CRITICAL HEIGHT	1.44m	**M**	24x6cm
ROD POSNS (CONT/AUTO)	1540/15	**M**	0/1000mm = fully out
NOMINAL FLUX (DESK)	5×10^7 n.cm^{-2}s^{-1}	**M**	
HALL TEMP	21.7°C	**M**	
CORE TEMPS (Zentrum/Rand)	N/A	**M**	
REF. TEMPS (Wald/Aare/Brugg)	N/A	**M**	
AIR PRESSURE	975.9mbar	**M**	
HUMIDITY	74%	**M**	

REACTIVITY CORRECTIONS FOR CRITICAL LOADINGS	**NUMBER PRESENT**	**TOTAL ¢**		**COMMENTS**
Control Rod Insertion (1540)	4	**M**	-36.8±1	measured Core 10
Control Rod Channels	4	**S**	-2.0±0.2	Core 1A value
Autorod Rest Worth	1	**S**	-7.7±0.5	Core 1A value
Autorod Insertion (15)	1	**M**	-7±0.4	measured in Core 10
Autorod Channel	1	**S**	-0.5±0.3	Core 1A value
Safety+Shutdown Rod Channels	8	**C,S**	-24±6	Core 1A value
Empty Channels R2	3	**S**	-4±1	scaled from Core 1A
Air gaps in C-Driver Holes	320	**C,S**	-8.3	Core 1A value
Channels in Upper Reflector	34	**S**	-3.6±2.0	Core 1A value
Start-up Source Penetrations	2	**S**	-1±0.2	Core 1A value
Nuclear Instrumentation (Ion.)	6	**S**	-8.4±1.2	
Nuclear Instrumentation (Fiss.)	2	**S**	-0.8±0.6	Core 1A

Total	**104±7¢**
Corrected k_{eff} (β_{eff} = 0.00720)	**1.0075±0.0001**

Table 7.19: Critical Balance for Reference State #1 of Core 10

7.3. INTEGRAL AND DIFFERENTIAL CONTROL ROD WORTHS

These parameters were measured, with the stable period technique (Section 6.2.2.), for every configuration. Additional independent checks were also made in some cases using a PNS technique. Tables 7.20 and 7.21, as well as Fig. 7.1 summarize the results for the integral control-rod worths for Cores 1 to 5. Other results for Cores 5, 7, 9 and 10 are reported in section 8.3.1.

	CORE				
	1 (ZEBRA)	1 (REST)*	1A	2	3
β_{eff}	0.00723	0.00723	0.00723	0.00723	0.00727
ROD 1	0.312±0.002	0.669±0.005	0.288±0.002	0.258±0.001	0.208±0.002
ROD 2	0.302±0.002	0.666±0.005	0.277±0.002	0.247±0.001	0.200±0.002
ROD 3	0.295±0.002	0.616±0.005	0.277±0.002	0.247±0.001	0.203±0.002
ROD 4	0.310±0.002	0.687±0.005	0.289±0.002	0.258±0.001	0.210±0.002
BANK	1.220±0.004	2.64±0.01	1.13±0.004	1.010±0.002	0.821±0.004

* Measurement of rest worths of ZEBRA control rods

Table 7.20: Summary of Integral Control Rod Worth Measurements in Cores 1-3 (All values in $)

	CORE				
	4.1	4.2	4.3	4.3 (-A/R)+	5
β_{eff}	0.00723	0.00723	0.00723	0.00723	0.00720
ROD 1	0.392±0.004	0.407±0.004	0.366±0.002	0.372±0.002	0.341±0.002
ROD 2	0.339±0.004	0.345±0.004	0.378±0.002	0.391±0.002	0.337±0.002
ROD 3	0.344±0.004	0.330±0.004	0.373±0.002	0.390±0.002	0.333±0.002
ROD 4	0.398±0.004	0.383±0.004	0.370±0.002	0.379±0.002	0.335±0.002
BANK	1.465±0.008	1.465±0.008	1.487±0.004	1.532±0.004	1.346±0.004

\+ Measurements repeated with auto-rod removed from system

Table 7.21: Summary of Integral Control Rod Worth Measurements in Cores 4-5 (All values in $)

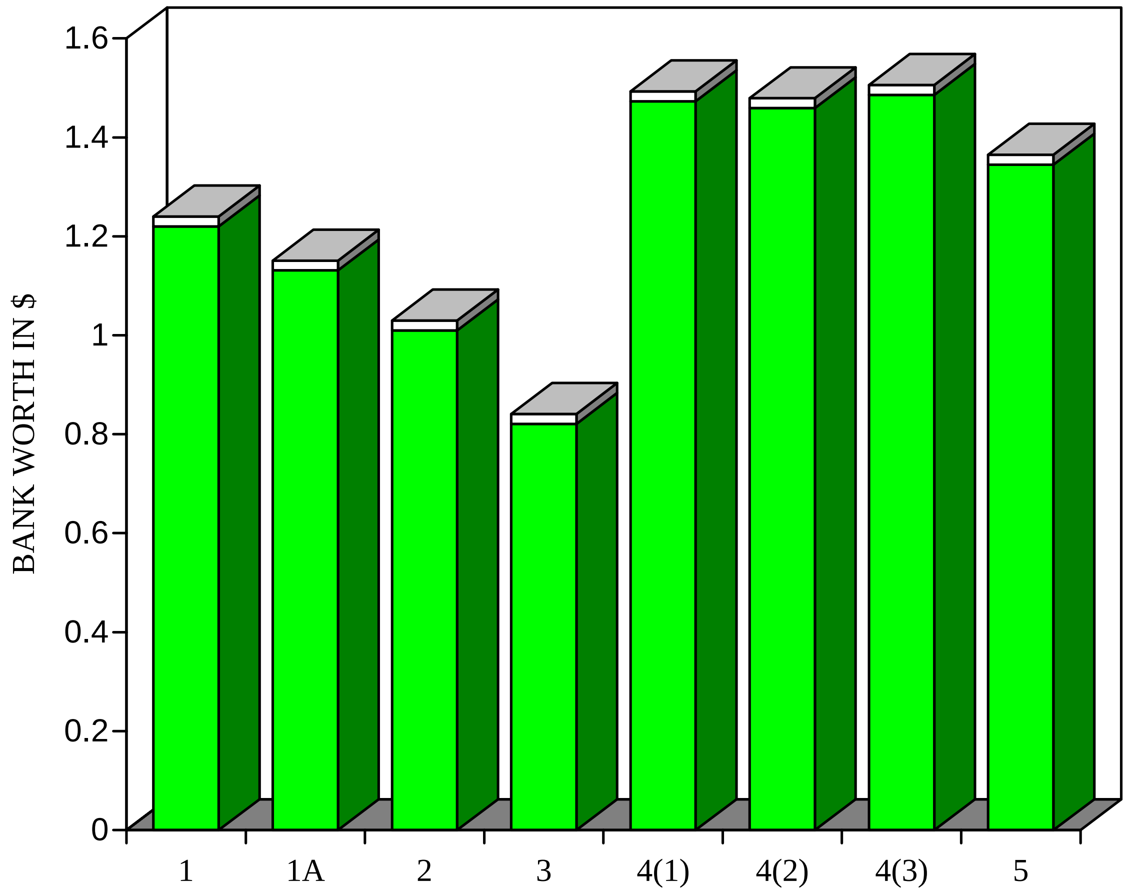

Fig. 7.1: **Comparison of Integral Control Rod Worths in Cores 1-5 (uppermost layer represents 1σ uncertainties)**

The following observations are worthy of mention:

Although quantitative conclusions are difficult to draw, since the core height of each configuration is different, it is qualitatively seen that the rod bank worths in Cores 1A, 2 and 3 generally decrease with increasing core moderation, as would be expected. It might also be expected that Cores 4 (1,2,3), by virtue of their higher M:F ratios, would also demonstrate a low rod-bank worth with respect to Core 1A. However, the effect of increased core moderation is evidently offset by increased leakage (lower packing density) and increased core height in addition to the fact that the effective core radius is somewhat larger in Core 4, due to the absence of the graphite packing pieces required for the support of the deterministic cores. Comparing now Core 5 with Cores 4(1,2,3) it is somewhat surprising to note that the bank worth is lower in Core 5, despite the reduced core moderation, smaller core height and lower packing density. It would seem that the effect of slightly increasing the effective core radius in the stochastic loadings plays a significant role. Finally, returning to Cores 4 (1,2,3), it is seen that the control-bank worths show no significant stochastic effects.

It can also be seen in Tables 7.20 and 7.21 that a small but significant common trend is evident in which rods 2 and 3 are seen to have around 4% lower worths than rods 1 and 4. Early suspicions that the effect was due to material inconsistencies between the individual rods were rejected on the grounds that the trend is also seen in the ZEBRA rod worths in Core 1. A second possibility was that this effect was due to irregularities in the outer surface of the pebble-bed and hence in the effective core-reflector boundary (see previous section). However, the results of a further set of measurements in Core 1A, in which the autorod had been removed from the system, showed the trend to have disappeared. This result implies very strongly that the observed asymmetry in the worths of the control rods is caused by the shadowing effect of the relatively low-worth autorod. Similar, but slightly smaller, effects have also been observed in the azimuthal variation of shutdown rod worths and in the azimuthal variation of thermal neutron reaction-rates measured in the radial reflector.

The main objective of the Core 4 configurations was to investigate the variation in the critical loadings and rod worths of nominally identical configurations; both as a result of variations in packing densities and of possible "clustering" of moderator or fuel pebbles. Despite the relatively small system dimensions it was anticipated that, due to the large number of pebbles present (~10000), any such stochastic effects would be averaged out over the whole system and not show any significant overall effect. In fact, the critical loadings of the three cores lay in a range of some 2.5% - a variation which was plausibly explained by corresponding variations in core height indicating that the configurations containing more pebbles were also correspondingly less densely packed. This range reduces to some 1% if the Core 4(1) result is ignored. This may be justifiable since some questions have been raised as to the randomness of the loading procedure adopted in this first core. As was seen in Fig. 7.1 the control-rod bank worths in Cores 4(1,2,3) did not vary significantly from core to core. A different picture, however, is seen in Fig. 7.2 below in which the azimuthal variation of control-rod worths is plotted for the three cores.

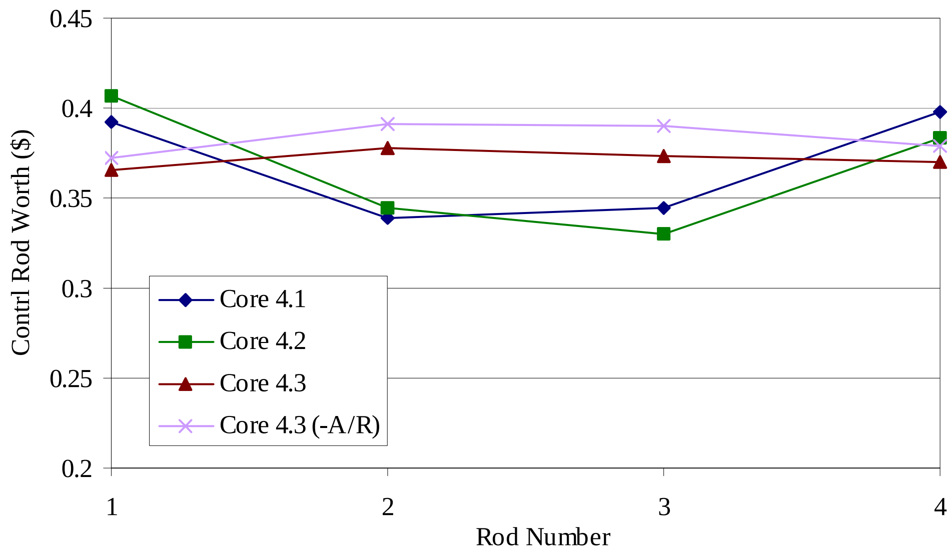

Fig. 7.2: Azimuthal Variation of Control Rod Worths in Cores 4(1,2,3)

It is immediately apparent that a very large azimuthal trend is seen, which is configuration-dependent. For example, rod 3 in Core 4.2 has a value 20% less than that of rod 1, whereas in Core 4.3 its worth is some 2% greater. The Core 4.3 results were also repeated with the autorod having been removed from the system. It is seen in Fig. 7.2 that a measurable effect is observed, but that this serves only to increase azimuthal asymmetry.

Tables 7.22 to 7.26 and Figs. 7.3 and 7.4 contain the results of measurements of differential worths of individual control rods in cores 1 to 5.

ROD RANGE IN mm+	REACTIVITY IN DOLLARS ($\times10^{-2}$)			
	ROD I	ROD II	ROD III	ROD IV
0-20	0.50±0.05	0.56±0.01	0.43±0.02	0.53±0.02
20-40	1.77±0.01	1.81±0.01	1.76±0.02	1.93±0.02
40-60	3.01±0.02	2.97±0.02	2.84±0.02	3.00±0.02
60-80	3.25±0.02	3.21±0.02	3.17±0.01	3.33±0.02
80-100	3.50±0.02	3.29±0.02	3.28±0.01	3.45±0.02
100-120	3.70±0.01	3.60±0.02	3.41±0.02	3.70±0.02
120-140	3.77±0.02	3.70±0.02	3.63±0.01	3.84±0.01
140-160	4.00±0.03	3.84±0.02	3.74±0.01	3.94±0.01
160-180	4.01±0.01	3.92±0.01	3.80±0.02	4.07±0.01
180-200	3.69±0.01	3.31±0.01	3.46±0.02	3.30±0.02
SUM	31.20±0.07	30.21±0.07	29.52±0.07	31.09±0.07

\+ 200mm = fully withdrawn

Table 7.22: Differential Worth Measurements of the ZEBRA Rods in Core 1 (β_{eff} = 0.007231)

ROD RANGE IN mm+	REACTIVITY IN DOLLARS ($\times10^{-2}$) ROD 1	ROD RANGE IN MM+	REACTIVITY IN DOLLARS ($\times10^{-2}$) ROD 4
2529-2399	2.04±0.02	2500-2400	1.57±0.02
2399-2299	2.10±0.02	2400-2300	2.04±0.02
2299-2200	2.47±0.02	2300-2200	2.38±0.02
2200-2100	2.71±0.02*	2200-2100	2.77±0.02
2100-2000	2.79±0.02	2100-2000	2.83±0.02
2000-1900	2.75±0.02	2000-1900	2.71±0.02
1900-1800	2.49±0.02	1900-1800	2.53±0.02
1800-1650	3.17±0.03	1800-1650	3.23±0.03
1650-1450	2.97±0.03	1650-1450	3.03±0.03
1450-1150	2.59±0.02	1450-0	5.83±0.02
1150-700	2.16±0.02		
700-6	0.92±0.02		
SUM⇒	29.1±0.1	SUM⇒	28.9±0.1

\+ 2500mm = fully inserted
* This value was originally measured to be 2.63, but later repeats indicated a value of 2.71

Table 7.23: Differential Worth Measurement of Control Rods 1 and 4 in Core 1A (β_{eff} = 0.007231)

ROD RANGE IN mm	REACTIVITY IN DOLLARS ($\times 10^{-2}$)	REACTIVITY IN DOLLARS ($\times 10^{-2}$)
	ROD 1	ROD 3
2500-2400	1.75±0.01	1.66±0.01
2400-2300	2.23±0.02	2.07±0.02
2300-2200	2.57±0.02	2.46±0.02
2200-2100	2.80±0.01	2.66±0.03
2100-2000	2.90±0.01	2.71±0.02
2000-1900	2.79±0.02	2.64±0.03
1900-1800	2.47±0.02	2.48±0.02
1800-1650	3.10±0.01	2.97±0.02
1650-1450	2.71±0.02	2.61±0.02
1450-1150	1.73±0.01	1.70±0.03
1150-700	0.49±0.01	0.51±0.02
700-0	0.03±0.02	0.05±0.01
SUM⇒	25.57±0.06	24.52±0.08

Table 7.24: Differential Worth Measurement of Control Rods 1 and 3 in Core 2 (β_{eff} = 0.00723)

ROD RANGE IN mm	REACTIVITY IN DOLLARS ($\times 10^{-2}$)
	ROD 1
2500-2400	1.43±0.01
2400-2300	1.78±0.02
2300-2200	2.02±0.02
2200-2100	2.19±0.02
2100-2000	2.10±0.02
2000-1900	1.95±0.02
1900-1800	1.68±0.02
1800-1650	1.89±0.02
1650-1450	1.75±0.02
1450-1150	1.70±0.02
1150-0	2.30±0.02
SUM⇒	20.79±0.07

Table 7.25: Differential Worth Measurements of Control Rod 1 in Core 3 (β_{eff} = 0.00727)

ROD RANGE IN mm	REACTIVITY IN DOLLARS ($\times 10^{-2}$) ROD 1
2500-2400	1.41±0.02
2400-2300	1.80±0.02
2300-2200	2.26±0.02
2200-2100	2.49±0.02
2100-2000	2.82±0.02
2000-1900	2.89±0.02
1900-1800	2.99±0.02
1800-1700	2.77±0.02
1700-1600	2.56±0.02
1600-1450	3.38±0.02
1450-1250	3.33±0.03
1250-950	2.88±0.02
950-0	2.48±0.02
SUM⇒	34.06±0.07

Table 7.26: Differential Worth Measurement of Control Rod 1 in Core 5 (β_{eff} = 0.00720)

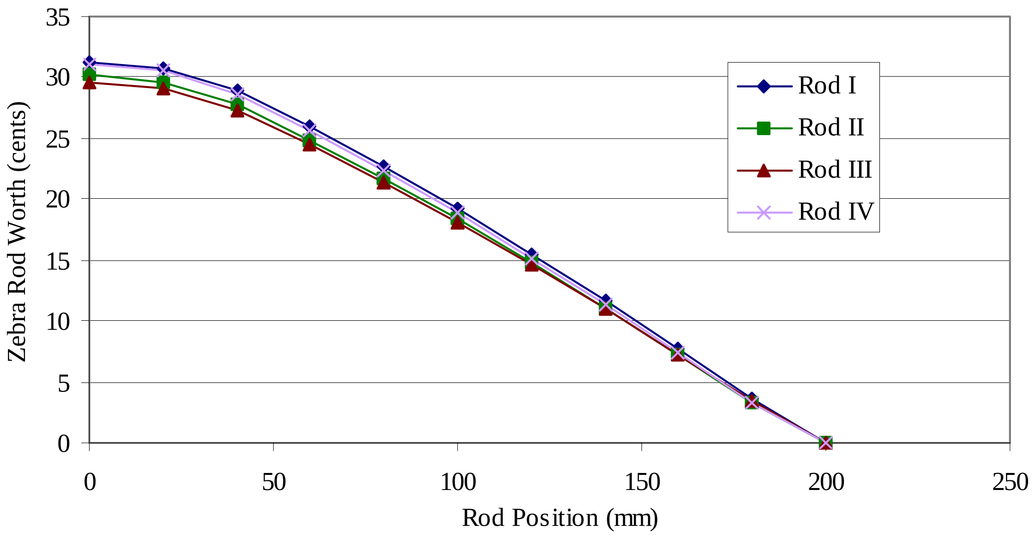

Fig. 7.3: Differential ZEBRA Rod worths in Core 1

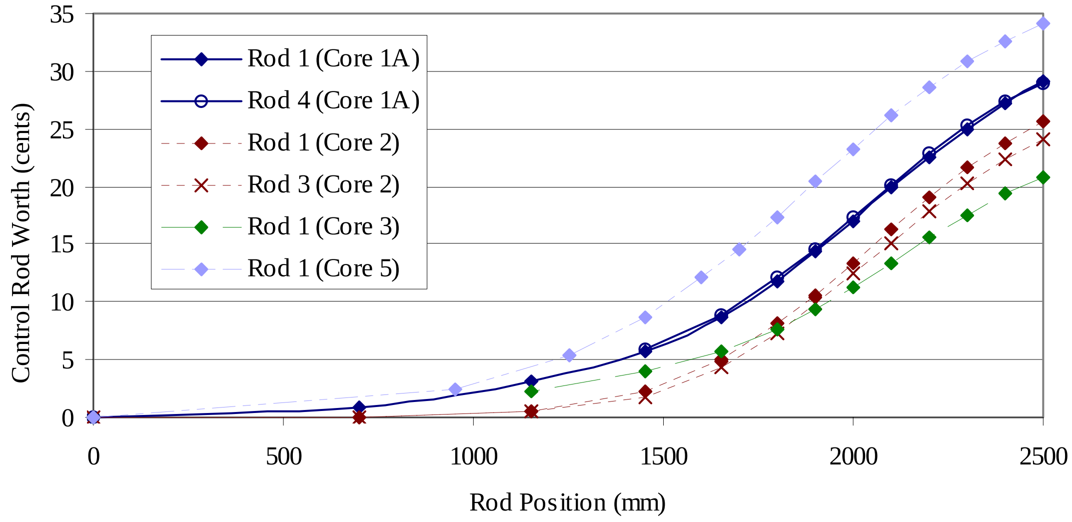

Fig. 7.4: Differential Control Rod worths in Cores 1A, 2, 3 and 5

The following observations can be made concerning the differential control-rod worths:

The agreement between the integral worths in Tables 7.20 and 7.21 and the summed differential curves in Tables 7.22 to 7.26 is generally excellent. This result confirms that control rod interaction effects are negligible and further that the claimed measurement uncertainties are realistic.

The ZEBRA rod curves clearly have very different forms than the conventional control rods, but are still far from linear.

The curves of rods 1 and 4 in Core 1A (Fig. 7.4 and Table 7.23) show great similarity.

The worth curves tend to peak in the center of the fuelled region.

7.4. SHUTDOWN ROD WORTHS

7.4.1. Epithermal Measurements

The combination of an undermoderated core and strongly interacting reflector zones renders accurate subcriticality measurements particularly difficult in a small-sized pebble-bed HTR. This results from the strong spatial effects in such systems, necessitating the application of relatively large calculated correction factors in the interpretation of both IK and PNS measurements (see sections 6.2.1 and 6.2.2).

In order to reduce the dependence of conventional experimental techniques on such calculational results, new techniques based on the use of epithermal neutron detectors were developed and applied in the HTR-PROTEUS programme [7.6 and 7.7]. The sensitivity to calculated correction factors and/or kinetic parameters was shown to be considerably reduced for both types of measurements when epithermal, rather than thermal, detectors are employed.

7.4.2. Shutdown Rod Worths in Cores 5, 7, 9, and 10

In Cores 5, 7, 9 and 10 different combinations of shutdown rods were measured applying in each case a variety of experimental methods. These ranged, from conventional (thermal) and newly developed (epithermal) IK and PNS techniques, using both Simmons-King and Gozani theories to analyze the PNS measurements. While statistical errors were generally smaller in the experiments using thermal detectors, it was the epithermal measurements which, due to their lower sensitivity to calculated correction factors, yielded the more reliable results. Nevertheless, the parallel application of several different independent techniques in each experimental configuration did allow a broad check on systematic errors.

In tables 7.27 to 7.30 are reported the results of the different measurement techniques for various combinations of shutdown rods in Cores 5, 7, 9 and 10, respectively. All the spatial dependent results (i.e. IK measurements and PNS measurements using Gozani theory) were corrected as explained in section 6.2.1.1.2 and 6.2.2.1.1. The uncertainties correspond to the 1σ statistical error for cases where only one measurement was made and in the other cases the uncertainties are standard deviations on the average values. Also indicated, in each case, is a weighted-average reactivity worth value $\overline{\$}$, calculated with:

$$\overline{\$} = \sum_j A_j \$_j \tag{7.1}$$

where $\$_j$ are the reactivities in dollar and the coefficients A_j are obtained from:

$$A_j = \frac{\frac{n_j}{\sigma_j}}{\sum_i \frac{n_i}{\sigma_i}} \tag{7.2}$$

n_j being the number of measurements of type j carried out in a given configuration and σ_j being the corresponding uncertainty (generally, the standard deviation or the 1σ statistical error when only one measurement was made). The uncertainty on the weighted average was calculated with:

$$\sigma = \left(\sum_j \left(A_j \sigma_j \right)^2 \right)^{\frac{1}{2}} \tag{7.3}$$

It may be noted that the inverse of the squared uncertainty was not used as weighting factor in the averaging, since this would have been particularly unrealistic in the present situation. For example, such weighting would have given much more importance to a result based on, say, two measurements with values lying fortuitously close to each other, than to another deduced from a large number of measurements with a reasonable spread among the individual values.

Rods inserted	5	5-6	5-6-7	5-6-7-8
Thermal Simmons-King PNS Measurement ($)	3.62 ± 0.06 [1]	7.54 ± 0.17 [1]	11.39 ± 0.32 [1]	15.03 ± 0.51 [7]
Thermal Gozani PNS measurement ($)	3.58 ± 0.07 [1]	7.65 ± 0.16 [1]	11.73 ± 0.25 [1]	15.15 ± 0.24 [6]
Epithermal Gozani PNS measurement ($)	3.48 ± 0.09 [1]	7.24 ± 0.21 [1]	11.05 ± 0.42 [1]	15.15 ± 0.23 [7]
Weighted average ($)	3.57 ± 0.04	7.50 ± 0.10	11.45 ± 0.18	15.13 ± 0.17

Table 7.27: Reactivity Worth Measurements for Various Combinations of the Shutdown Rods in Core 5 (The values in square brackets represent the number of measurements made for a given configuration)

Rods inserted	5-6-7-8
Thermal Simmons-King PNS Measurement ($)	9.21 ± 0.10 [5]
Thermal Gozani PNS measurement ($)	10.36 ± 0.40 [5]
Epithermal Gozani PNS measurement ($)	9.98 ± 0.16 [7]
Weighted average ($)	9.66 ± 0.09

Table 7.28: Reactivity Worth Measurements for Various Combinations of the Shutdown Rods in Core 7 (The values in square brackets represent the number of measurements made for a given configuration)

Rods inserted	6	5-6	5-6-7	5-6-7-8
Thermal IK measurement ($)	3.73 ± 0.02 [2]	7.71 ± 0.09 [2]	11.69 ± 0.23 [2]	16.00 ± 0.41 [2]
Epithermal IK measurement ($)	3.63 ± 0.08 [1]	-	11.36 ± 0.20 [2]	-
Thermal Simmons-King PNS Measurement ($)	3.69 ± 0.06 [3]	7.74 ± 0.19 [5]	11.63 ± 0.33 [3]	15.63 ± 0.53 [6]
Thermal Gozani PNS measurement ($)	3.77 ± 0.01 [2]	7.88 ± 0.05 [3]	12.25 ± 0.11 [2]	16.39 ± 0.36 [4]
Epithermal Gozani PNS measurement ($)	3.73 ± 0.08 [4]	7.85 ± 0.14 [5]	11.85 ± 0.24 [4]	16.43 ± 0.45 [8]
Weighted average ($)	3.74 ± 0.01	7.82 ± 0.06	11.83 ± 0.10	16.17 ± 0.24

Table 7.29: Reactivity Worth Measurements for Various Combinations of the Shutdown Rods in Core 9 (The values in square brackets represent the number of measurements made for a given configuration)

Rods inserted	5	5-6	5-6-7	5-6-7-8
Thermal IK measurement ($)	2.75 ± 0.02 [1]	6.17 ± 0.07 [2]	9.38 ± 0.60 [3]	12.99 ± 1.3 [2]
Epithermal IK measurement ($)	2.63 ± 0.06 [1]	5.56 ± 0.10 [1]	8.61 ± 0.34 [6]	11.80 ± 0.19 [3]
Thermal Simmons-King PNS Measurement ($)	2.65 ± 0.05 [4]	5.48 ± 0.12 [4]	8.42 ± 0.33 [4]	11.42 ± 0.32 [8]
Thermal Gozani PNS measurement ($)	2.69 ± 0.06 [4]	5.72 ± 0.30 [4]	9.38 ± 0.15 [4]	12.12 ± 0.37 [8]
Epithermal Gozani PNS measurement ($)	2.59 ± 0.05 [1]	5.47 ± 0.16 [1]	8.64 ± 0.18 [1]	11.71 ± 0.28 [9]
Weighted average[1] ($)	2.66 ± 0.03	5.54 ± 0.09	8.91 ± 0.13	11.74 ± 0.16

[1] The results obtained from the thermal IK measurements were not considered while deducing the weighted-average values. The large discrepancy as regard to the other techniques was probably due to an inadequacy of the Core 10 r-Θ TWODANT model used for the calculation of the correction factors.

Table 7.30: Reactivity Worth Measurements for Various Combinations of the Shutdown Rods in Core 10 (The values in square brackets represent the number of measurements made for a given configuration)

It can be seen that, except for Core 10, there is a relatively good agreement between the different methods used to measure the reactivity. In Core 10, the results obtained with the thermal IK technique generally show large discrepancies with respect to the others. This is probably due to an inadequacy of the r-Θ model used for the calculation of the correction factor. On the other hand, it can be seen that the epithermal IK measurements are very consistent, underlining that the use of epithermal detectors greatly reduces the dependence upon calculations. The same r-Θ model was used to correct the epithermal measurements but as the corrections were much smaller than for the thermal measurements the epithermal results were not much affected by the inadequacy of the model.

It can be seen in Tables 7.27 to 7.30 that, in all cores, the individual rod worth increases slightly with the number of rods inserted. The reactivity worth of the four shutdown rods inserted is always bigger than four times the reactivity worth of an individual rod. This arises from positive shadowing effects as reported for other HTR-PROTEUS measurements [7.8].

Also indicated quite clearly is the decrease in shutdown rod worths in going from the Core 5 to Core 7 and from the Core 9 to Core 10 configurations, in consistency with the expected effect of the water ingress simulation in Cores 7 and 10.

7.5. KINETIC PARAMETER (β_{eff}/Λ)

In this section the results of the kinetic parameter measurements carried out in Cores 1, 2, 3 and 5 are presented. Tables 7.31 to 7.34 show the prompt neutron decay α_0 obtained with the PNS technique for different subcritical states.

Zebra rod withdrawal	Reactivity via stable period ($)	Start channel for fit	End channel for fit	$\alpha_0(s^{-1})$ Det. 1 Det. 2
0mm	-0.90±0.01	51	300	-9.32±0.026 -9.36±0.029
50mm	-0.751±0.005	51	300	-8.56±0.027 -8.57±0.032
70mm	-0.628±0.005	51	350	-7.91±0.029 -7.97±0.031
90mm	-0.493±0.005	51	350	-7.38±0.035 -7.37±0.028
110mm	-0.353±0.003	51	350	-6.71±0.032 -6.78±0.027
130mm	-0.208±0.002	51	350	-6.09±0.030 -6.09±0.027
140mm	-0.132±0.002	61	300	-5.77±0.032 -5.78±0.034
157mm	0.0			α_C

Table 7.31: Results of α_0 Measurements in Core 1.

Control rod insertion	Reactivity via stable period ($)	Start channel for fit	End channel for fit	$\alpha_0(s^{-1})$ Det. 1 Det. 2
2500mm	-0.878±0.01	51	350	-8.42±0.042 -8.42±0.045
2300mm	-0.724±0.005	46	350	-7.77±0.030 -7.77±0.035
2100mm	-0.511±0.005	46	350	-6.82±0.033 -6.81±0.031
1900mm	-0.292±0.005	41	350	-5.93±0.035 -5.89±0.035
1530mm	0.0			α_C

Table 7.32: Results of α_0 Measurements in Core 2.

Control rod insertion	Reactivity via stable period ($)	Start channel for fit	End channel for fit	$\alpha_0(s^{-1})$ Det. 1 Det. 2 Det. 3	$\bar{\alpha}_0(s^{-1})$
2500mm	-0.712±0.005	41	375	-8.77±0.06 -8.79±0.06 -8.76±0.04	-8.77±0.03
2200mm	-0.505±0.005	41	375	-7.75±0.05 -7.73±0.11 -7.70±0.03	-7.73±0.04
1900mm	-0.262±0.002	51	375	-6.59±0.05 -6.52±0.05 -6.47±0.04	-6.53±0.03
1700mm	-0.143±0.001	61	375	-5.93±0.06 -5.93±0.06 -5.91±0.04	-5.92±0.03
1240mm	0.0			α_C	

Table 7.33: Results of α_0 Measurements in Core 3.

Control rod insertion	Reactivity via stable period ($)	Start channel for fit	End channel for fit	$\alpha_0(s^{-1})$ Det. 1 Det. 2 Det. 3	$\bar{\alpha}_0(s^{-1})$
2500mm	-0.941±0.005	71	375	-7.79±0.03 -7.69±0.02 -7.74±0.04	-7.74±0.03
2300mm	-0.810±0.004	71	375	-7.24±0.03 -7.20±0.02 -7.23±0.03	-7.22±0.03
2100mm	-0.616±0.003	96	375	-6.52±0.03 -6.45±0.02 -6.51±0.04	-6.49±0.03
1900mm	-0.384±0.002	66	375	-5.63±0.03 -5.60±0.02 -5.67±0.03	-5.63±0.03
1700mm	-0.151±0.001	66	375	-4.86±0.04 -4.84±0.03 -4.86±0.05	-4.853±0.03
1553mm	0.0			α_C	

Table 7.34: Results of α_0 Measurements in Core 5.

A plot of the value of α_0 derived from each fit against start channel, and for each detector, is shown in Fig. 7.5 for a typical measurement in Core 3. It shows a plateau region in which, within experimental uncertainties, the value of α_0 is independent of start channel and detector position.

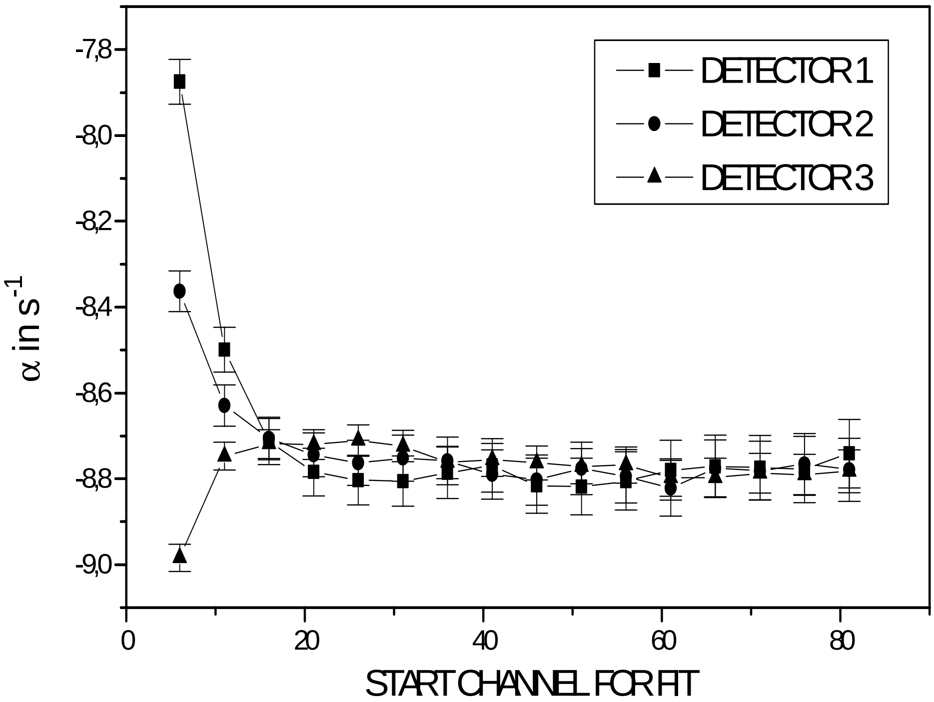

Fig. 7.5: A Tornado Plot Representation of Three Detector Responses in Core 3

These measured values of α_0 from the tables are plotted, as a function of reactivity, for Cores 1 to 5 in Figs 7.6 to 7.9. Also shown in the figures are fits to the data of the form recommended in Section 6.3.2 along with a linear fit for comparison. The extrapolations to $\rho = 0$ for both cases are given in Table 7.35 along with the calculated factors f_C and the corresponding values of β_C/Λ_C (see section 6.4).

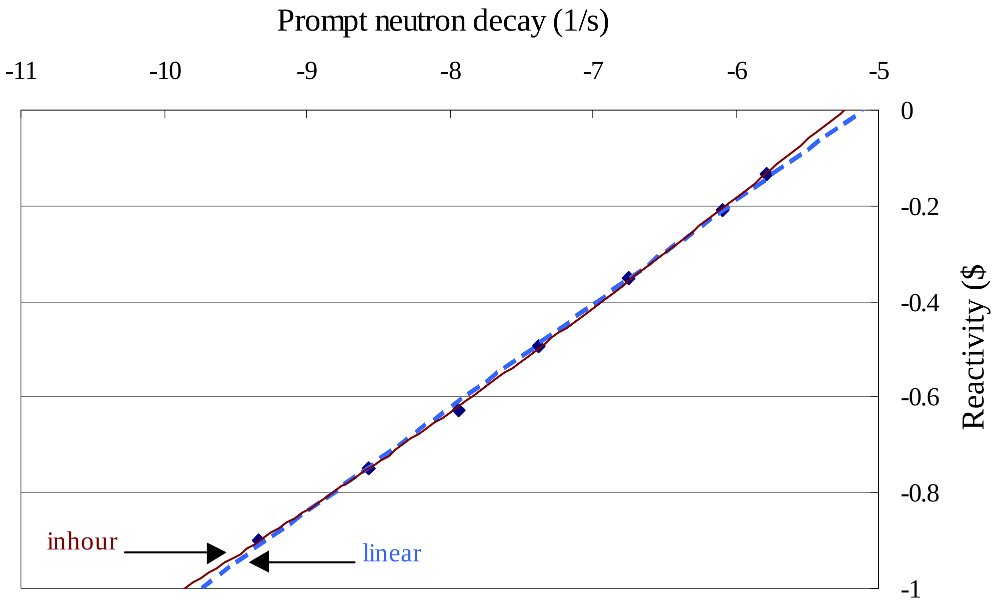

Fig. 7.6: Prompt neutron decay as function of the reactivity in Core 1

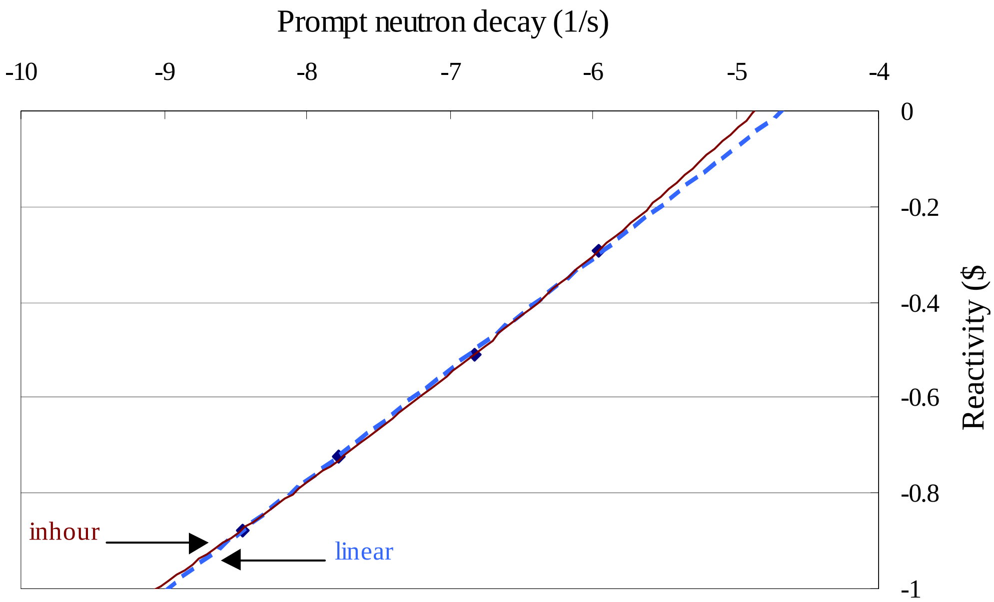

Fig. 7.7: Prompt neutron decay as function of the reactivity in Core 2

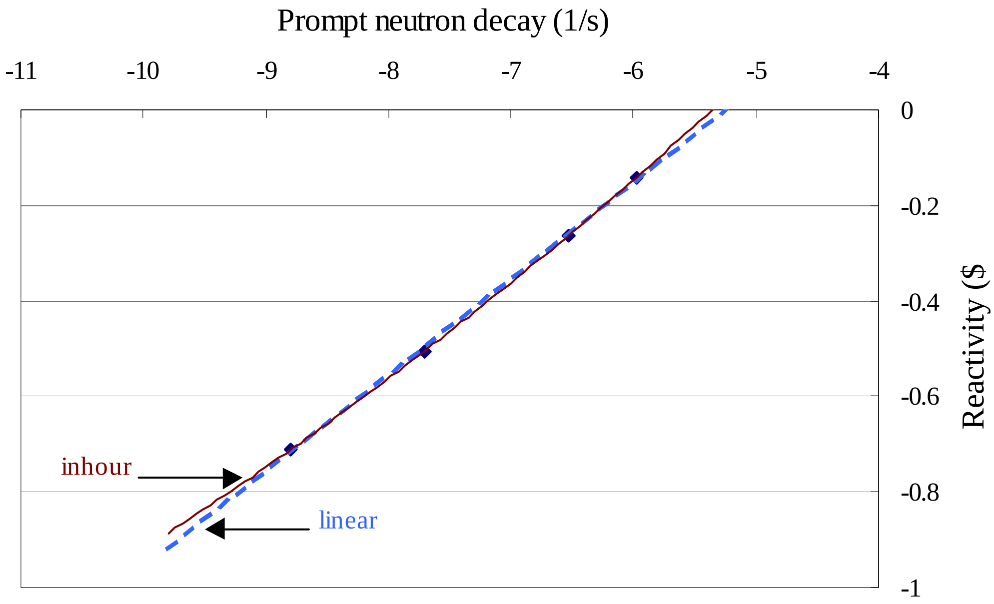

Fig. 7.8: Prompt neutron decay as function of the reactivity in Core 3

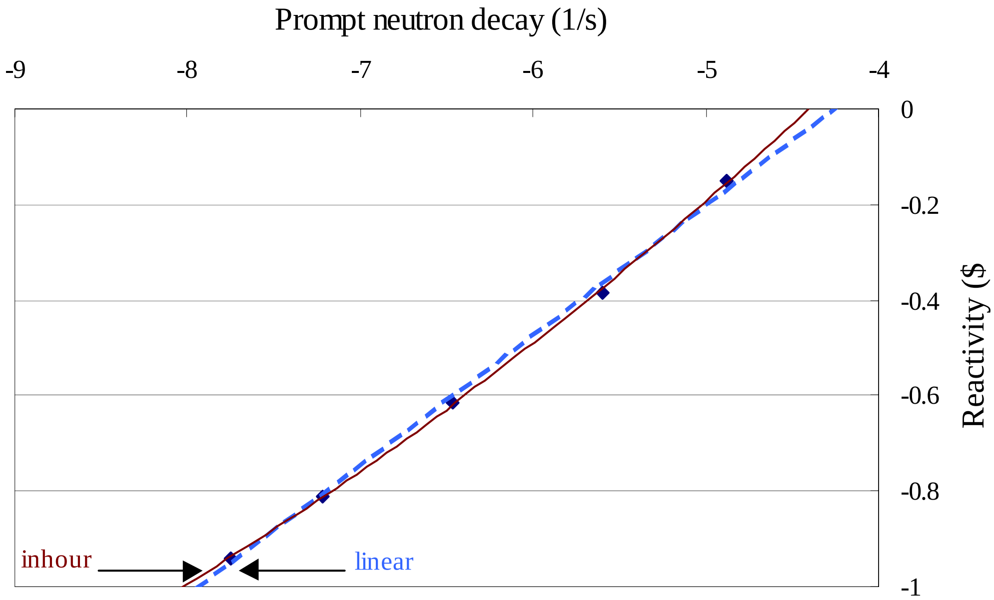

Fig. 7.9: Prompt neutron decay as function of the reactivity in Core 5

	Fit type	χ^2	α_C	f_c	β_C/Λ_C
Core1	Inhour	$5.6\text{x}10^{-5}$	-5.27± 0.02	1.151± 0.002	4.58±0.06
	Linear	$1.3\text{x}10^{-4}$	-5.17± 0.04	1.160± 0.004	4.46±0.04
Core 2	Inhour	$2.5\text{x}10^{-5}$	-4.90± 0.07	1.18±0.01	4.14±0.07
	Linear	$2.9\text{x}10^{-5}$	-4.64± 0.07	1.22±0.01	3.79±0.07
Core 3	Inhour	$7.9\text{x}10^{-5}$	-5.34± 0.05	1.150± 0.005	4.64±0.05
	Linear	$2.9\text{x}10^{-6}$	-5.21± 0.06	1.150± 0.006	4.51±0.06
Core 5	Inhour	$9.9\text{x}10^{-5}$	-4.51± 0.024	1.253± 0.003	3.60±0.02
	Linear	$2.9\text{x}10^{-6}$	-4.31± 0.06	1.332± 0.009	3.23±0.05

Table 7.35: Measured Values of α_c and β_{eff}/Λ in Core 1, 2, 3 and 5

7.6. OTHER PARAMETER MEASUREMENTS

The following parameter measurements were also carried out on HTR-PROTEUS during the course of the CRP:

a. Reaction rate ratio distributions using foil activation and miniature fission chambers: Measurement results can be found in Section 8.3 including a comparison with calculation results.

b. Water ingress effects on core reactivity using polyethylene rods: Measurement results can be found in Section 8.5 including a comparison with calculation results.

c. Reactivity effects of small absorbing and moderating samples: Measurement results can be found in Section 8.6 including a comparison with calculation results.

REFERENCES

[7.1] WILLIAMS T.,'On the Choice of Delayed Neutron Parameters for the Analysis of Kinetics Experiments in ^{235}U Systems', Ann. Nucl. Energy, 23, (1996)

[7.2] WILLIAMS T.,'LEU-HTR PROTEUS: Configuration Descriptions and Critical Balances for the Cores of the HTR-PROTEUS Experimental Programme', PSI Internal Report TM-41-95-18, (1996)

[7.3] WILLIAMS T.,'HTR PROTEUS Core 1: ZEBRA Control Rod S-Curves and Rest Worths', PSI Internal Report TM-41-92-40, (1992)

[7.4] WILLIAMS T., BOURQUIN P. and CHAWLA R., 'HTR PROTEUS CORE 1: Reactivity Corrections for the Critical Balance', PSI Internal Report TM-41-93-20, (1993)

[7.5] WILLIAMS T., 'HTR PROTEUS Core 1A: The Replacement of the ZEBRA Control Rods by Conventional Control Rods', PSI Internal Report TM-41-93-25, (1993)

[7.6] ROSSELET M., 'Reactivity Measurements and their Interpretation in Systems with Large Spatial Effect' Thesis No. 1930, Swiss Federal Institute of Technology, Lausanne (1999)

[7.7] ROSSELET M., CHAWLA R. and WILLIAMS T., 'Epithermal Inverse Kinetic Measurements and Their Interpretation Using a Two-Group Point-Kinetic Model' Nucl. Science and Eng., 135, (2000)

[7.8] WILLIAMS T. et al., 'Absorber-Rod Interaction and Asymmetry Effect in Experimental LEU-HTR Configurations', Proc. 1994 ANS Topical Mtg. on Advances in Reactor Physics, Knoxville, USA (1994)