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SMR/1220-6

Workshop on

Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety

13 March - 14 April 2000

Miramare - Trieste, Italy

Nuclear Reactor Core Design

G.B. Bruna
FRAMATOME
Paris, France

UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4.SMR/1056-37

WORKSHOP ON NUCLEAR REACTION DATA AND NUCLEAR REACTORS: PHYSICS, DESIGN AND SAFETY

23 February - 27 March 1998

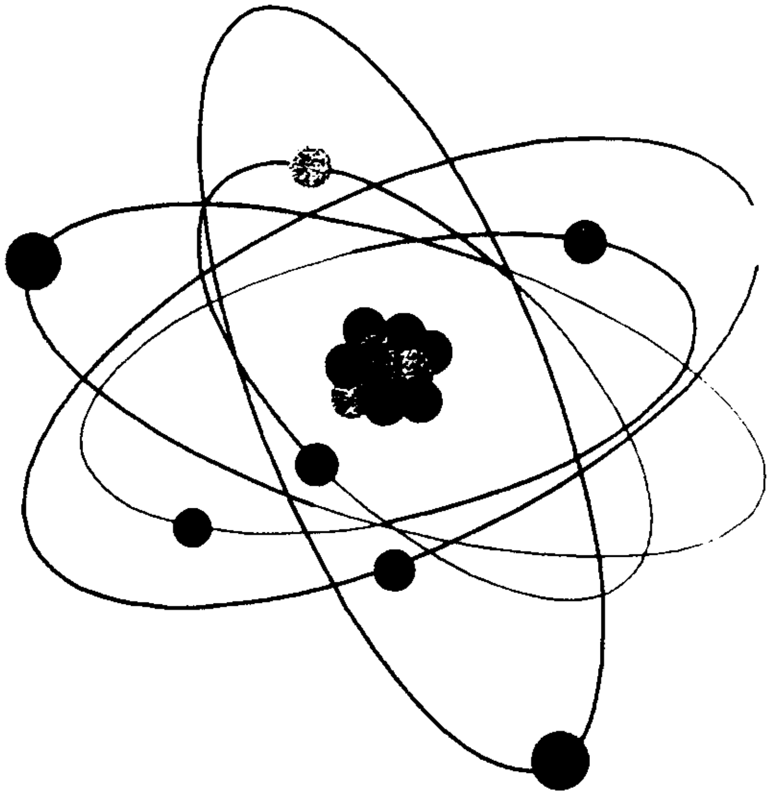
Miramare - Trieste, Italy

Nuclear Reactor Core Design

G.B. Bruna
FRAMATOME
92084 Paris
France

Nuclear Reactor Core Design

- Computation Chain Qualification:
  - via critical experiments
    - CAMELEON
    - EPICURE
    - GEDEON
  - via exploitation of operating experience



Nuclear Reactor Core Design

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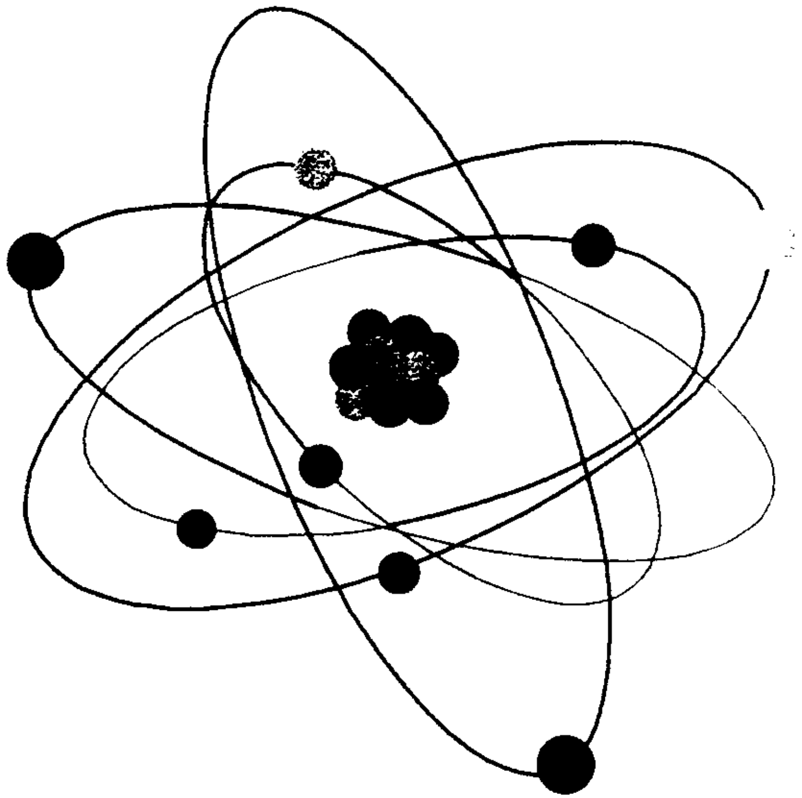

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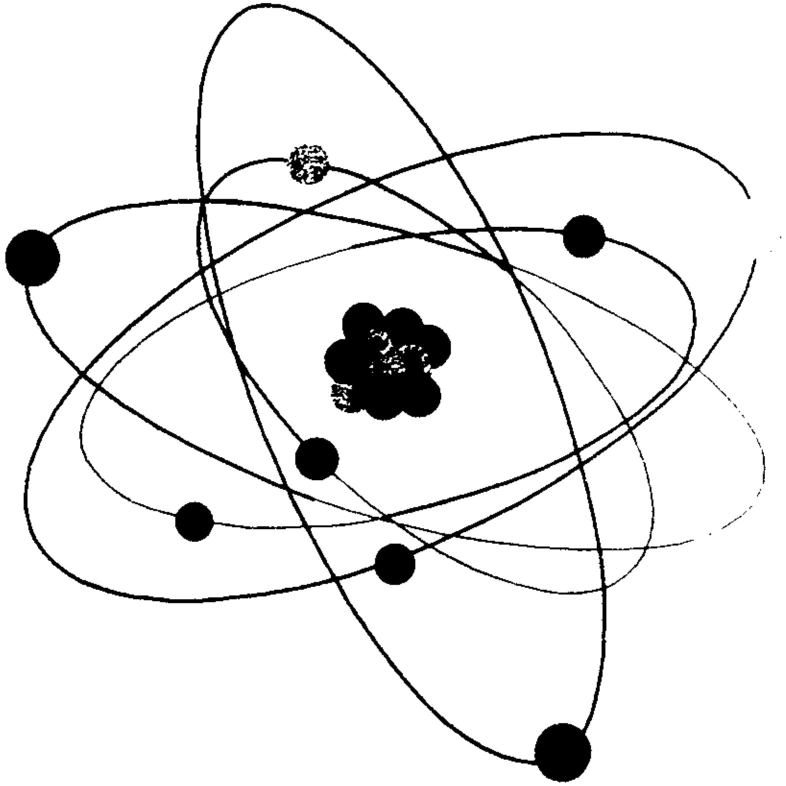
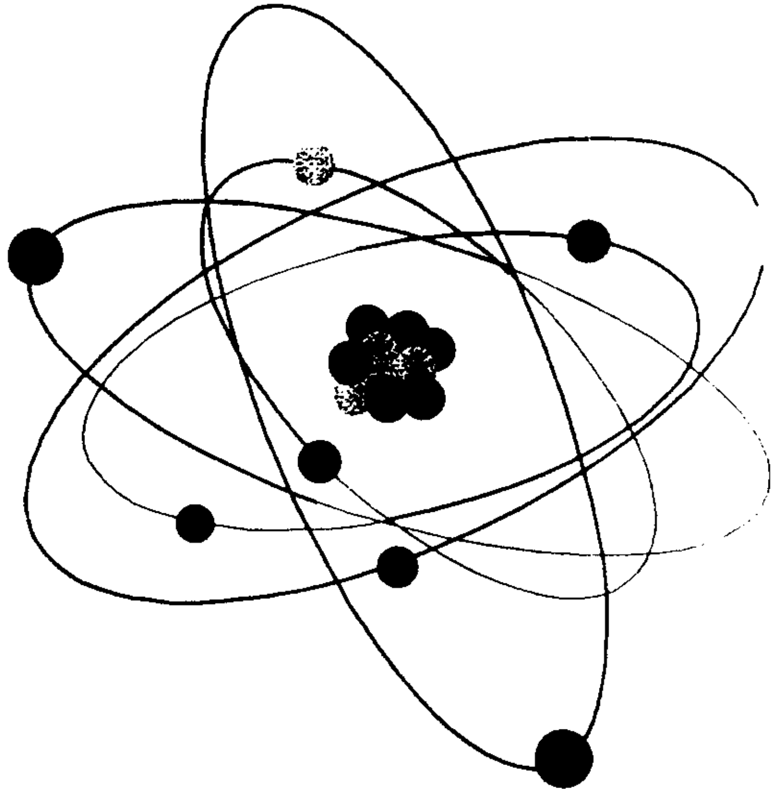
Nuclear Reactor Core Design

- Computational Chain:
- Properties and Structure
  - MMI
  - Cell Code
  - Core Code
  - Validation Chain
  - Exploitation Codes
  - DBMS

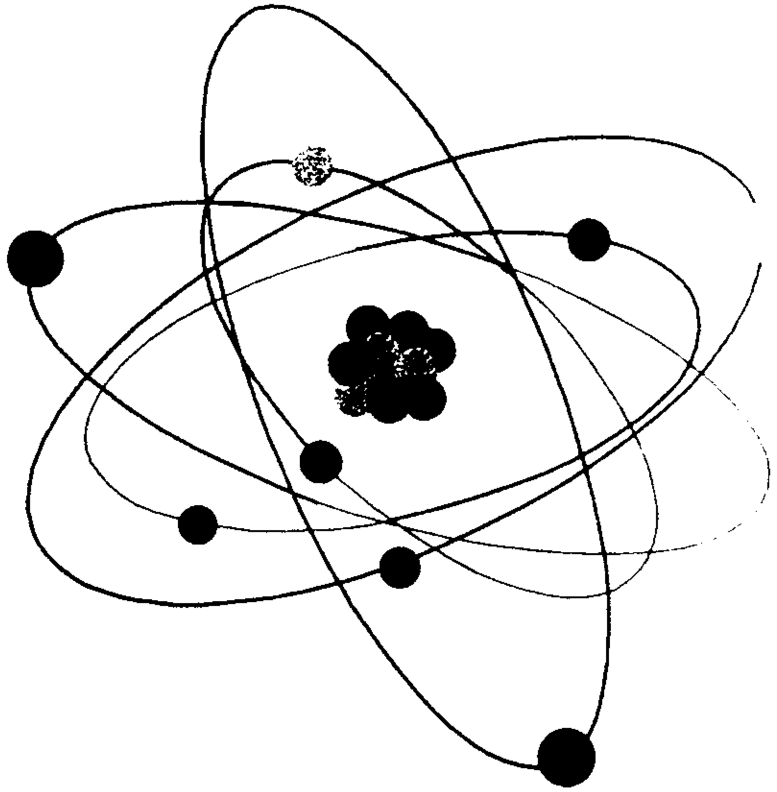


Nuclear Reactor Core Design

- Safety and Economics
- Reactor Operation and Control:
  - digital core control and protection systems of N4 NPPs



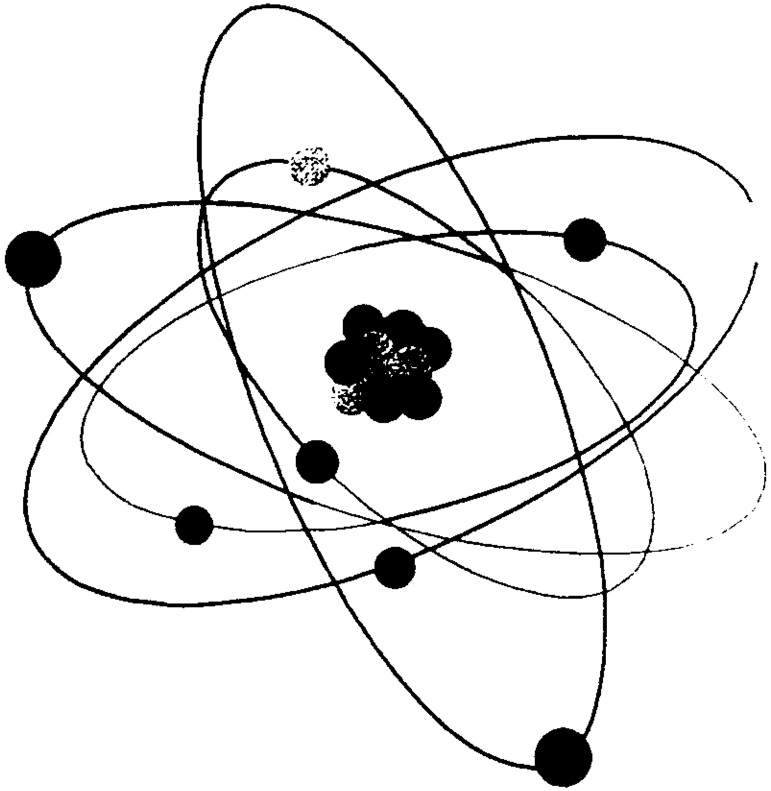
Nuclear Reactor Core Design



- Reactor Core Design:
  - Main parameters in reactor core design
  - Control of reactivity and power:
    - needs:reactivity effect
    - availabilities: control devices
  - Criteria and margins
  - Manufacturing

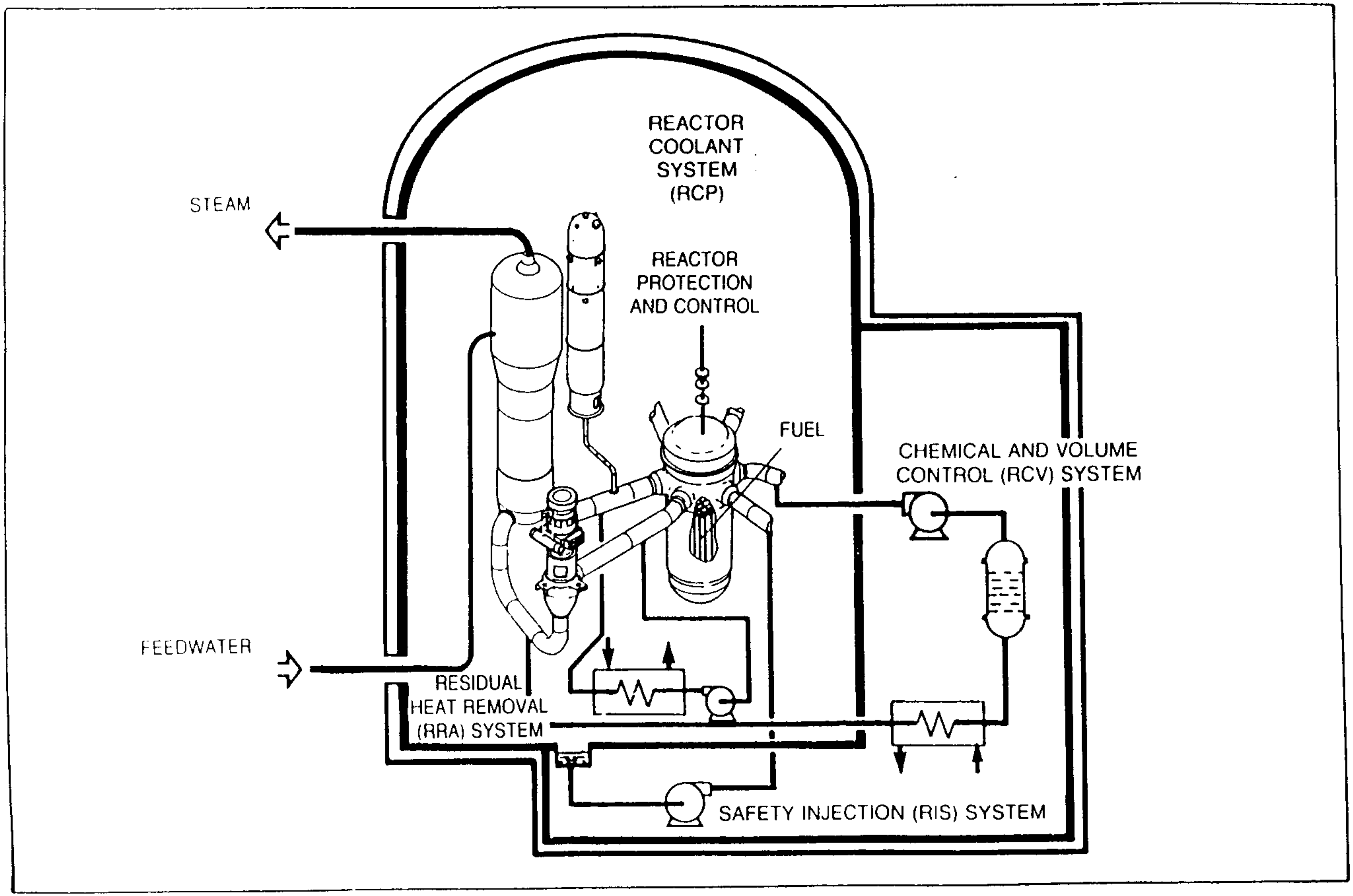
Nuclear Reactor Core Design
Summary

- Reactor Core Design
- Safety and Economics
- Reactor Operation and Control
- Computational Chain
- Chain Qualification



NUCLEAR REACTOR CORE DESIGN

NUCLEAR STEAM SUPPLY SYSTEM (NSSS)



MAIN GOALS AND ACHIEVEMENTS

THE MAIN GOAL OF A POWER PLANT IS TO PRODUCE A CHEAP ENERGY IN THE SAFEST WAY

IN ORDER TO ACHIEVE THIS TWO-FOLD GOAL, THE DESIGN AND THE EXPLOITATION OF THE PLANT MUST:

- *GUARANTEE THE RESPECT OF THE SAFETY CRITERIA AT ANY TIME*
- *MAXIMISE THE ENERGY RELEASE FROM THE FUEL ACCORDING TO A GIVEN EXPLOITATION STRATEGY*

DESIGN:

- *DEFINITION OF THE OPTIMUM EXPLOITATION CONDITIONS*
- *DEFINITION OF THE NORMAL EXPLOITATION RANGE*
- *EVALUATION OF THE SYSTEM REACTIVITY BALANCE FOR NORMAL OPERATION*

NORMAL OPERATION:

- *CONTROL OF LOCAL POWER*

INCIDENTAL AND ACCIDENTAL CONDITIONS:

- *RESPECT OF THE SAFETY CRITERIA*

CONTROL OF REACTIVITY AND POWER

0

OBSERVABLES

$$\delta\rho = \frac{<\Phi^*, \delta H \Phi>}{<\Phi^*, F\Phi>}$$

$$AO = C_1 \frac{<F,\Phi>_h - <F,\Phi>_l}{<F,\Phi>_h + <F,\Phi>_l}$$

$$P_{i,j,k} = C_2 \frac{<F,\Phi>_{i,j,k}}{\sum_{i,j,k} <F,\Phi>_{i,j,k}}$$

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MAIN PARAMETERS IN REACTOR CONTROL

REACTIVITY

$$\delta\rho = \frac{< \Phi_0^*, \left[\delta A + (1-\rho)\delta P\right]\Phi' >}{< \Phi_0^*, P'\Phi' >}$$

$$A_0\Phi_S + P_0\Phi_S = S$$

$$S = \rho P_0 \Phi_0$$

$$\Phi s = \Phi_0 + \delta\Phi$$

$$\left[A_0 + \left(1 - \rho\right) P_0\right] \Phi_0 = 0$$

$$\left(A_0 + P_0\right)\left(\Phi_0 + \delta\Phi\right) = \rho P_0 \Phi_0$$

$$\left(A_0 + P_0\right) \delta\Phi = 0$$

$$k = \frac{1}{1-\rho}$$

$$\lambda_0 = \frac{1}{k}$$

$$A_0 + \frac{P_0}{k}\Phi_0 = 0$$

$$A_0\Phi_0 + \lambda_0 P_0 \Phi_0 = 0$$

$$A_0^{\,t}\Phi_0^* + \lambda_0 P_0^{\,t}\Phi_0^* = 0$$

$$S = \rho P_0 \Phi_0 + \delta S$$

$$\begin{cases} A_0 \Phi_0 + P_0 (1 - \rho) \Phi_0 = 0 \\ A_0 \delta\Phi + P_0 \delta\Phi = \delta S \end{cases}$$

$$A'\Phi' + \lambda' P'\Phi' = 0$$

$$A' = A_0 + \delta A$$

$$P' = P_0 + \delta P$$

$$\Phi' = \Phi_0 + \delta\Phi$$

$$\lambda' = \frac{1}{k'} = \left(1 - \rho'\right)$$

$$\rho' = \rho + \delta\rho$$

$$\left(A_0 + \delta A\right)\Phi' + \left[1 - (\rho + \delta\rho)\right]\left(P_0 + \delta P\right)\Phi' = 0$$

$$< \Phi_0^*, (A_0 + \delta A)\Phi' > + < \Phi_0^*, [1-(\rho+\delta\rho)](P_0 + \delta P)\Phi' >= 0,$$

et

$$< \Phi_0^*, A_0\Phi' > + < \Phi_0^*, (1-\rho)P_0\Phi' > + < \Phi_0^*, \delta A\, \Phi' > + < \Phi_0^*, (1-\rho)\delta P\Phi' > - < \Phi_0^*, \delta\rho P'\Phi' >= 0$$

$$< \Phi_0^*, [\delta A + (1-\rho)\delta P]\Phi' >=< \Phi_0^*, \delta\rho P'\Phi' >$$

$$\delta\rho = \frac{< \Phi_0^*, [\delta A + (1-\rho)\delta P]\Phi' >}{< \Phi_0^*, P'\Phi' >}$$

MAIN PARAMETERS IN REACTOR CONTROL

POWER PEAK

$$P_{ow}P_{eak} = \mathrm{Max}\left[\frac{< P_{i,j,k} >_{z}}{< P_{i,j,k} >_{I,J,Z}}\right]$$

$$P_{i,j,k} = \sum_{n}\left(N_n \sigma_n^{fiss}\right)_{i,j,k} \Phi_{i,j,k}$$

THE REACTIVITY BALANCE OF THE REACTOR CORE

THE CONTROL OF REACTIVITY

THE REACTIVITY BALANCE:

- *AVAILABILITY: CONTROL DEVICES*
  - *SOLUBLE BORON*
  - *BLACK RODS*
  - *GRAY RODS*
  - *BURNABLE POISONS*
  - *EXTRACTIBLEPOISONS*

- *NEEDS: REACTIVITY SOURCES AND MARGINS*
  - *EXTRA REACTIVITY*
  - *XENON, SAMARIUM*
  - *LOW-LIFE ACTINIDES*
  - *POWER EFFECT*
  - *TEMP. EFFECT*
  - *CRITERIA*
  - *MARGINS*

REACTIVITY NEEDS:

REACTIVITY LOSSES: BURN-UP AND BREEDING PROCESS
F. P. BUILD - UP

POWER AND TEMPERATURE EFFECTS

CRITERIA AND MARGINS

THE BURN-UP AND BREEDING PROCESS

THE F.P. BUILD-UP

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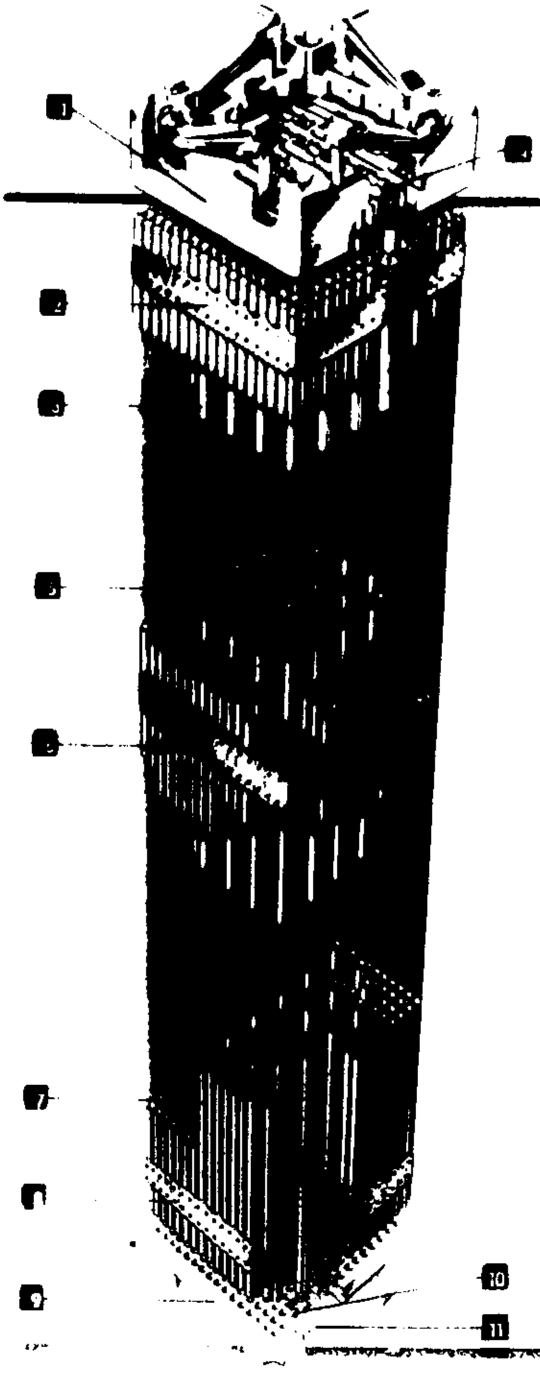
AFA 2G

AFA-2G FUEL ASSEMBLY

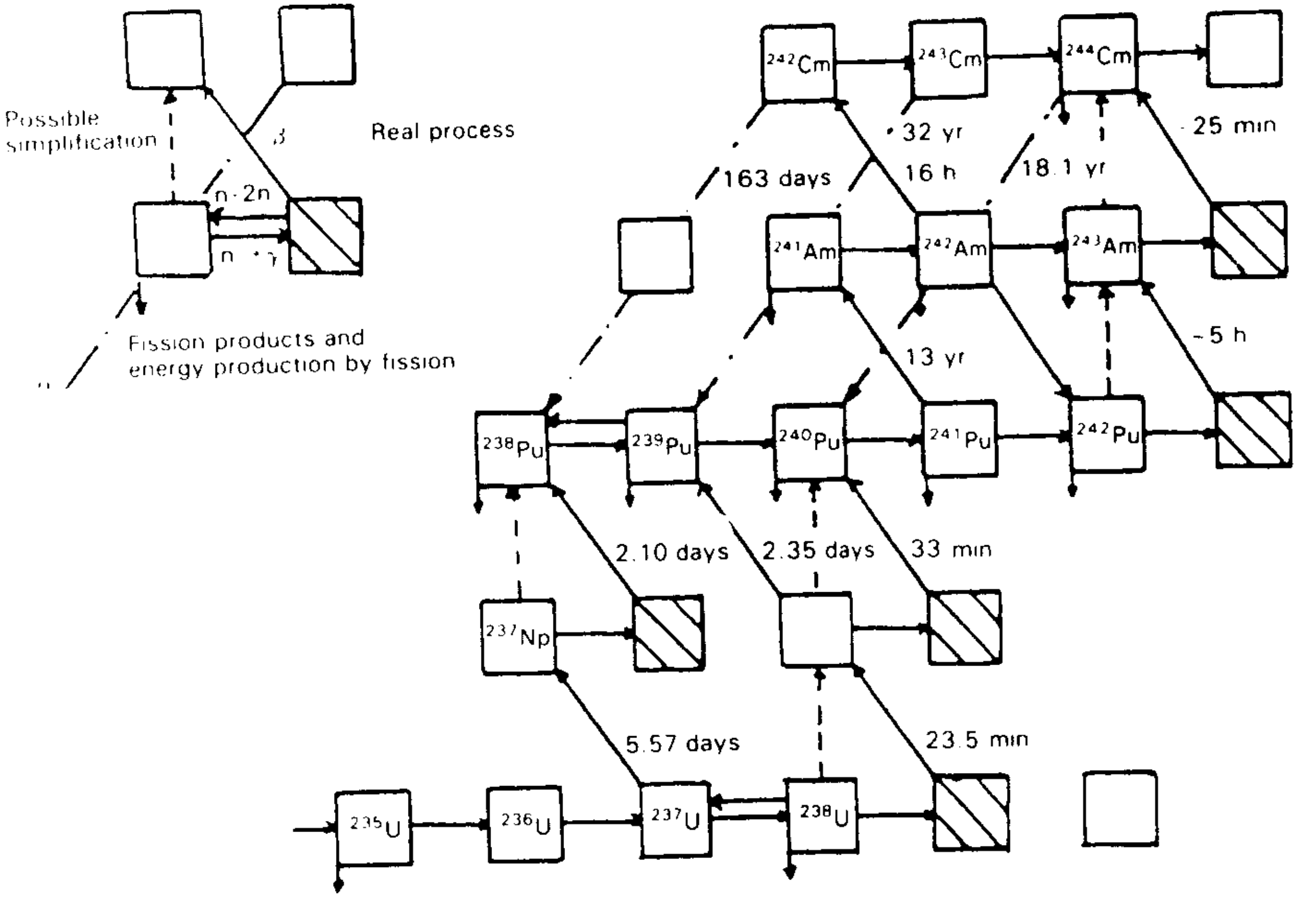


1 [illegible]
2 [illegible]
3 [illegible]
4 [illegible]
5 [illegible]
6 [illegible]
7 Fuel rod
8 Bottom grid
9 [illegible]
10 [illegible]
11 [illegible]

Fragema

UO_2 pellet.

[illegible]



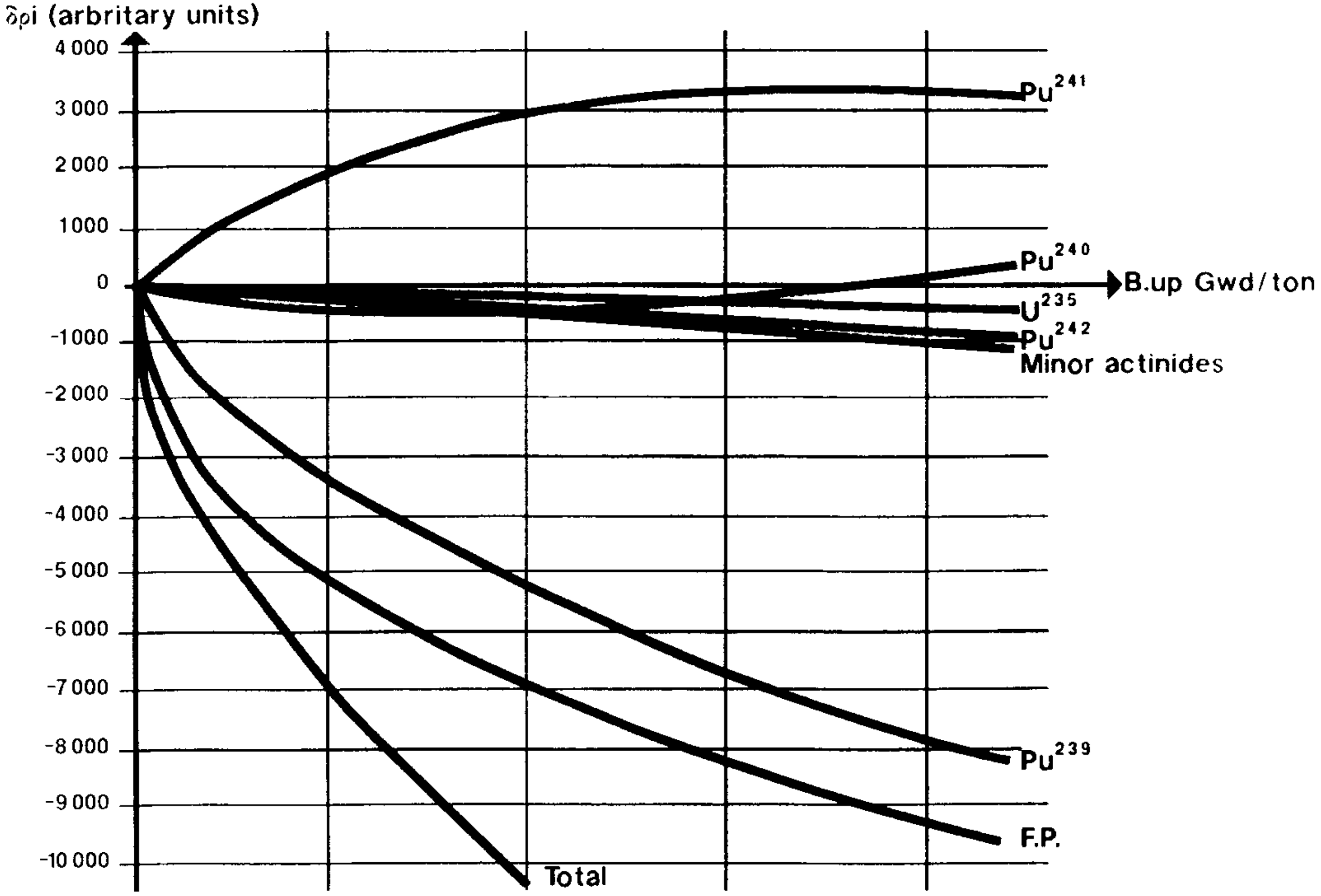
ACTINIDE CHAIN

TYPICAL REACTIVITY LOSS IN A PWR FOR VARIOUS FUELING (averaged assembly values)

	UO_2	MOX	HCLWR
• URANIUM	80	5	1
• PLUTONIUM	–20	41	26
• MINOR ACTINIDES	3	7	16
• FISSION PRODUCTS	33	47	57
• OTHERS	4	*	*
TOTAL	100	100	100
• Actual reactivity loss in an equivalent 10 Gwd/ton cycle ($1.0\ 10^{-5}$ units)	8 500	4 300	3 500

* Lower than 0.5

CONTRIBUTION OF THE MAIN FAMILIES TO REACTIVITY LOSS



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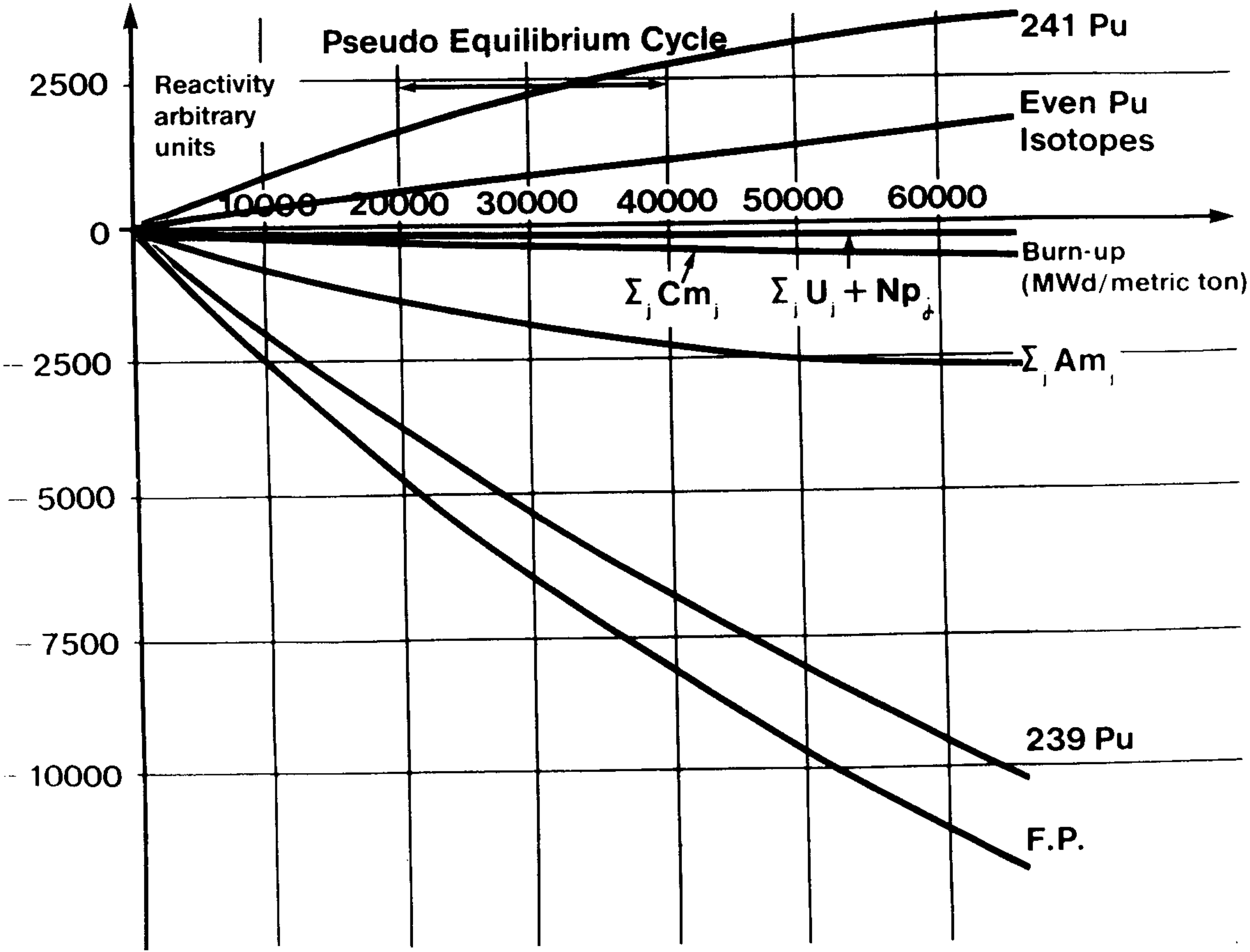
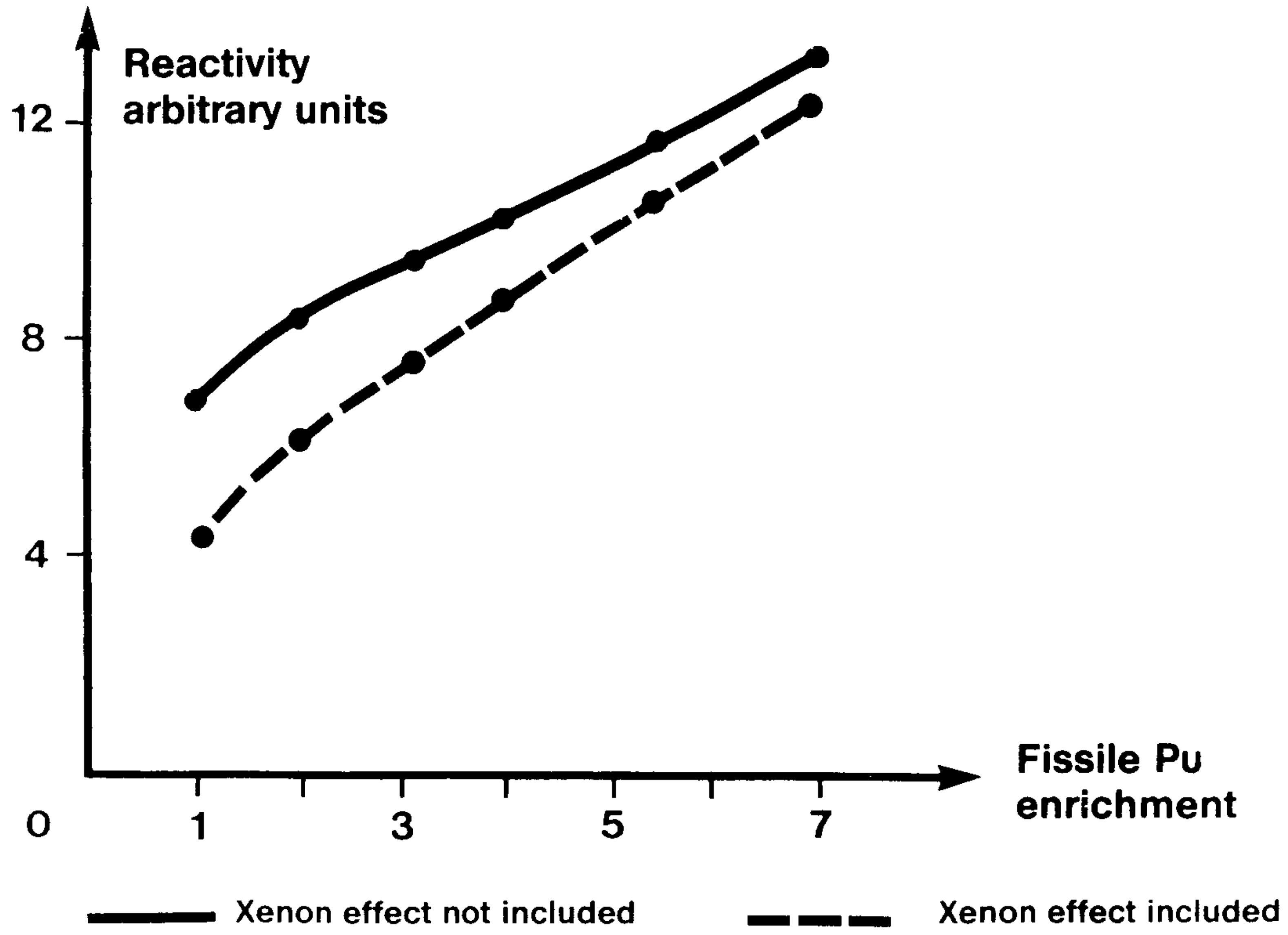
Contribution of main isotope families to reactivity loss



Pu RCVS REACTIVITY VERSUS FISSILE Pu ENRICHMENT



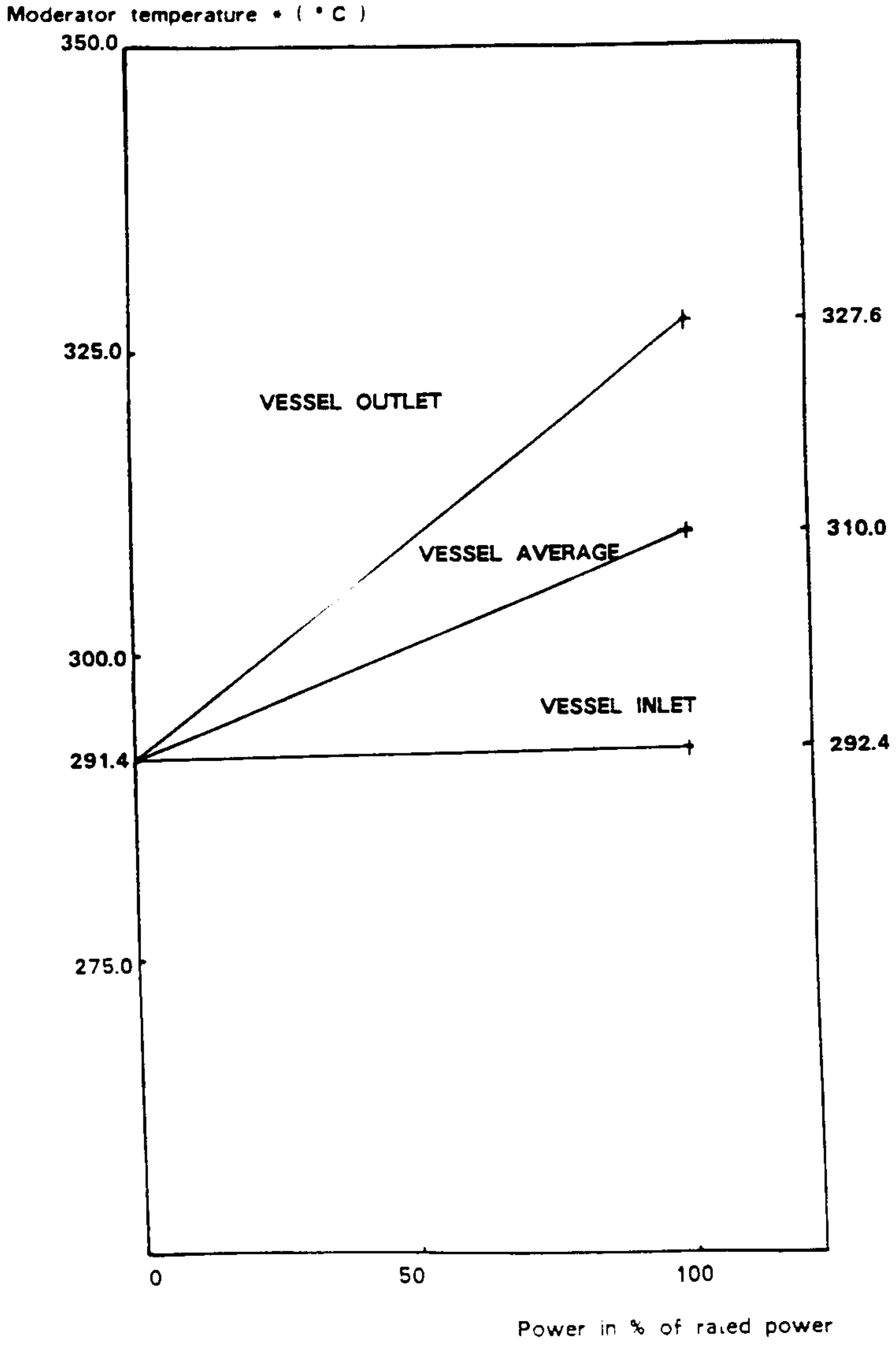
POWER AND TEMPERATURE EFFECT

CONTRIBUTION OF THE MAIN ISOTOPES TO THE CORE AVERAGED POWER AND TEMPERATURE EFFECT

	Spectral Effect	Direct Effect	Higher Order correction	Balance
U 235	+ 175	− 4	− 2	+ 169
U 238	− 87	+ 37	+ 1	− 49
Pu 239	+ 10374	− 219	− 104	+ 10051
Pu 240	− 1886	+ 43	+ 19	− 1824
Pu 241	+ 4001	− 98	− 40	+ 3863
Pu 242	− 300	+ 10	+ 3	− 287
Minor Act.	− 148	0	+ 2	− 146
F.P.	− 948	+ 22	+ 10	− 916
Structures	− 23	− 3	0	− 26
Water	− 151	− 113	− 61	− 325
B_4C	− 1436	− 67	− 5	− 1508
Total	+ 9571	− 392	− 177	+ 9002

(pcm)

Moderator temperature as a function of power level



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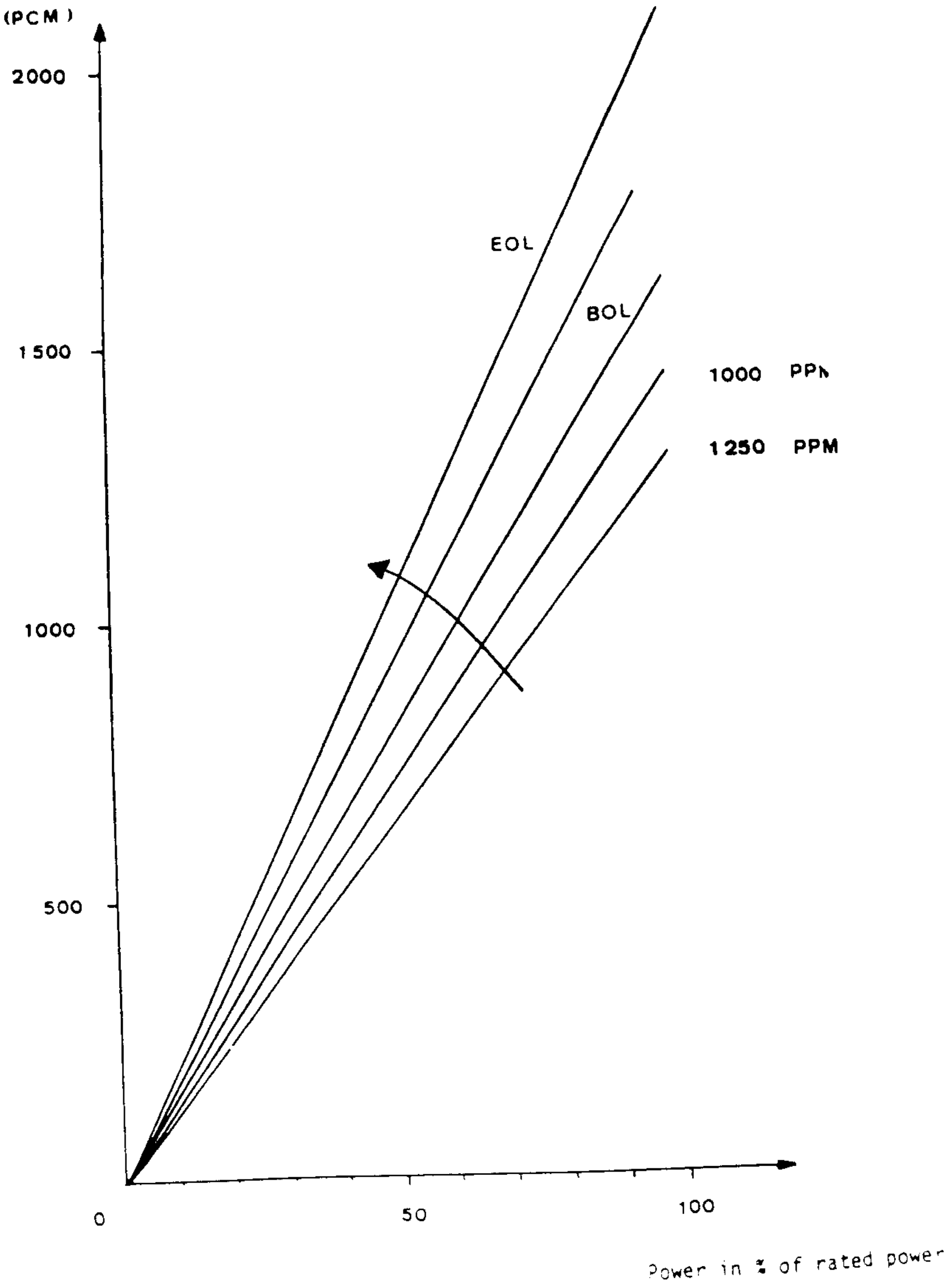
TOTAL NEGATIVE REACTIVITY GENERATED BY POWER ESCALATION



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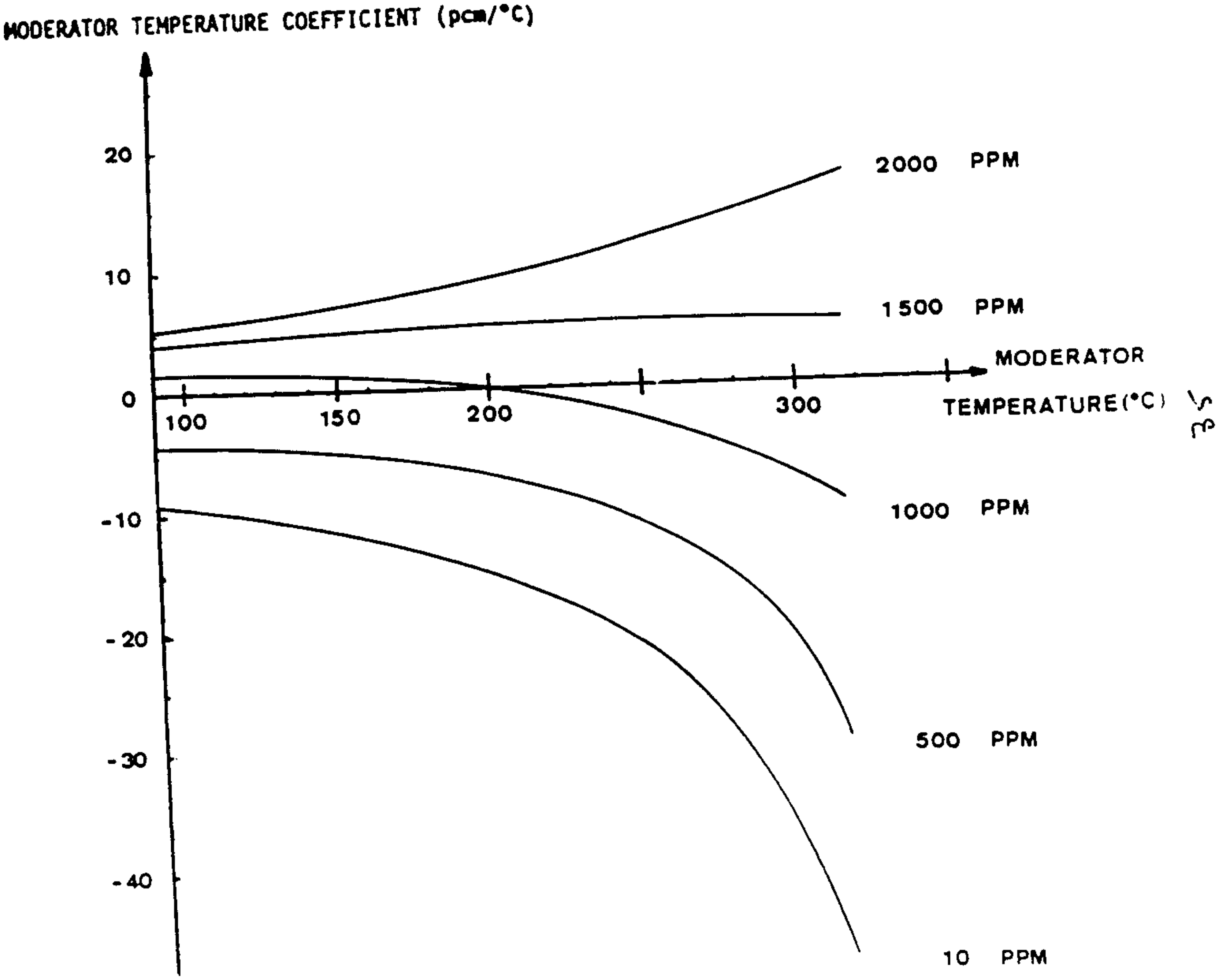
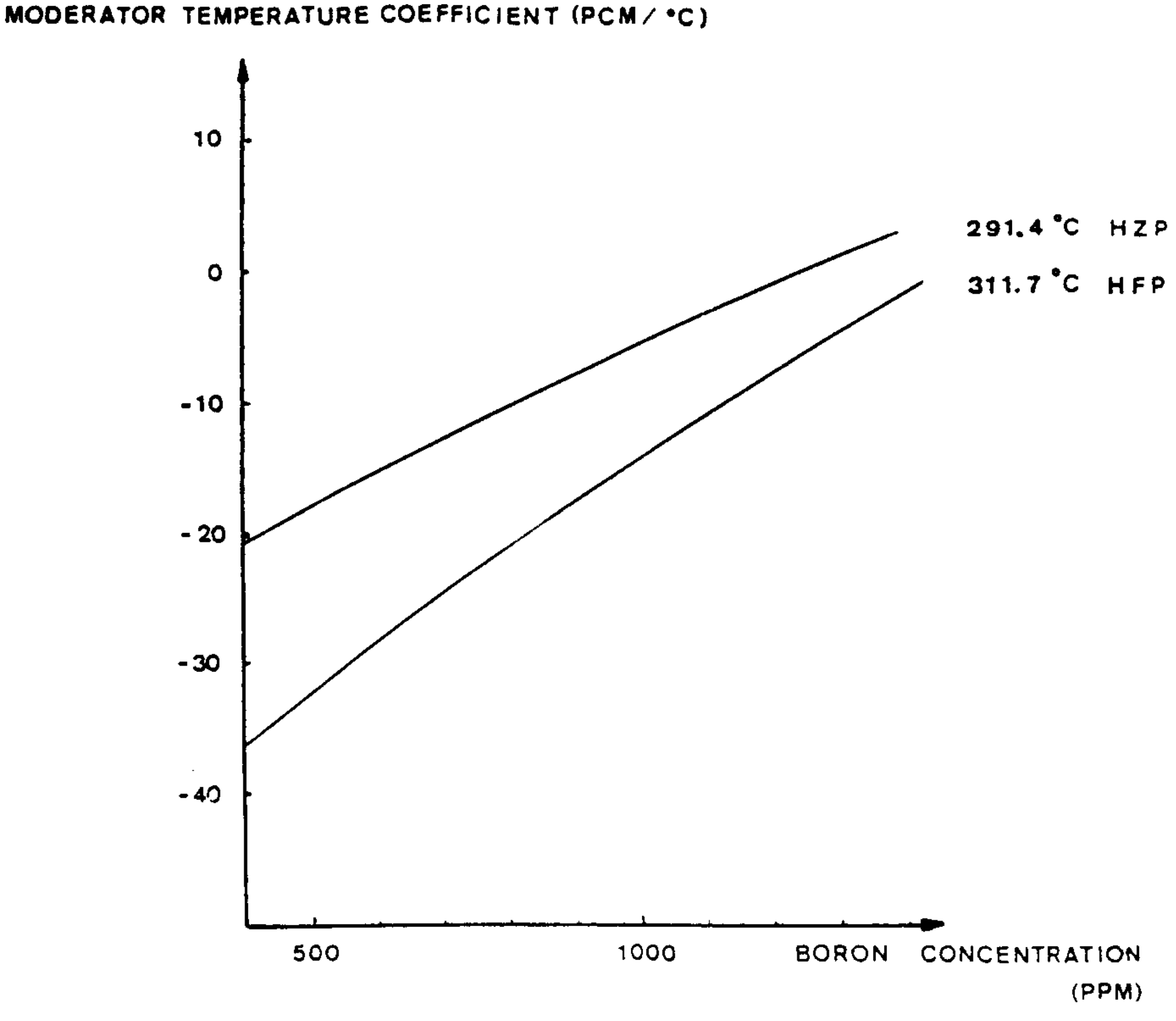
Moderator temperature coefficient as a function of moderator temperature, BOL, CY1, HZP, ARO



Moderator temperature coefficient as a function of boron concentration BOL, CY1, ARO



SPECTRAL EFFECTS RELATED TO A 10 % INCREASE OF THE WATER FRACTION IN THE CELL (ARBITRARY UNITS)

FRAMATOME

DIRECT EFFECT: 1360

GROUP	ABSORPTION	PRODUCTION	SCATTERING	TOTAL
1		+ 10		+ 10
2				
3				
4	− 200	+ 100	+ 60	− 40
5	− 190	+ 40	+ 30	− 120
6	− 1320	+ 2230		+ 910
	− 1710	+ 2380	+ 90	+ 760

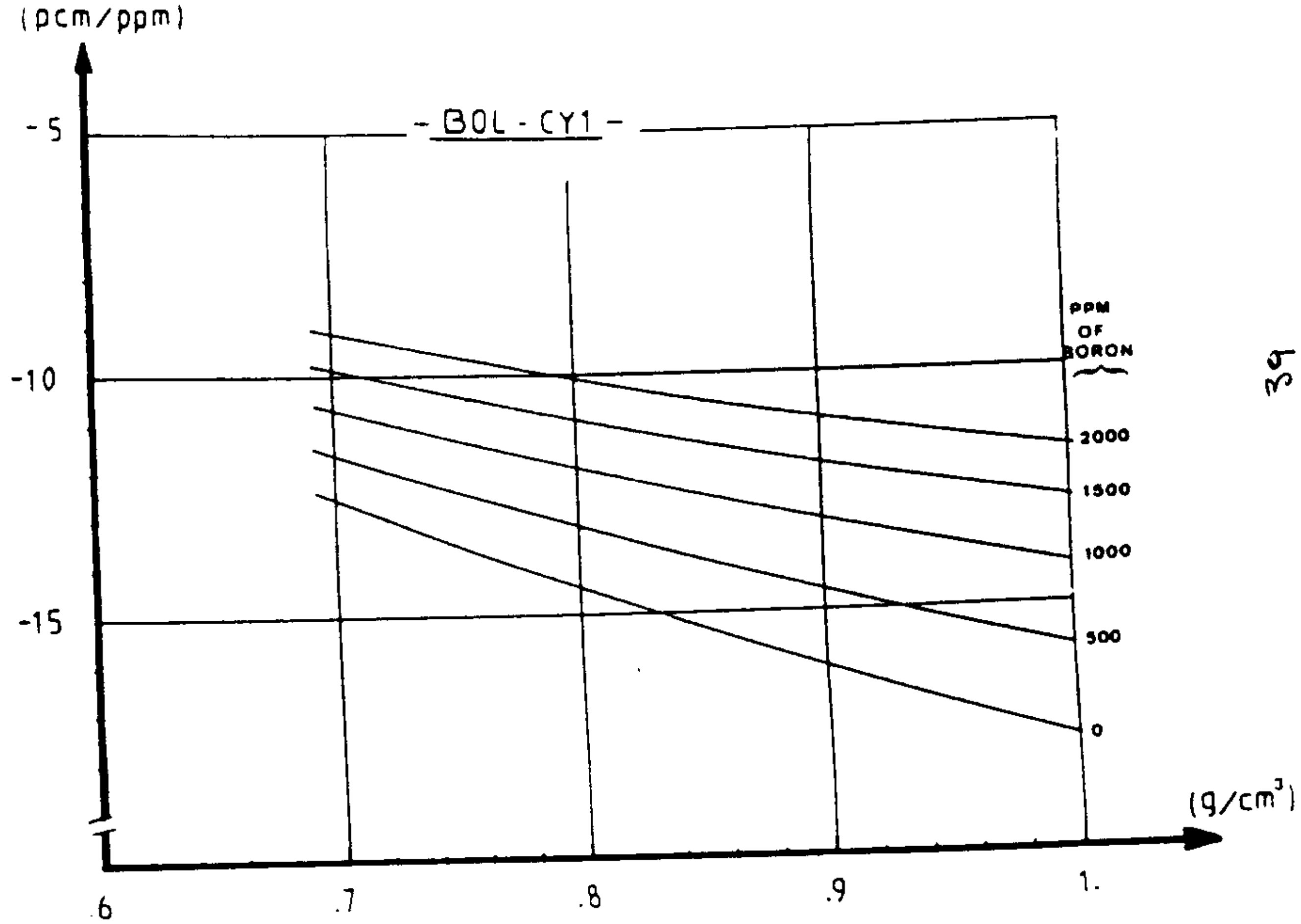
HOW TO CONTROL THE EXCESS REACTIVITY?

QUASI-HOMOGENEOUS POISONING: SOLUBLE BORON,

INHOMOGENEOUS POISONING:

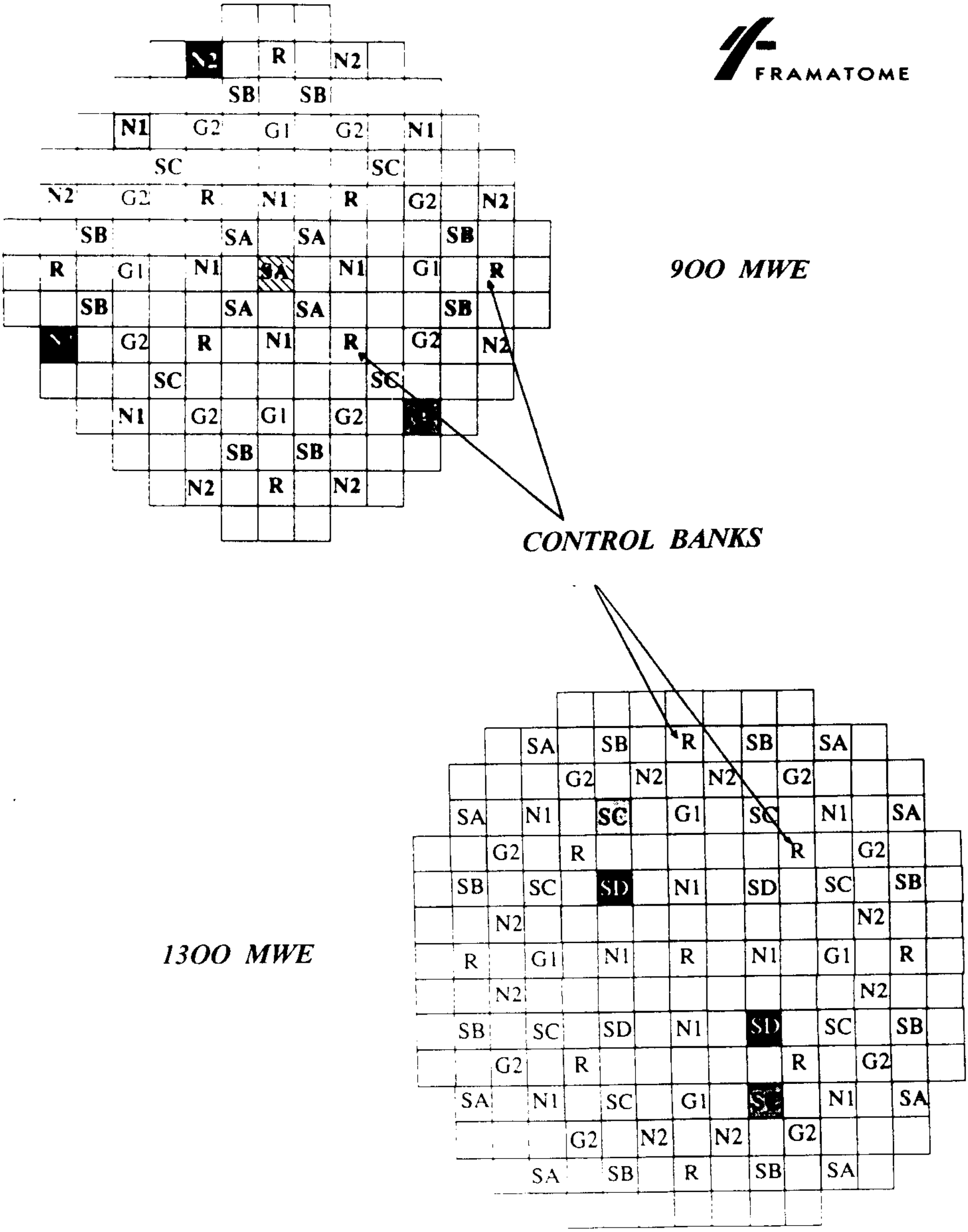
- *CONTROL RODS,*
- *BURNABLE POISONS,*
- *SPECTRAL SHIFT RODS.*

Differential worth of soluble
boron versus moderator density,
at BOL, cycle 1



CONTROL BANKS

FRAMATOME

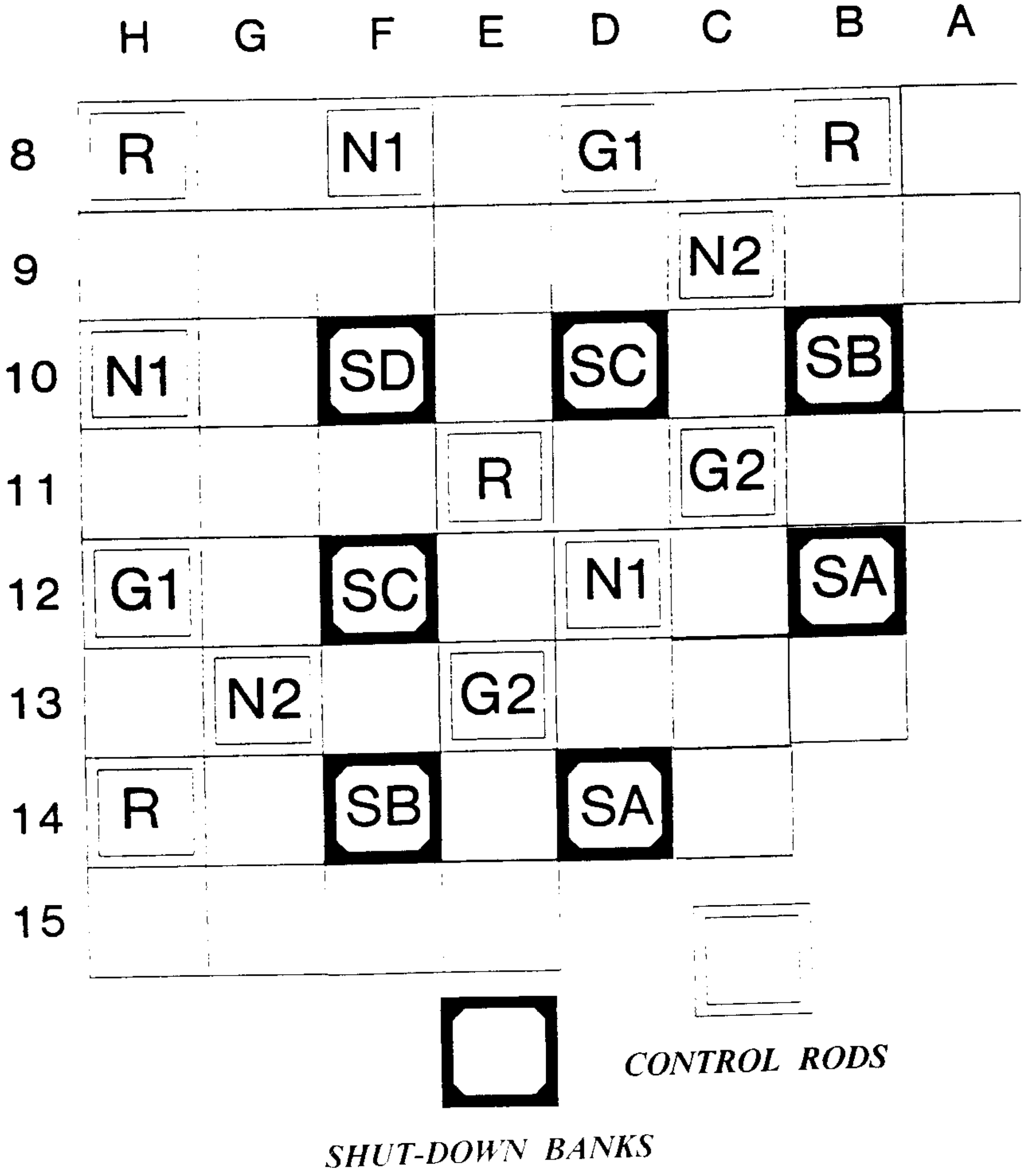


TYPICAL CORE LAY-OUTS

FRAMATOME

1300 MWE PWR

POSITION OF CONTROL AND SHUT-DOWN BANKS

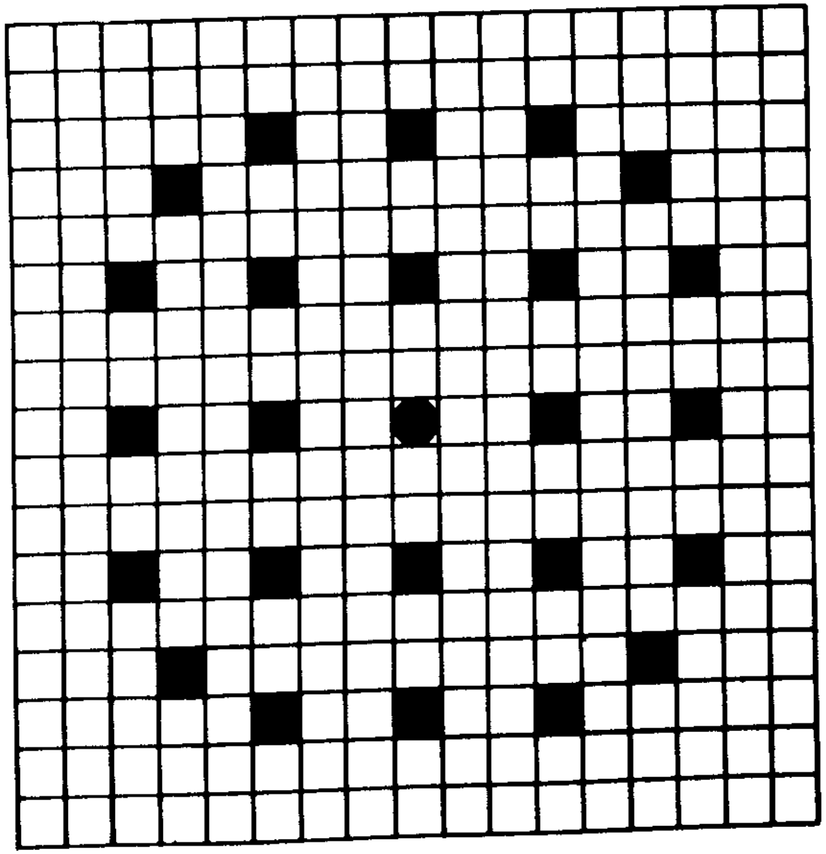


	H	G	F	E	D	C	B	A
8	R		N1		G1		R	
9						N2		
10	N1		SD		SC		SB	
11				R		G2		
12	G1		SC		N1		SA	
13		N2		G2				
14	R		SB		SA			
15								

CONTROL RODS

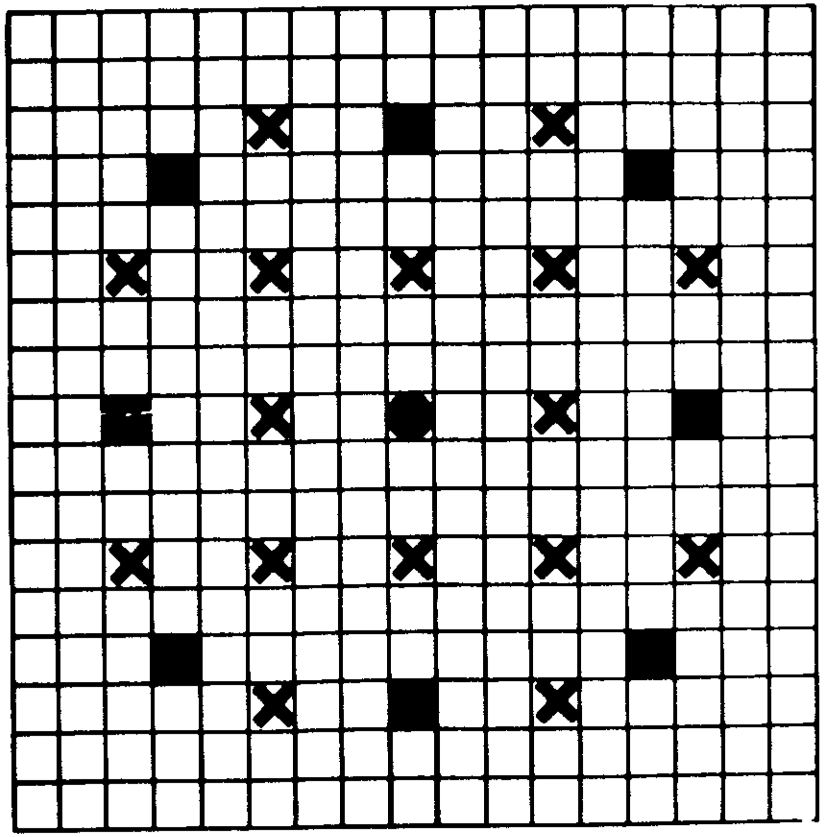
SHUT-DOWN BANKS

CONTROL ROD ASSEMBLIES



Black Rod Assembly

- ■ 24 Ag - In - Cd rods
- ● Instrumentation Thimble



Gray Rod Assembly

- ■ 8 Ag - In - Cd rods
- ☒ 16 Steel rods

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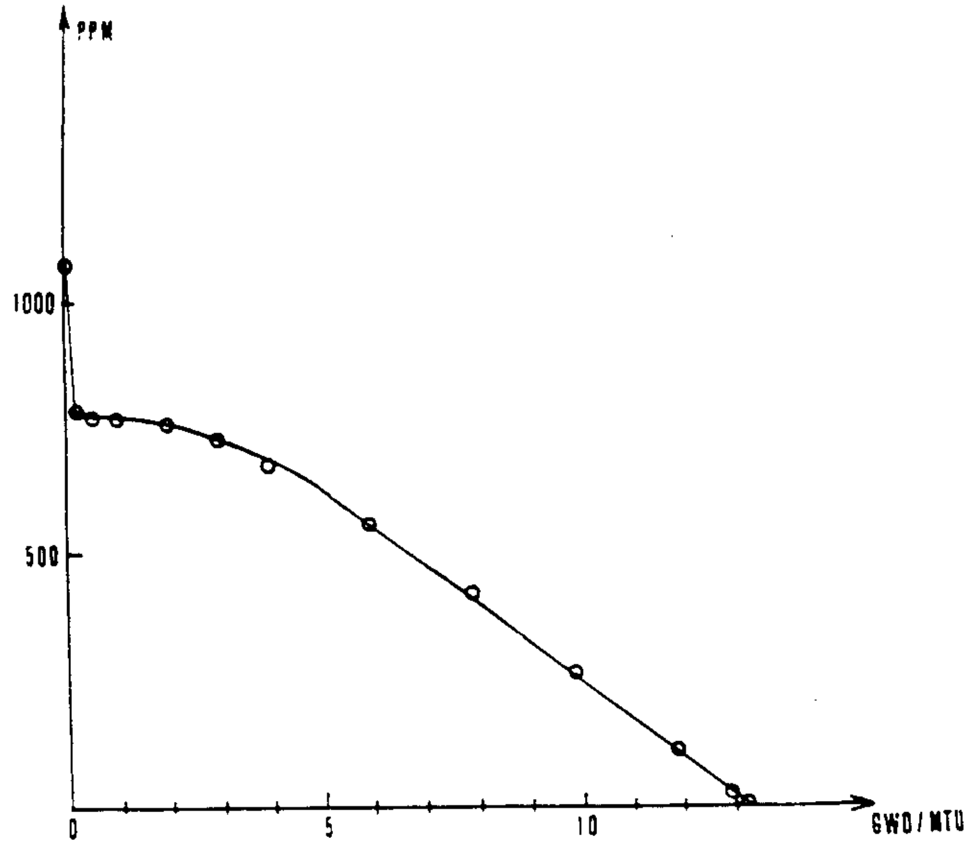
SOLUBLE BORON

Critical boron concentration variations as a function of cycle 1 burnup



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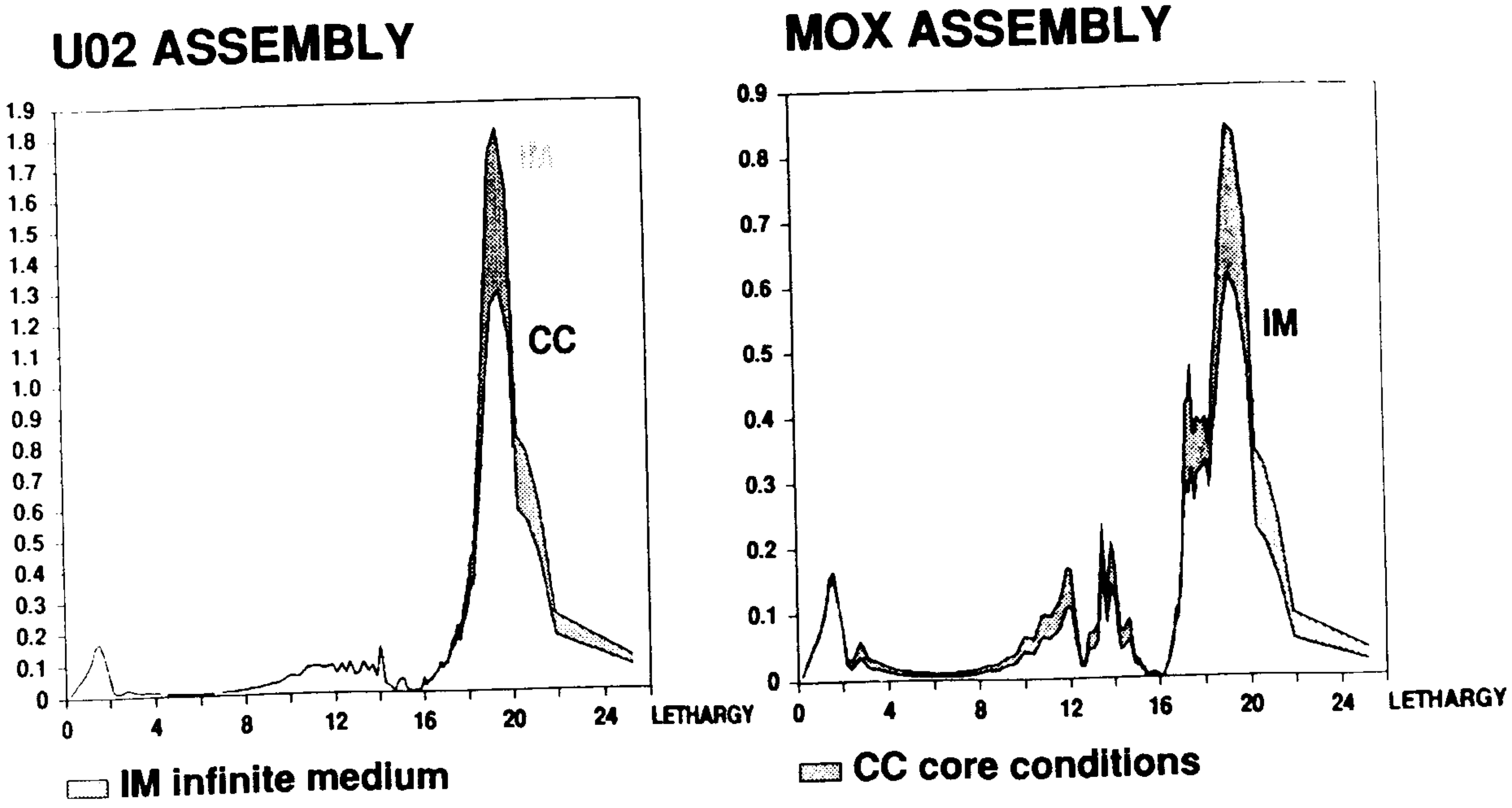
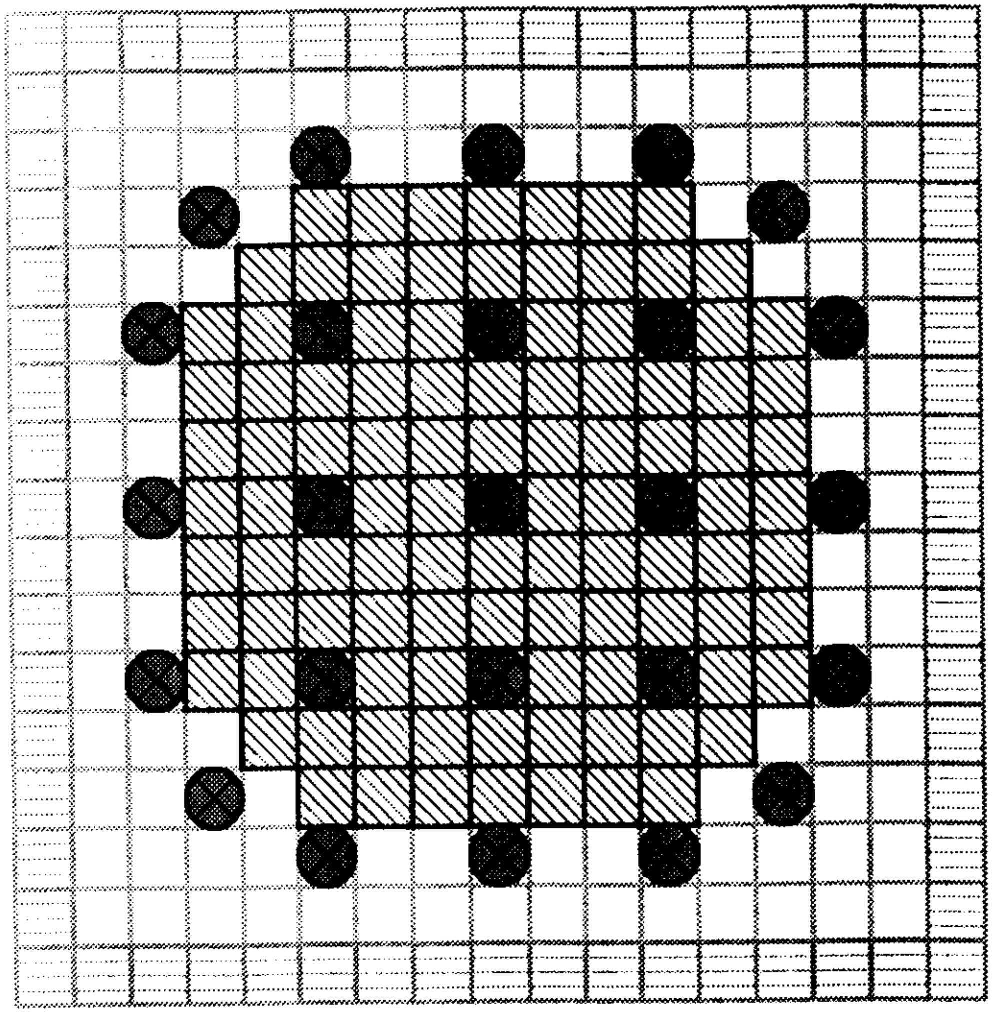
FISSION REACTION RATES vs LETHARGY



U02 ASSEMBLY

MOX ASSEMBLY

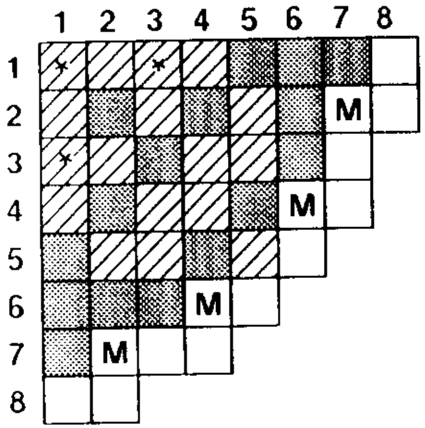
MOX ASSEMBLY LAYOUT



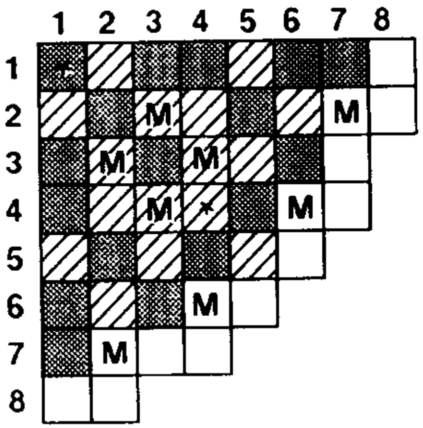
▤	Outer zone	64 pins
☐	Intermediate zone	100 pins
▨	Internal zone	100 pins
■	Instrumentation tube	
⊗	Guide-tube	

TYPICAL MOX RELOADING STRATEGY

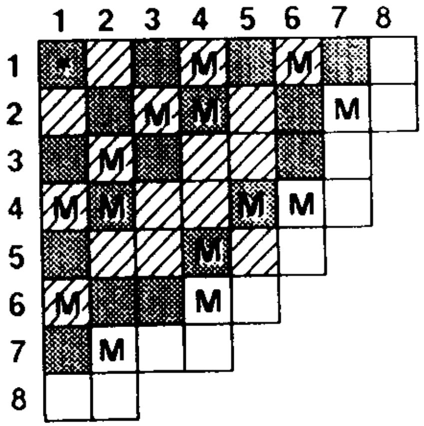
1st CYCLE



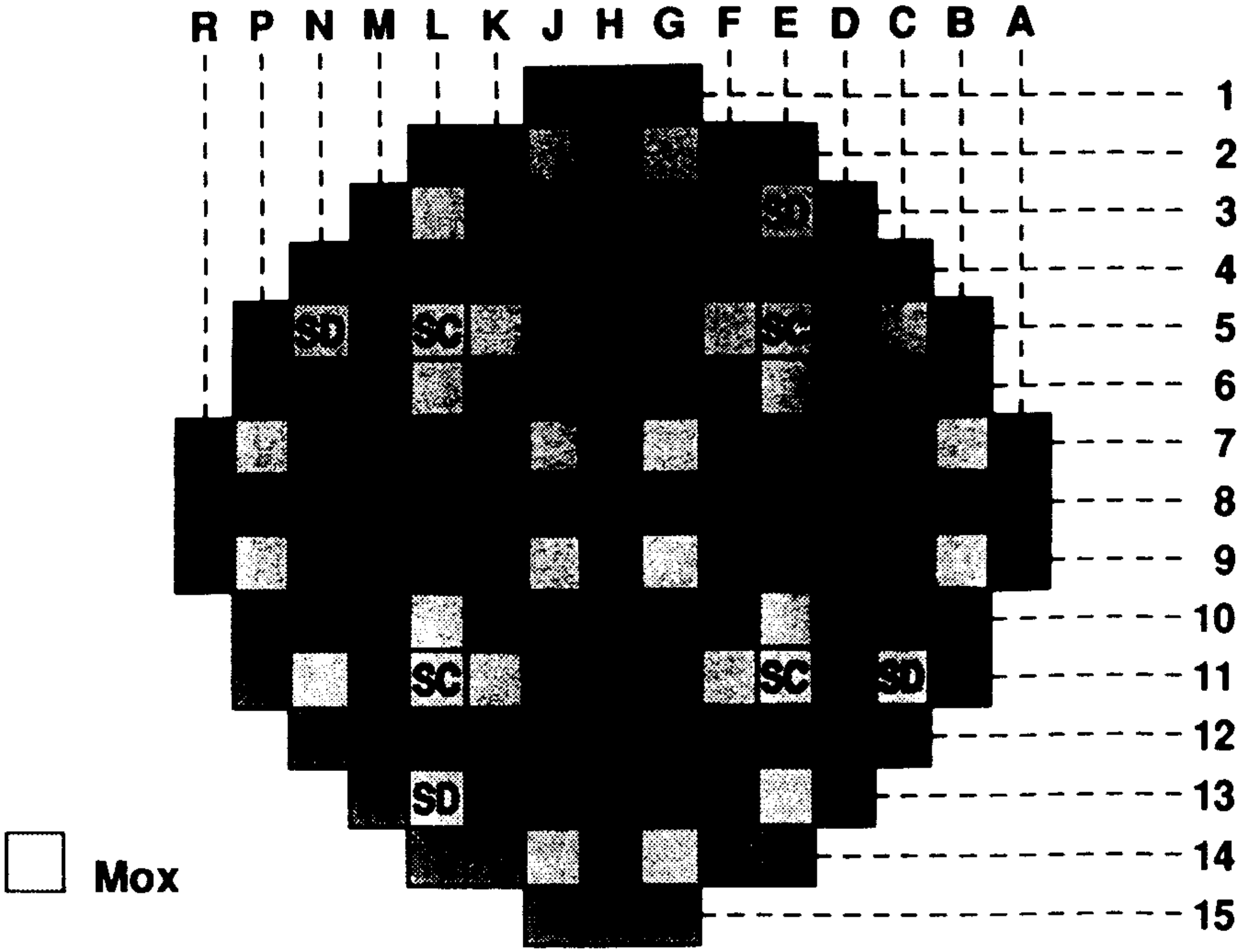
2nd CYCLE

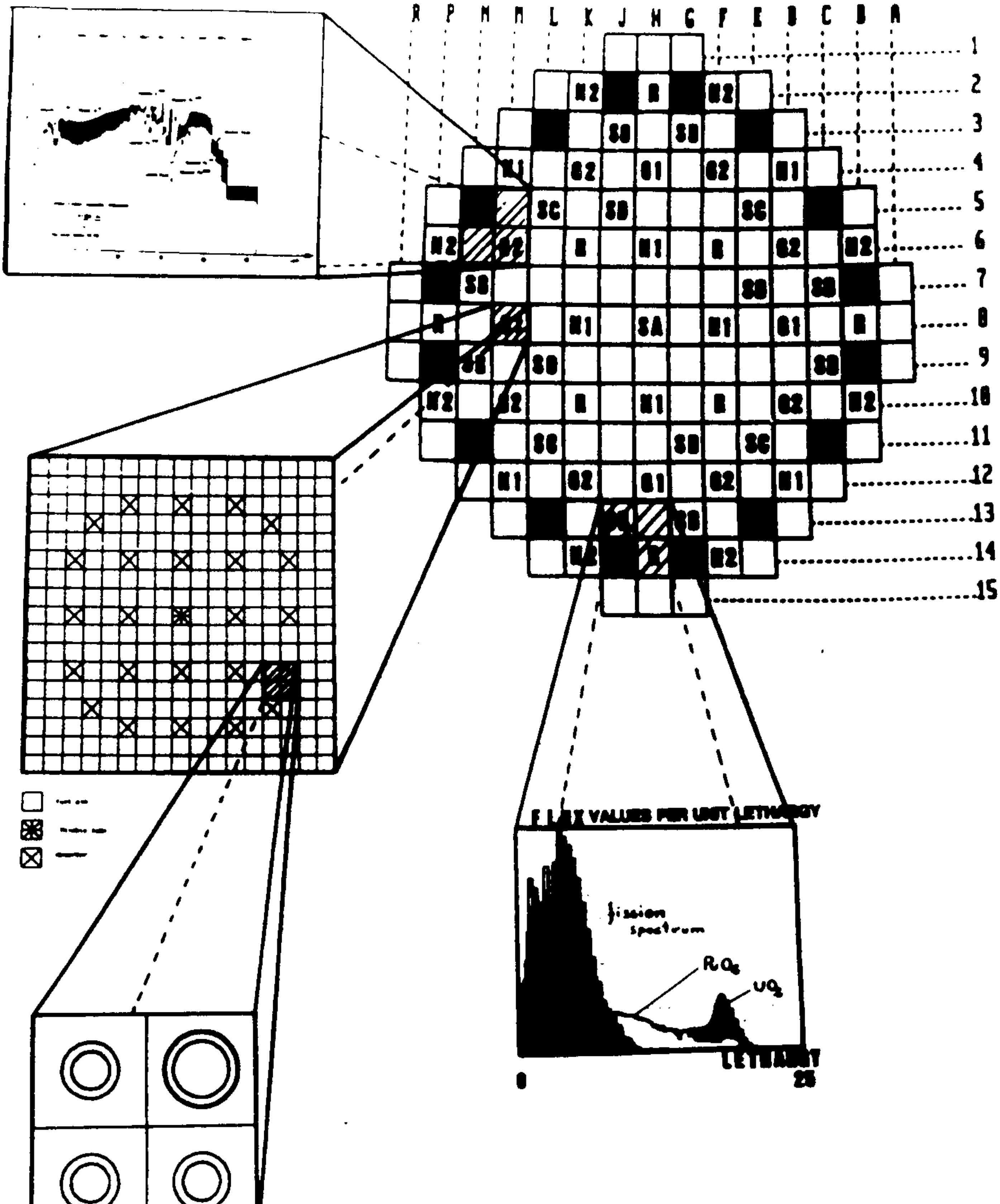


3rd CYCLE



SB 207


R
P
N
M
L
K
J
H
G
F
E
D
C
B
A
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
SD
SC
SC
SD
SC
SC
SD
SD
Mox


R P N M L K J H G F E D C B A
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
H2 R H2
SD SD
H1 G2 G1 G2 H1
SC SB SC
H2 G2 R H1 R G2 H2
SB SB SB
R H1 SA H1 G1 R
SB SB SB
H2 G2 R H1 R G2 H2
SC SB SC
H1 G2 G1 G2 H1
SB
H2 R H2
FLUX VALUES PER UNIT LETHARGY
fission spectrum
PuO2
UO2
LETHARGY
0
25

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$$\mathrm{Max}\left[P_{i,j,k}\right] = \left(\frac{P_{i,j,k}}{\bar{P}}\right) * \bar{P} =$$

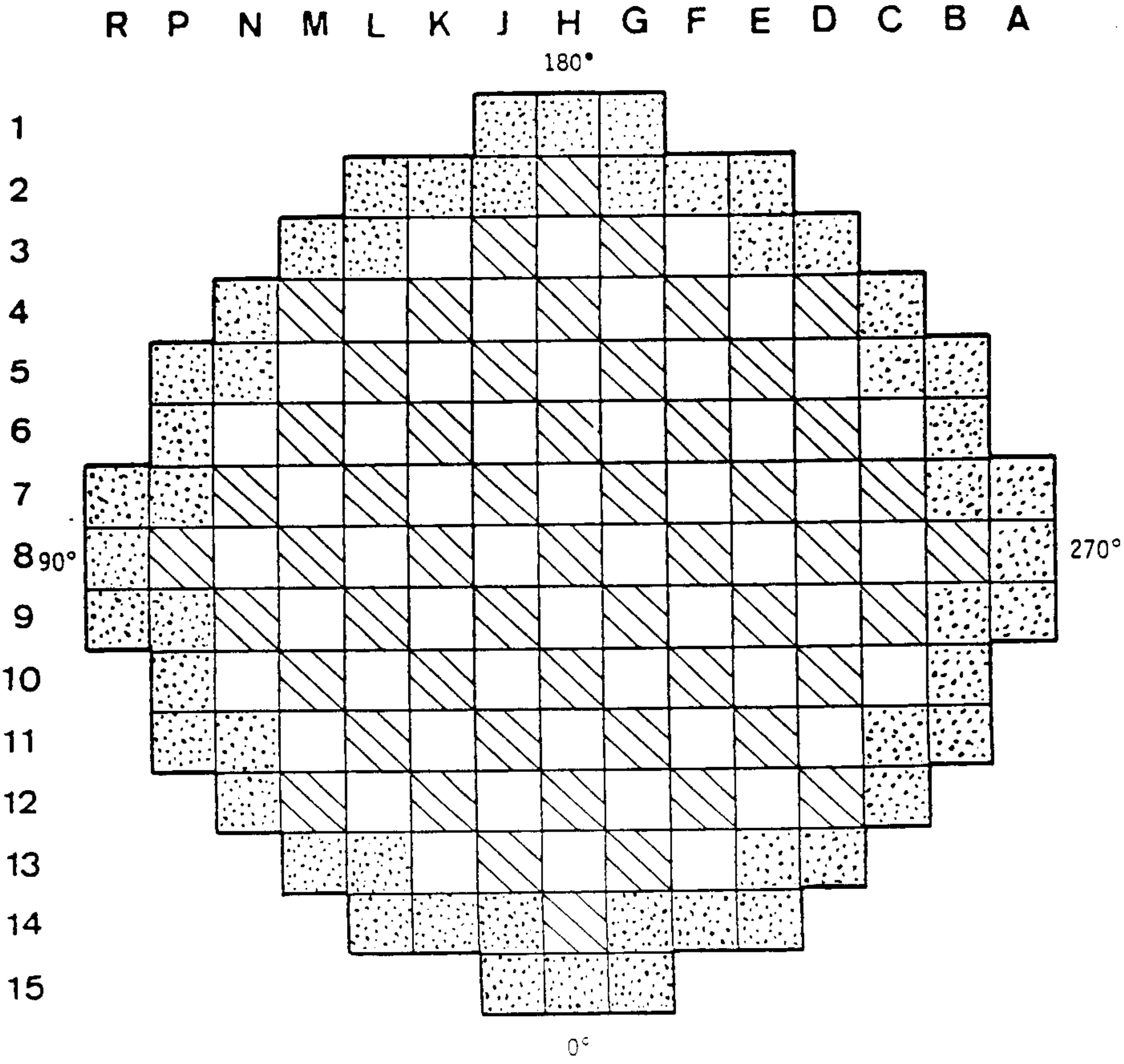
$$= \frac{P_k}{\bar{P}} * \frac{P_{i,j}}{\bar{P}} * \bar{P}^{2} =$$

$$= \left(\frac{P_k * P_{i,j}}{\bar{P}}\right) * \bar{P} * \left(\mathrm{Th}_f\right)$$

THE BURNABLE POISONS:

- *PYREX*
- *GADOLINIA*

CORE PATTERN - CYCLE 1



CYCLE 1 ENRICHMENTS

▨ Région 1 : 1,8 %

☐ Région 2 : 2,4 %

▒ Région 3 : 3,1 %

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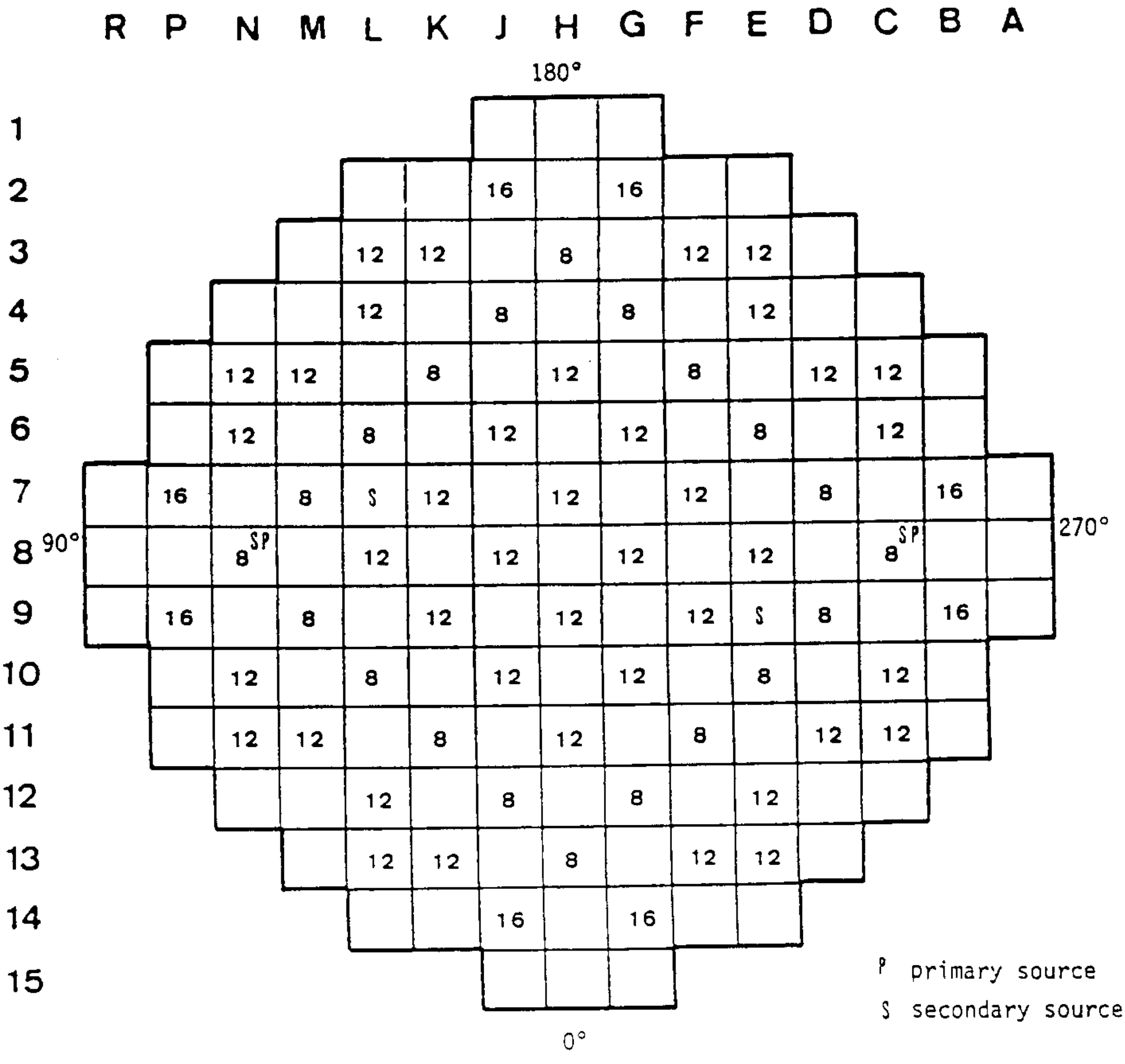
DISTRIBUTION OF BURNABLE POISON RODS IN THE CORE FOR CYCLE 1

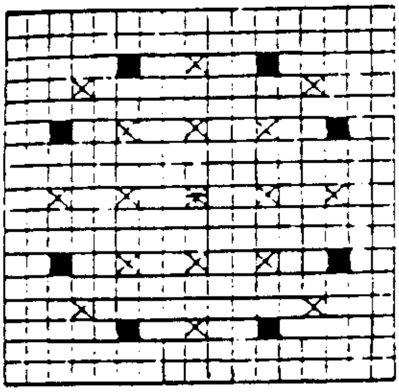


	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1															
2							16		16						
3					12	12		8		12	12				
4					12		8		8		12				
5			12	12		8		12		8		12	12		
6			12		8		12		12		8		12		
7		16		8	S	12		12		12		8		16	
8			8^{SP}		12		12		12		12		8^{SP}		
9		16		8		12		12		12	S	8		16	
10			12		8		12		12		8		12		
11			12	12		8		12		8		12	12		
12					12		8		8		12				
13					12	12		8		12	12				
14							16		16						
15															

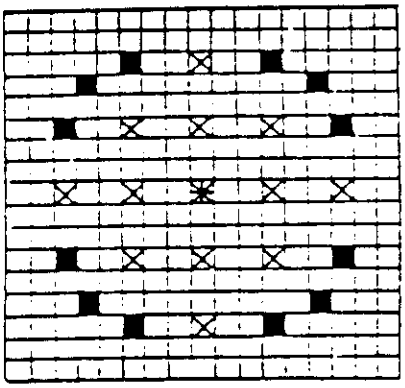
P primary source
S secondary source

X	Location of sources
XX	Number of burnable poison rods in the assembly

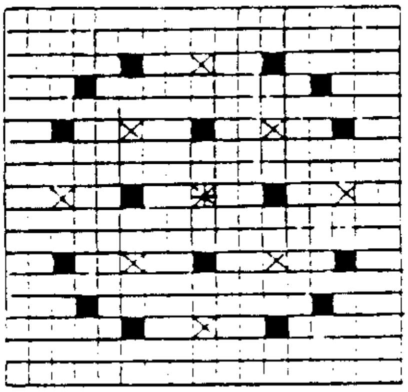
DISTRIBUTION OF BURNABLE POISON RODS IN FUEL ASSEMBLIES



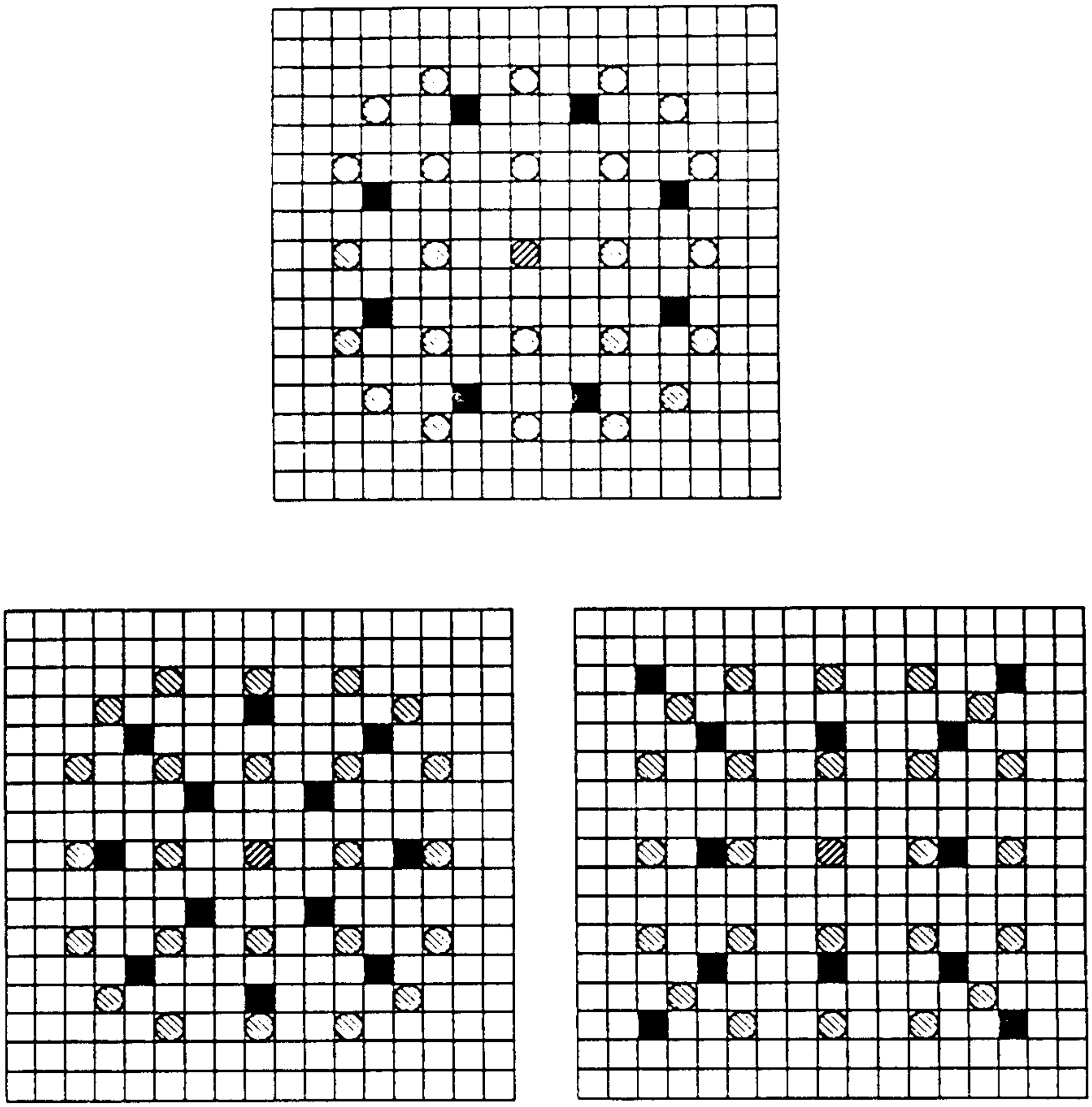
8 BP rods



12 BP rods



16 BP rods

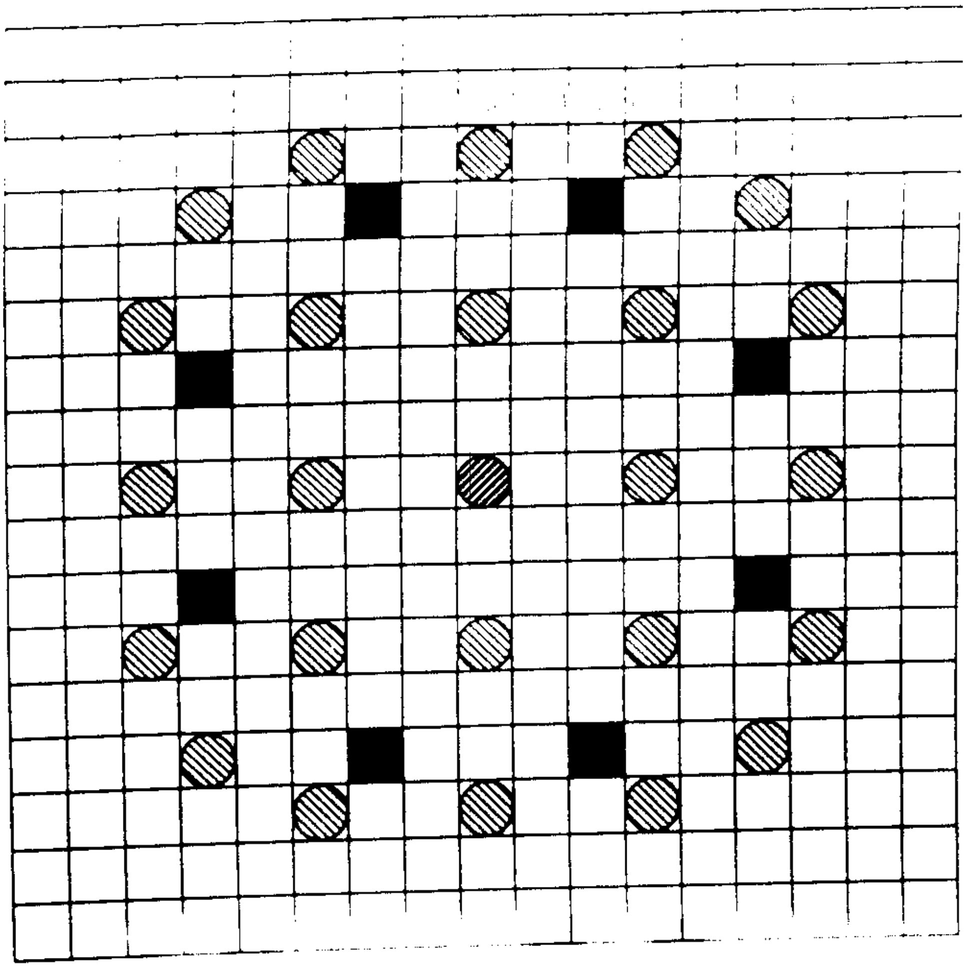


■ URANIUM OXIDE - GADOLINIUM OXIDE PINS

◍ WATER TUBES

▨ INCORE INSTRUMENTATION GUIDE TUBES

GADOLINIUM ASSEMBLY LAY-OUT



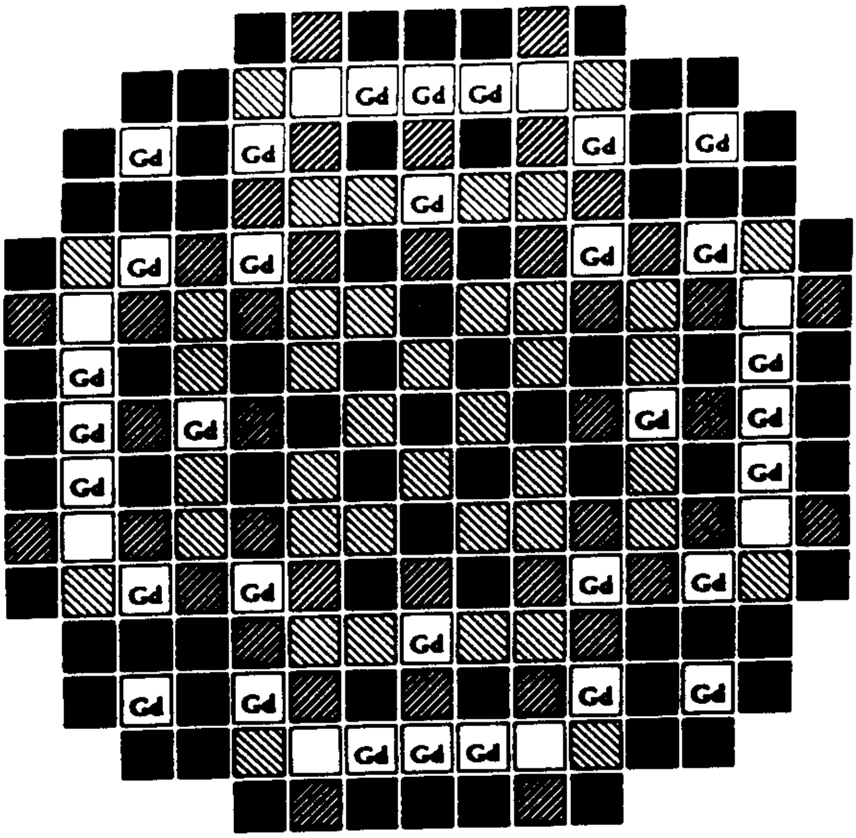
▨ *INCORE INSTRUMENTATION GUIDE TUBE*

▨ *WATER TUBES*

■ *URANIUM OXIDE - GADOLINIUM OXIDE PINS*

TYPICAL 8 GADOLINIUM PINS ASSEMBLY LAY-OUT

FRAMATOME



■ *5TH CYCLE ASSEMBLIES*

▨ *4TH CYCLE ASSEMBLIES*

▧ *THIRD CYCLE ASSEMBLIES*

■ *SECOND CYCLE ASSEMBLIES*

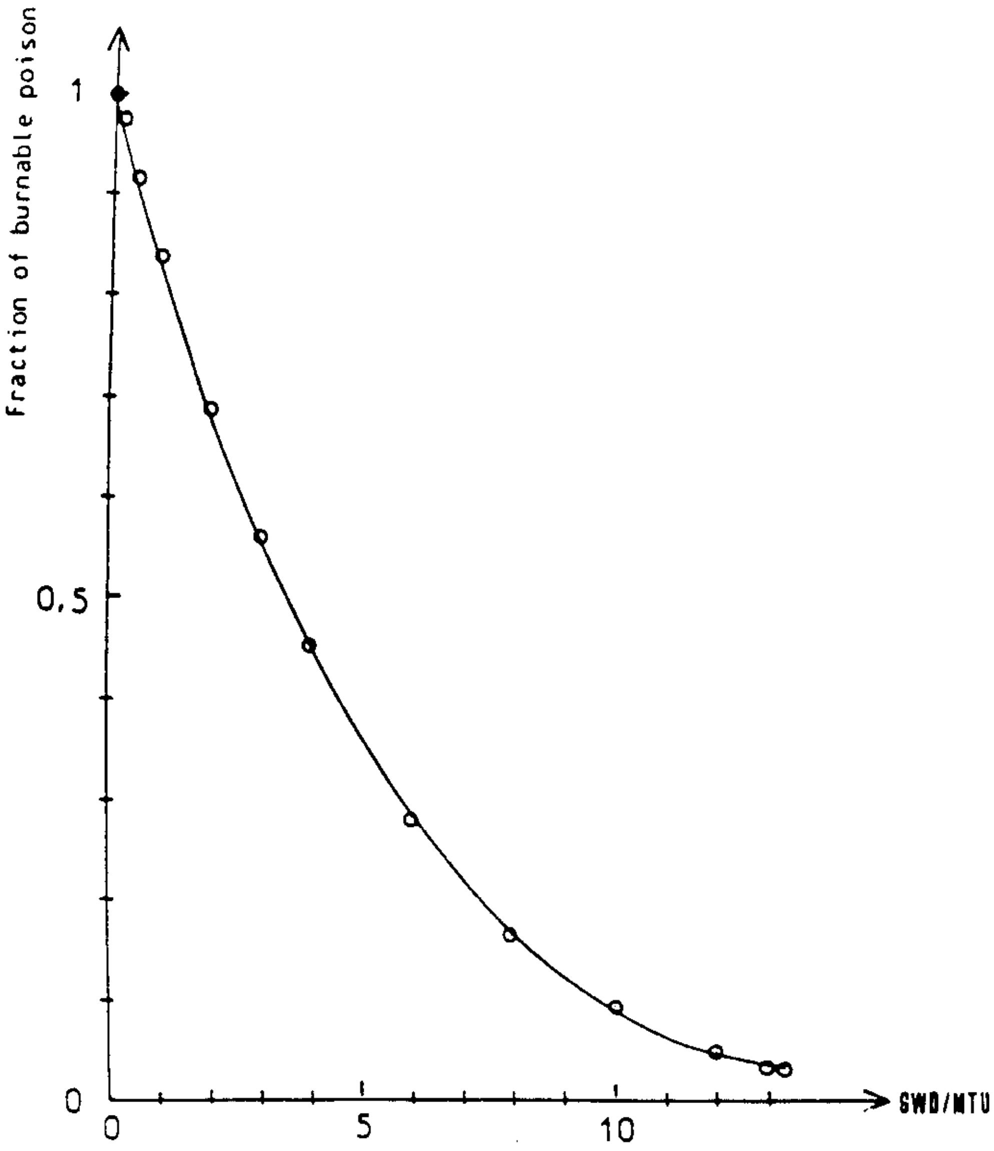
□ *FIRST CYCLE ASSEMBLIES*

TYPICAL GADOLINIUM EQUILIBRIUM CORE LAY-OUT

1300 MWE *(HYBRID LOADING STRATEGY)*

FRAMATOME

FRACTION OF BURNABLE POISON VS CYCLE 1 BURN-UP

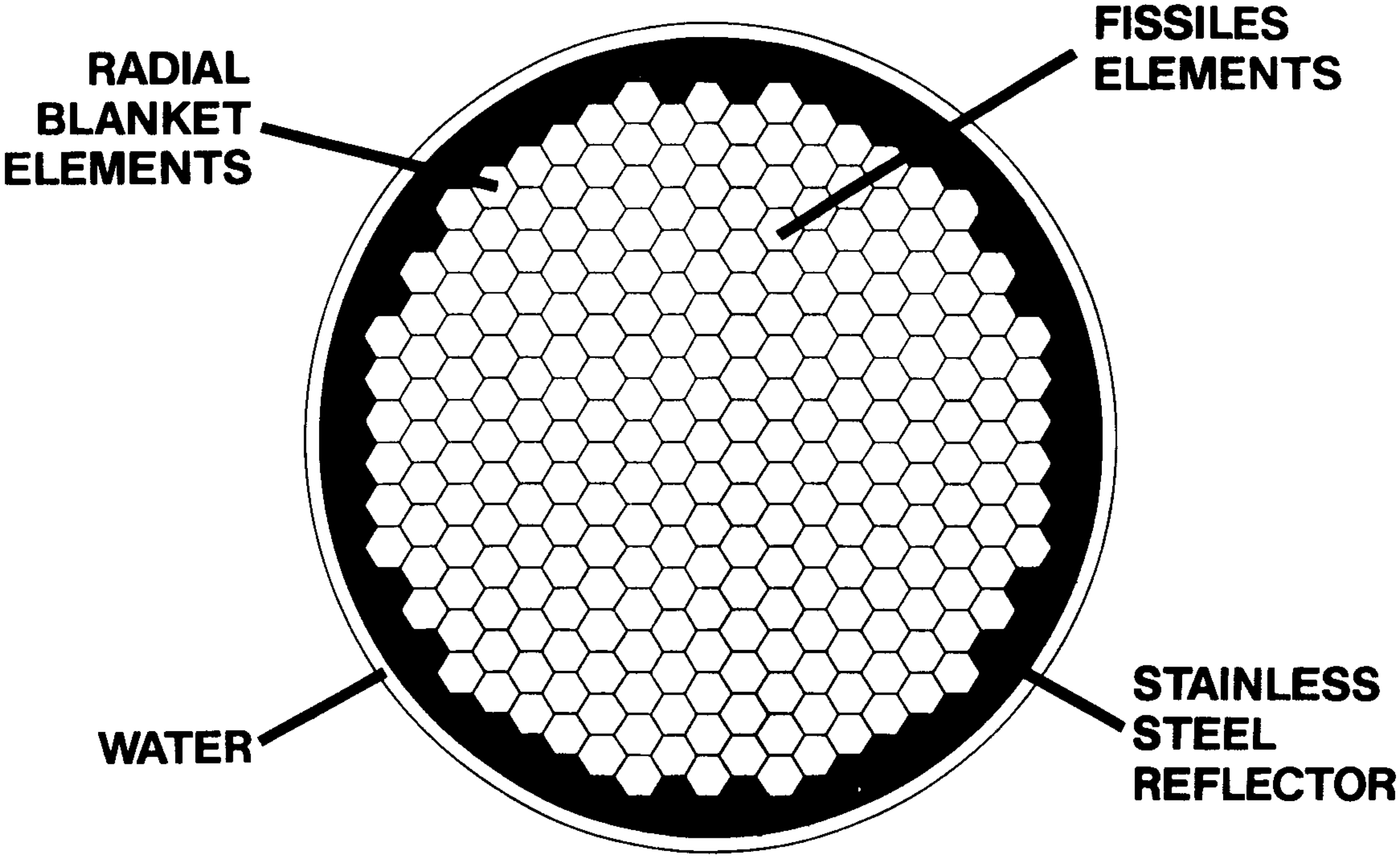


FRAMATOME

FRAMATOME

THE SPECTRAL SHIFT

Pu FUELED RCVS
SIMPLIFIED CORE LAY-OUT



RADIAL
BLANKET
ELEMENTS

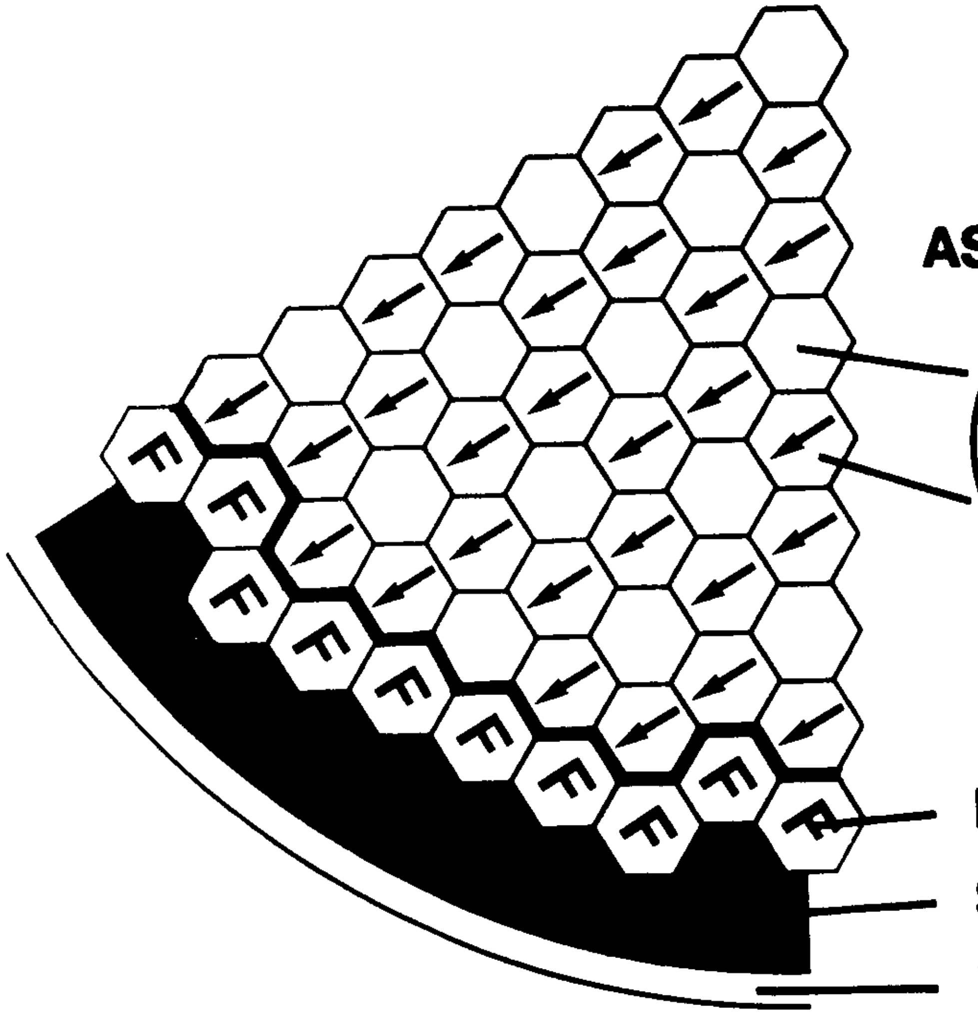
FISSILES
ELEMENTS

WATER

STAINLESS
STEEL
REFLECTOR

FRAMATOME

1 /6 Pu FUELED RCVS CORE LAY-OUT



ASSEMBLIES EQUIPPED WITH

ABSORBENT CLUSTER

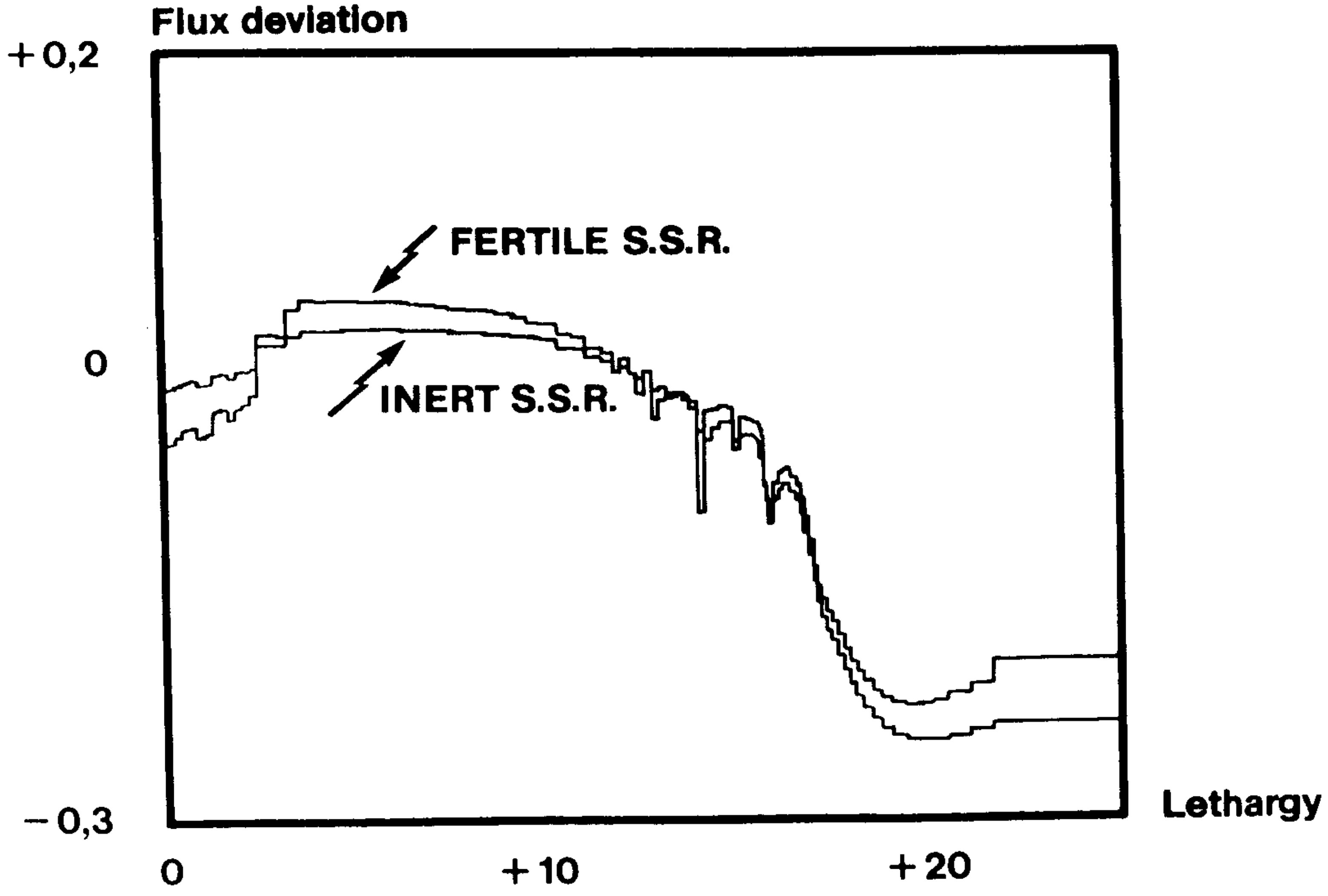
SPECTRAL SHIFT CLUSTER

RADIAL BLANKET ELEMENTS

STAINLESS STEEL REFLECTOR

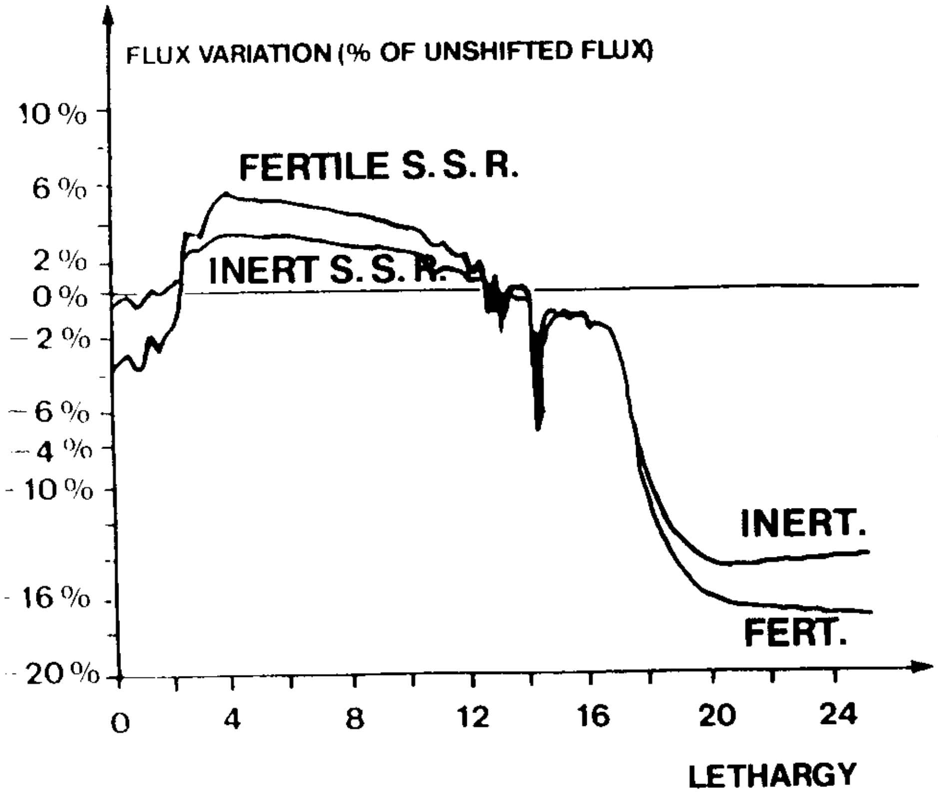
WATER

SPECTRAL SHIFT EFFECT ON THE NEUTRON SPECTRUM

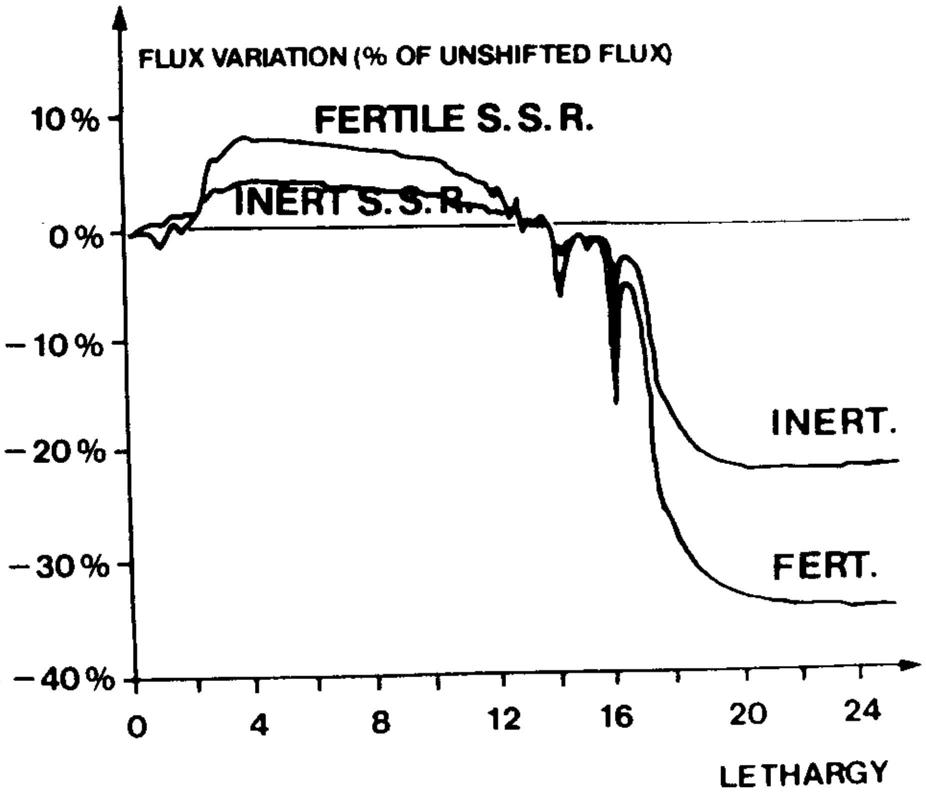


FRAMATOME

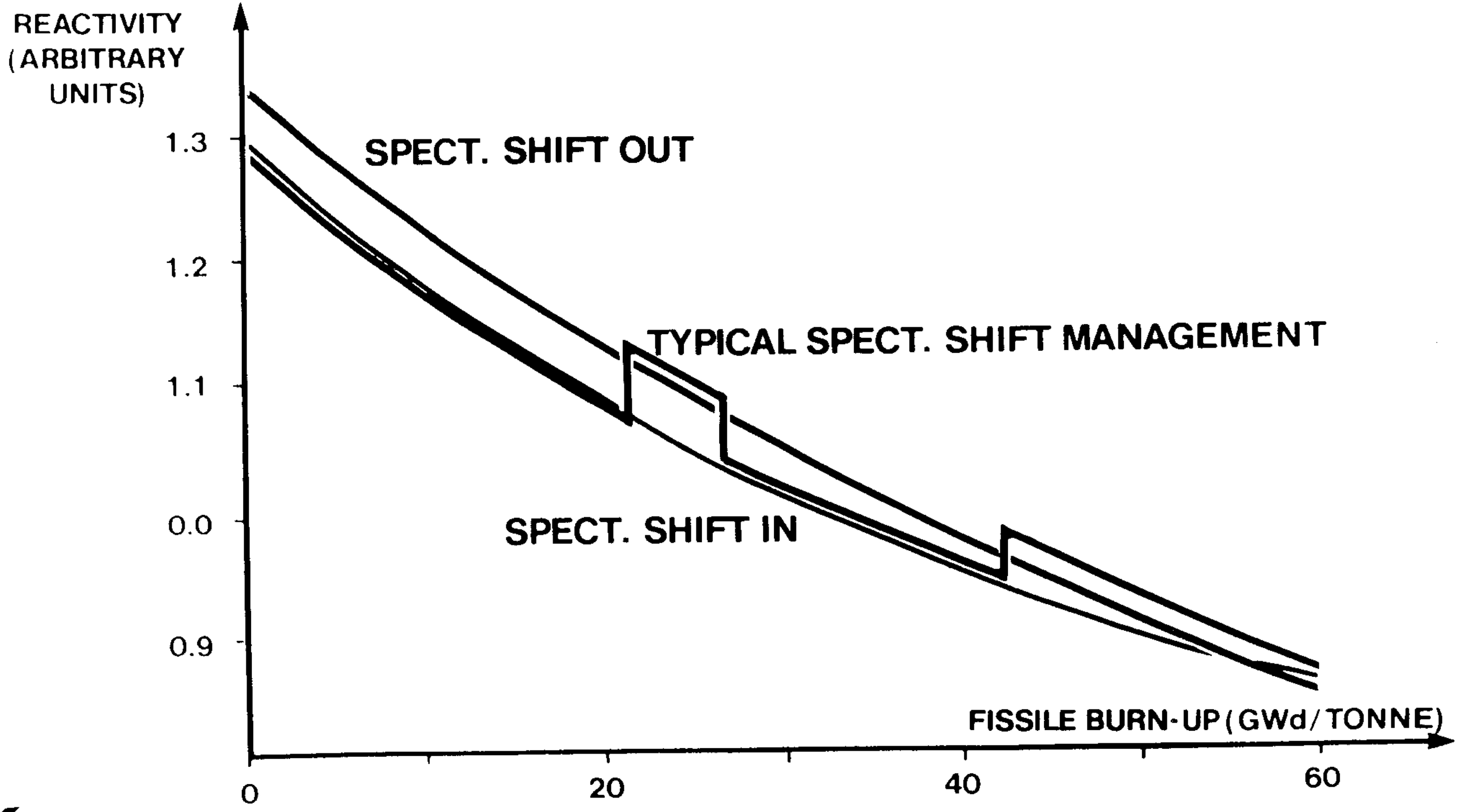
SPECTRAL SHIFT EFFECT
ON THE NEUTRON SPECTRUM
(ZERO BURN-UP)



SPECTRAL SHIFT EFFECT
ON THE NEUTRON SPECTRUM
(40 GWd/TONNE)



SPECTRAL SHIFT MANAGEMENT EFFECT



SAFETY

SAFETY AND ECONOMICS

SAFETY ACTS ON A PLANT DESIGN VIA A NUMBER OF CRITERIA, WHICH TRANSLATE INTO A SYNTHETIC PRESCRIPTIVE WAY THE NEED FOR THE INTEGRITY OF THE FUEL AND THE CONFINEMENT DURING THE NORMAL OPERATION, THE SHUT-DOWN AND ANY INCIDENTAL OR ACCIDENTAL SITUATION

OWING TO THEIR NATURE, THE SAFETY CRITERIA ARE ADAPTED TO THE PLANT FEATURES, TO THE NATURE OF THE GRID AND THE EXPLOITATION CONSTRAINTS: THEY CAN VARY SIGNIFICANTLY FROM COUNTRY TO COUNTRY

THE COST OF A NUCLEAR PRODUCED KWE CAN SPAN A WIDE RANGE, DEPENDING ON MANY INDEPENDENT PARAMETERS STRICTLY RELATED TO THE COUNTRY: GRID, INDUSTRIAL CAPACITY, ABUNDANCE OF FOSSIL FUELS, FINANCING AND INFLATION RATE, ETC.

IN THIS CONTEXT, THE POWER PLANT DESIGNER IS OFTEN PARTICULARLY INTERESTED IN THE <u>FUEL CYCLE COST</u> FIGURE

TRANSLATION OF THE SAFETY CRITERIA INTO DESIGN CONSTRAINTS

THE THREE LEVELS OF THE CONFINEMENT

- *THE CLADDING*
- *THE VESSEL*
- *THE CONCRETE CONFINEMENT*

1) THE CLADDING:
- *OVERPOWER*
- *OVER PRESSURE, (FISSION PRODUCTS BUILD-UP)*
- *BUBBLING AND CORROSION*
- *INTERACTION PELLET - CLADDING*
- *AGEING*

2) THE VESSEL:
- *OVER PRESSURE*
- *AGEING, (DPA)*

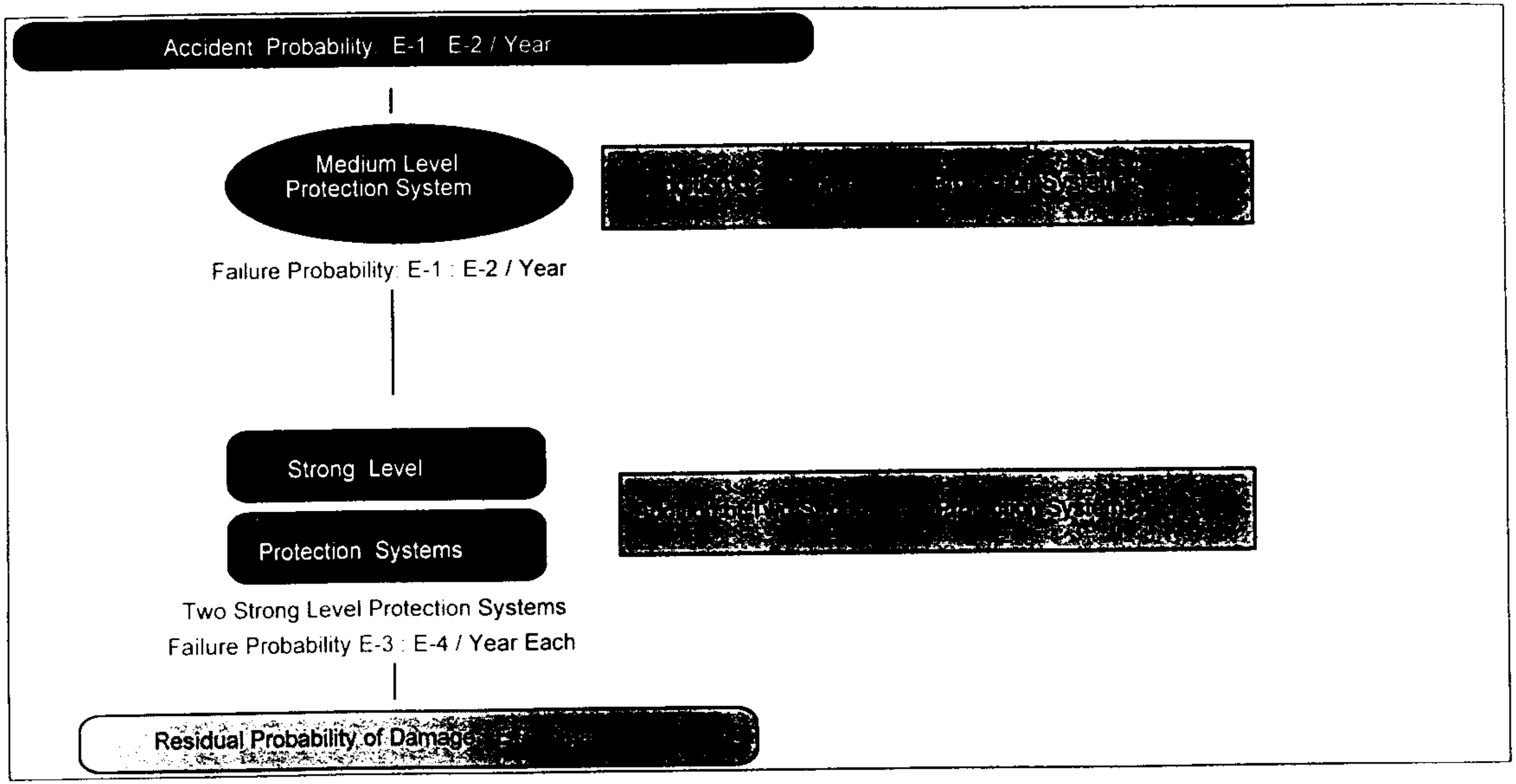
3) THE CONCRETE CONFINEMENT
- *OVER PRESSURE*

CRITERIA & MARGINS

IN ORDER TO GUARANTEE THE RESPECT OF THE MAXIMUM VALUES OF THE LOCAL POWER ALLOWED BY THE CLADDING INTEGRITY CRITERIA, PROJECT MARGINS ARE INFORCED ON EVERY COMPUTED REACTOR PARAMETER; THESE MARGINS ARE MORE IMPORTANT WHEN THE ON-LINE CONTROL IS LOW OPERATING

SOURCES OF UNCERTAINTY:

- *THE COMPUTATIONAL METHODOLOGY*
- *THE BASIC DATA, (X. S. LIBRARIES)*
- *ALEA, (TECHNOLOGY OF THE FUEL, FABRICATION UNCERTAINTIES, LOADING, POSITION OF CONTROL BANKS, ETC.)*



Accident Probability E-1 E-2 / Year

Medium Level Protection System

[redacted]

Failure Probability: E-1 : E-2 / Year

Strong Level

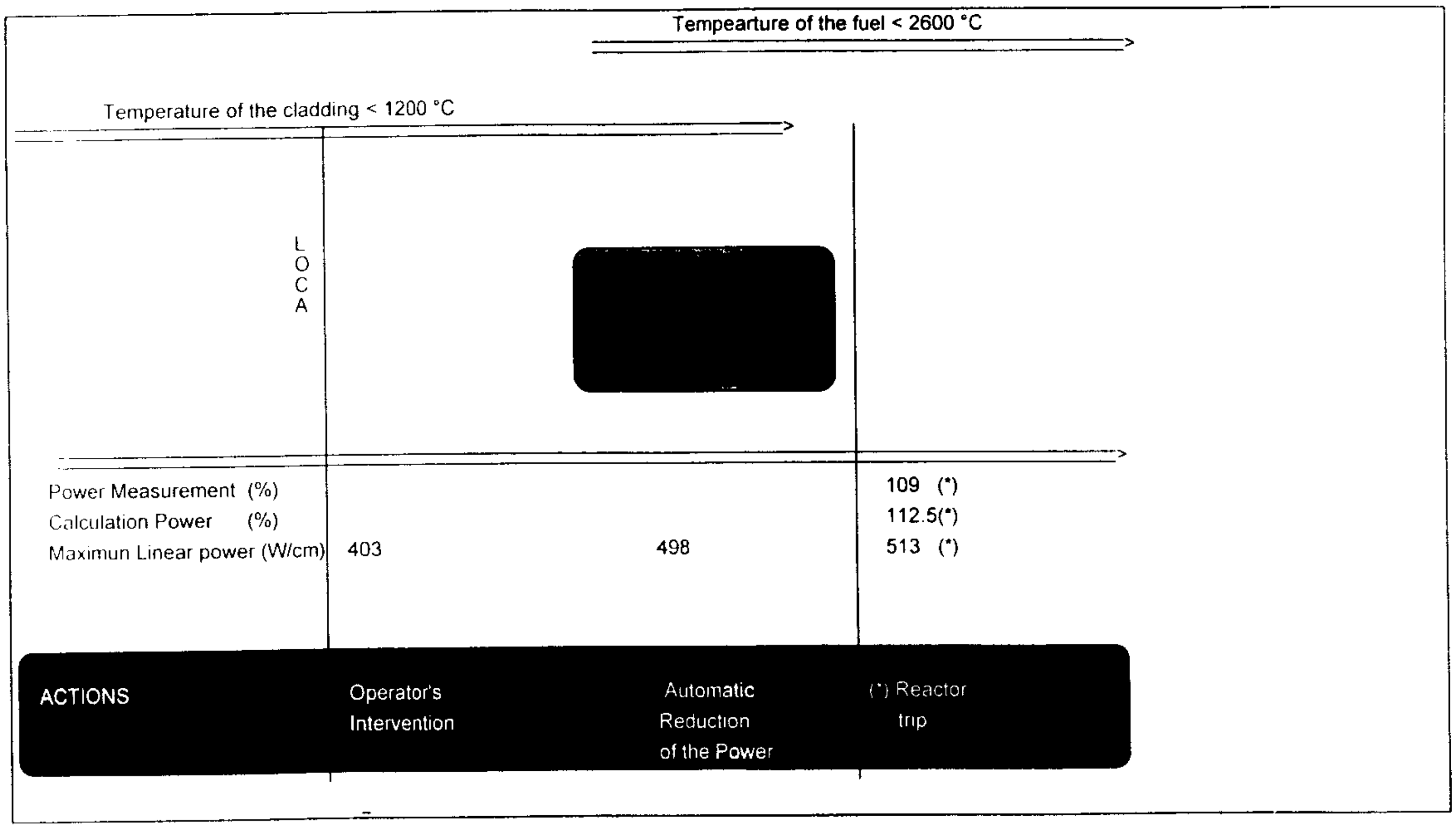
Protection Systems

[redacted]

Two Strong Level Protection Systems

Failure Probability E-3 : E-4 / Year Each

Residual Probability of Damage [redacted]



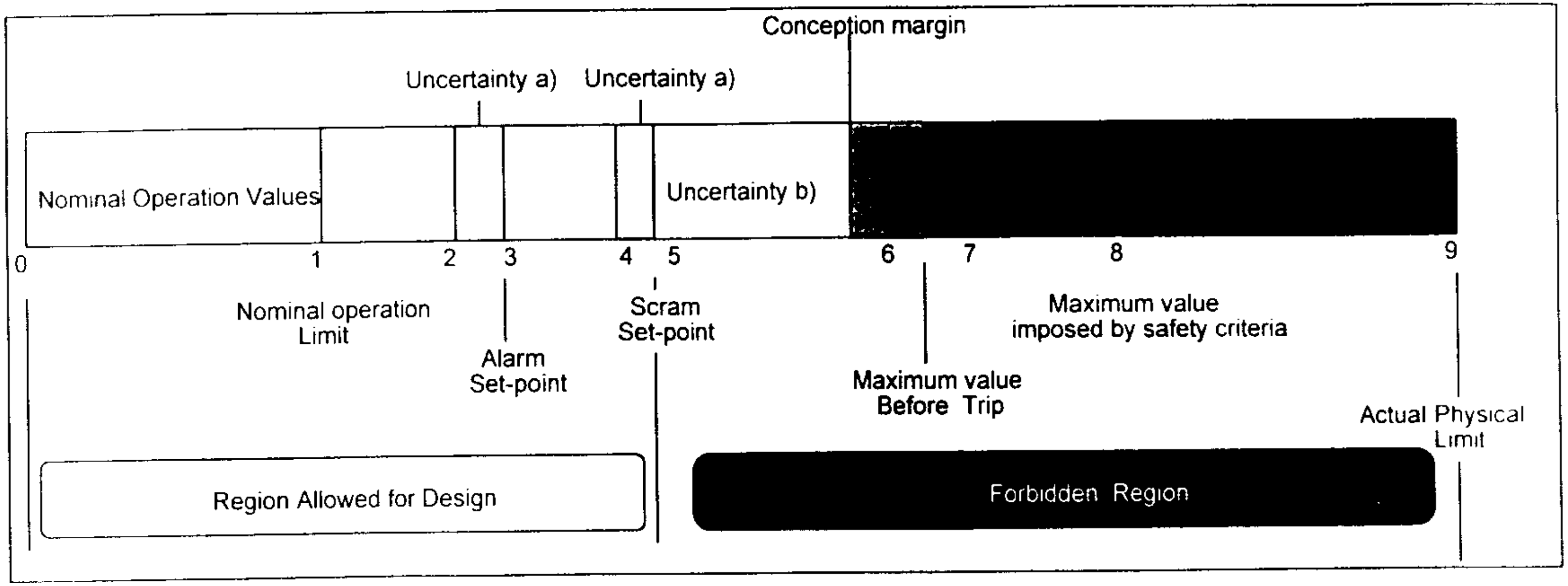
Tempearture of the fuel < 2600 °C

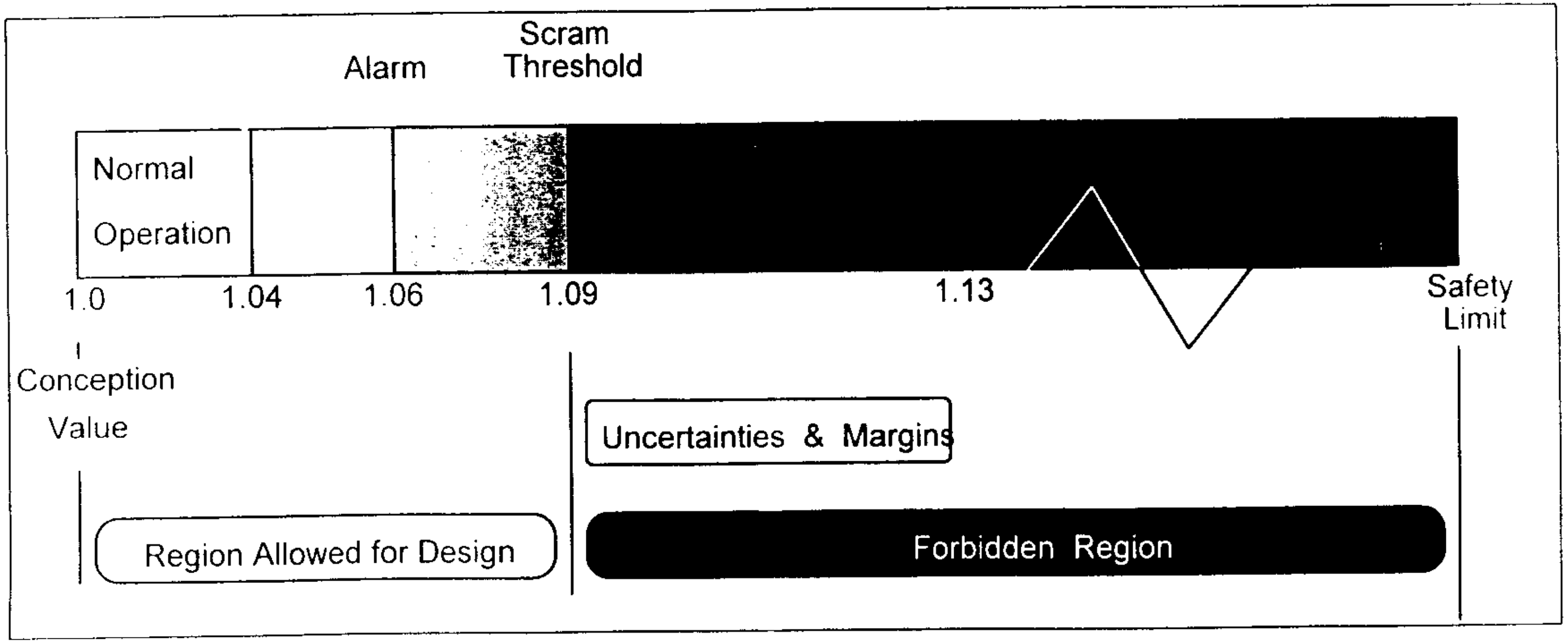
Temperature of the cladding < 1200 °C

L
O
C
A

[redacted]

Power Measurement (%)			109 (*)
Calculation Power (%)			112.5(*)
Maximun Linear power (W/cm)	403	498	513 (*)
ACTIONS	Operator's Intervention	Automatic Reduction of the Power	(*) Reactor trip


Conception margin
Uncertainty a)
Uncertainty a)
Nominal Operation Values
Uncertainty b)
0
1
2
3
4
5
6
7
8
9
Nominal operation Limit
Alarm Set-point
Scram Set-point
Maximum value Before Trip
Maximum value imposed by safety criteria
Actual Physical Limit
Region Allowed for Design
Forbidden Region


Scram
Threshold
Alarm
Normal
Operation
1.0
1.04
1.06
1.09
1.13
Safety
Limit
Conception
Value
Uncertainties & Margins
Region Allowed for Design
Forbidden Region

ECONOMICS

FRAMATOME

SOME CONSIDERATIONS ON THE ECONOMY OF NUCLEAR POWER

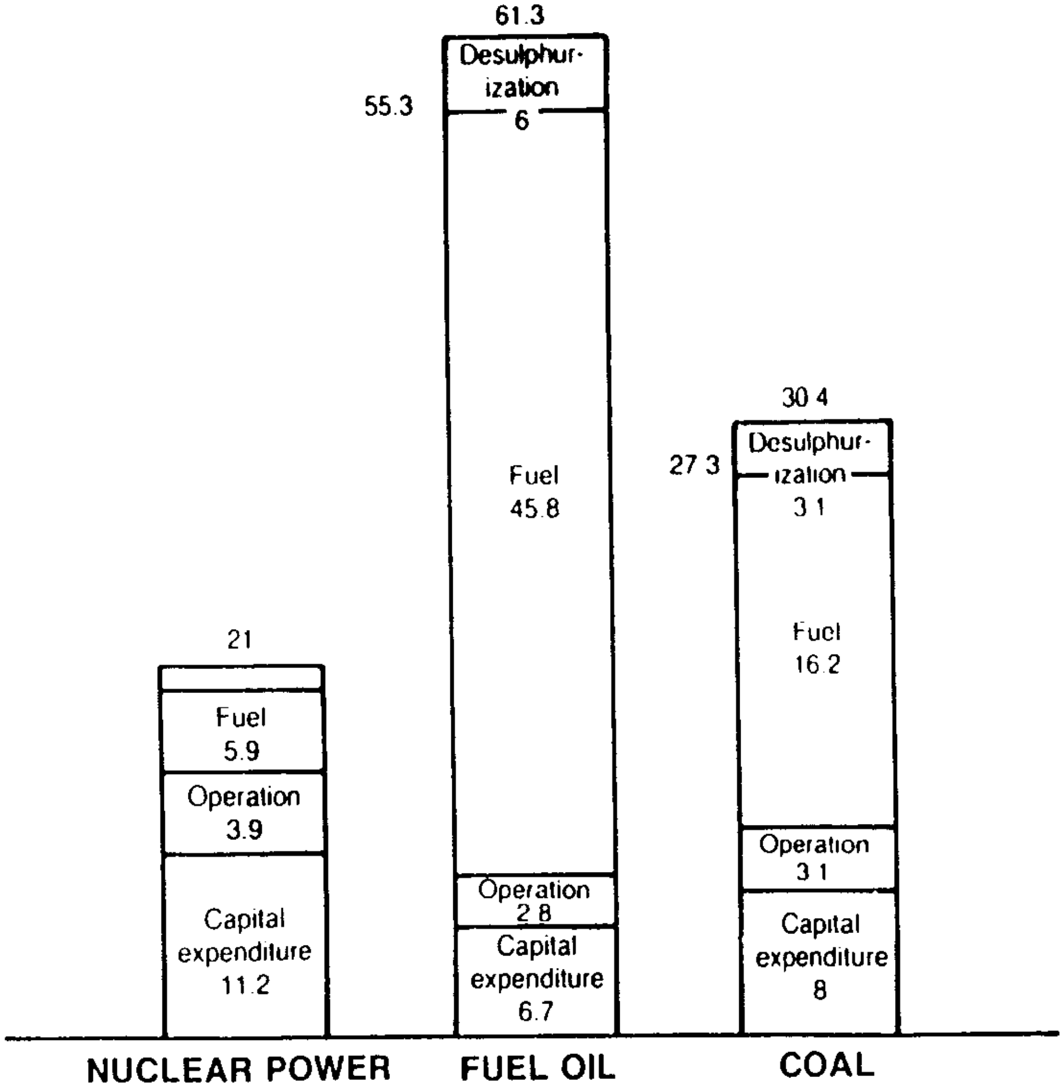
THE FUEL CYCLE

- *THE MINING*
- *THE ENRICHMENT*
- *THE FABRICATION PROCESS*
    - *THE PELLET*
    - *THE FUEL ROD*
    - *THE FUEL ASSEMBLY*
- *THE REACTOR CYCLE*
- *THE POST IRRADIATION STORAGE*
- *THE REPROCESSING*

THE CYCLE COST

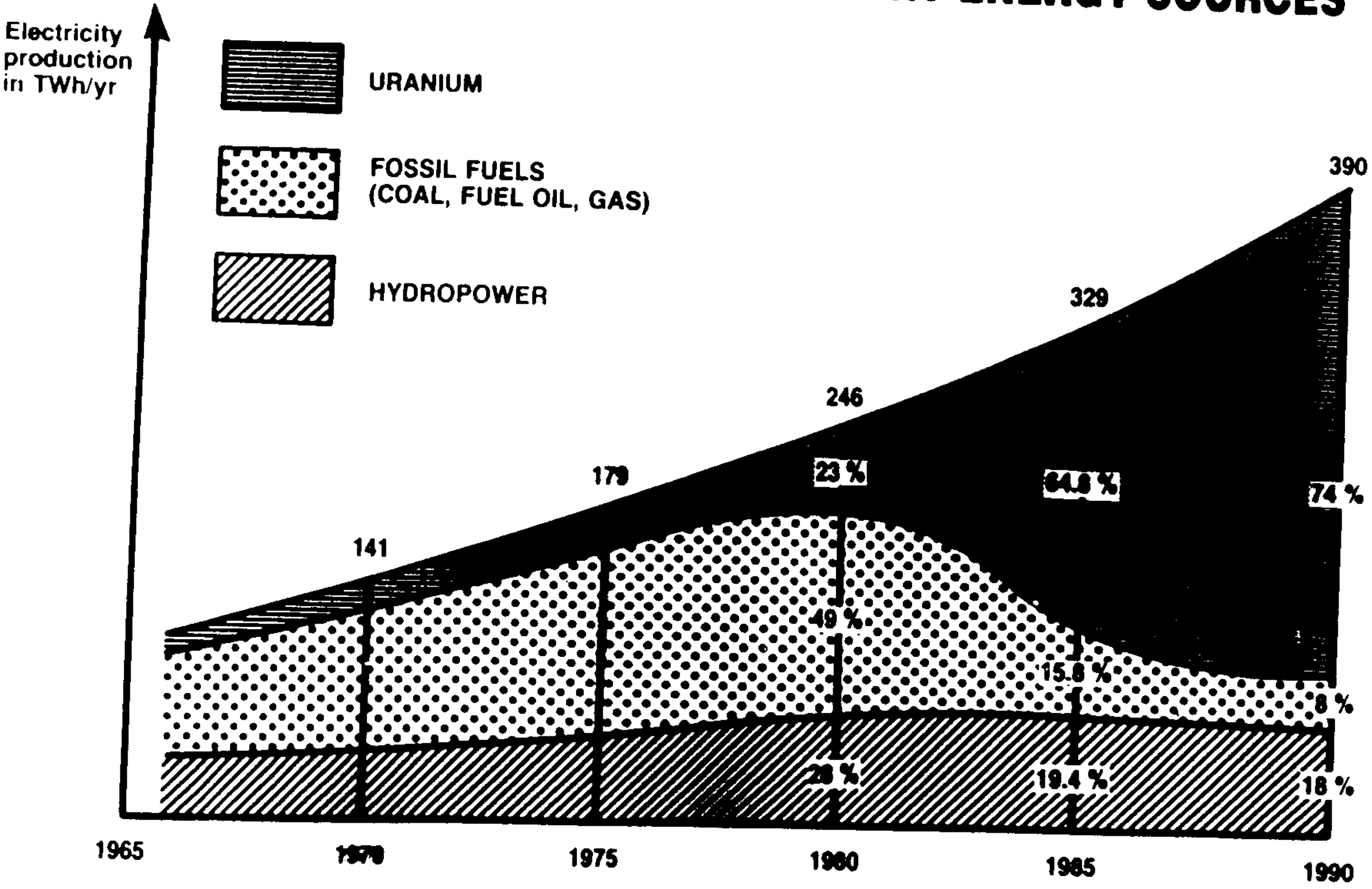
- *THE INVESTMENT, (INTERESTS AND ACTUALISATION RATE)*
- *THE FABRICATION*
- *THE EXPLOITATION, (LOADING STRATEGY, REFUELLING, GRID FOLLOW-ON)*
- *THE STORAGE AND REPROCESSING*

STRUCTURE OF THE COST PER KILOWATT-HOUR



Value in 1986 French Centimes for a Unit Commissioned in 1995

ELECTRICAL PRODUCTION IN FRANCE BETWEEN 1965 AND 1990 : CONTRIBUTION OF THE DIFFERENT PRIMARY ENERGY SOURCES



FRAMATOME

LOADING STRATEGIES

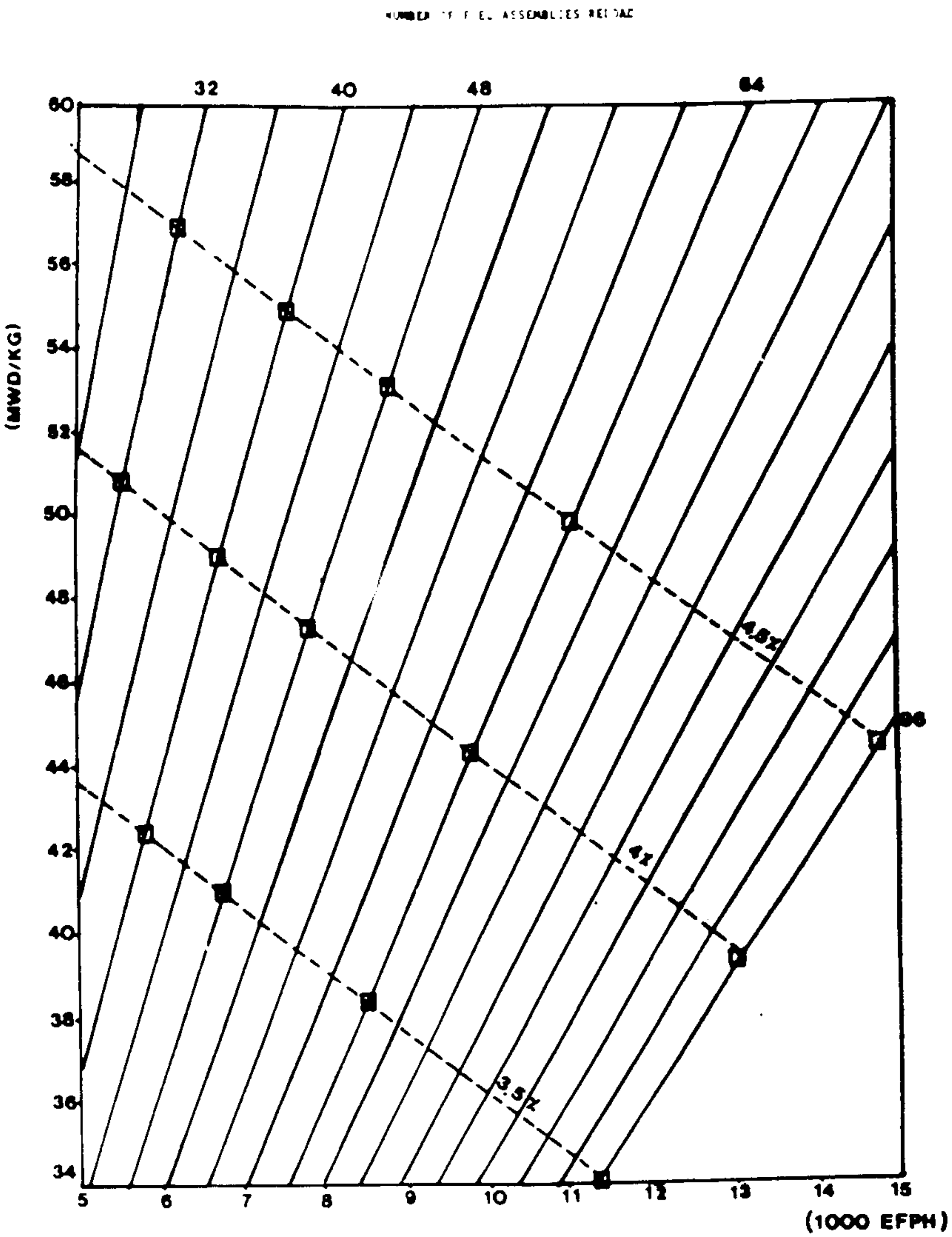
CRITERIA:

- MAXIMISE THE ENERGY RELEASE PER ASSEMBLY
- RESPECT THE SAFETY CRITERIA AT ANY TIME IN THE CYCLE FOR EVERY EXPLOITATION CONDITION
- FULFILL THE NEEDS OF THE EXPLOITING COMPANY AS REGARDS THE EXPLOITATION CONDITIONS, (GRID FOLLOW-ON, REFUELLING SCHEDULE AND PLANNING)

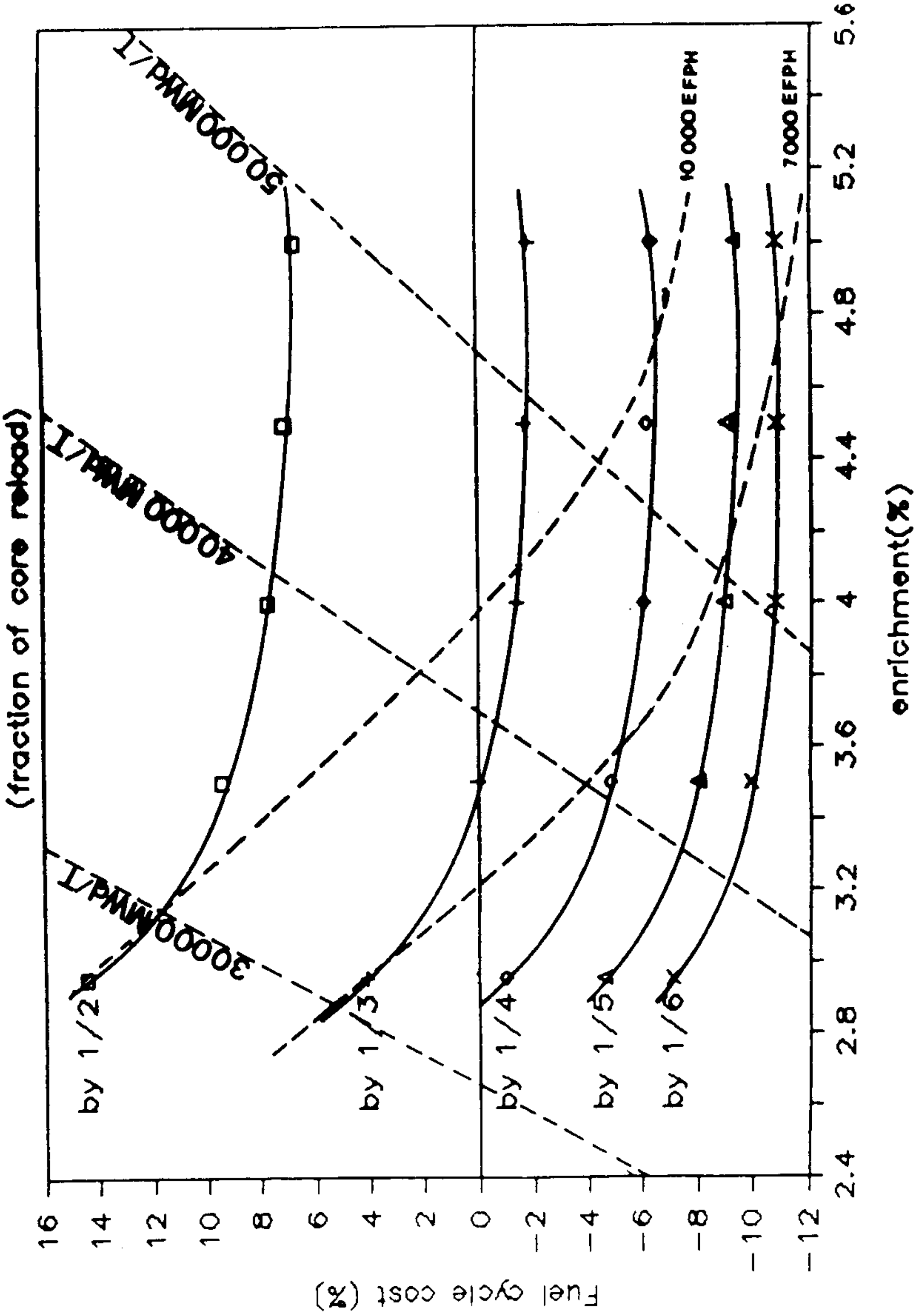
SEVERAL REFUELLING STRATEGIES:

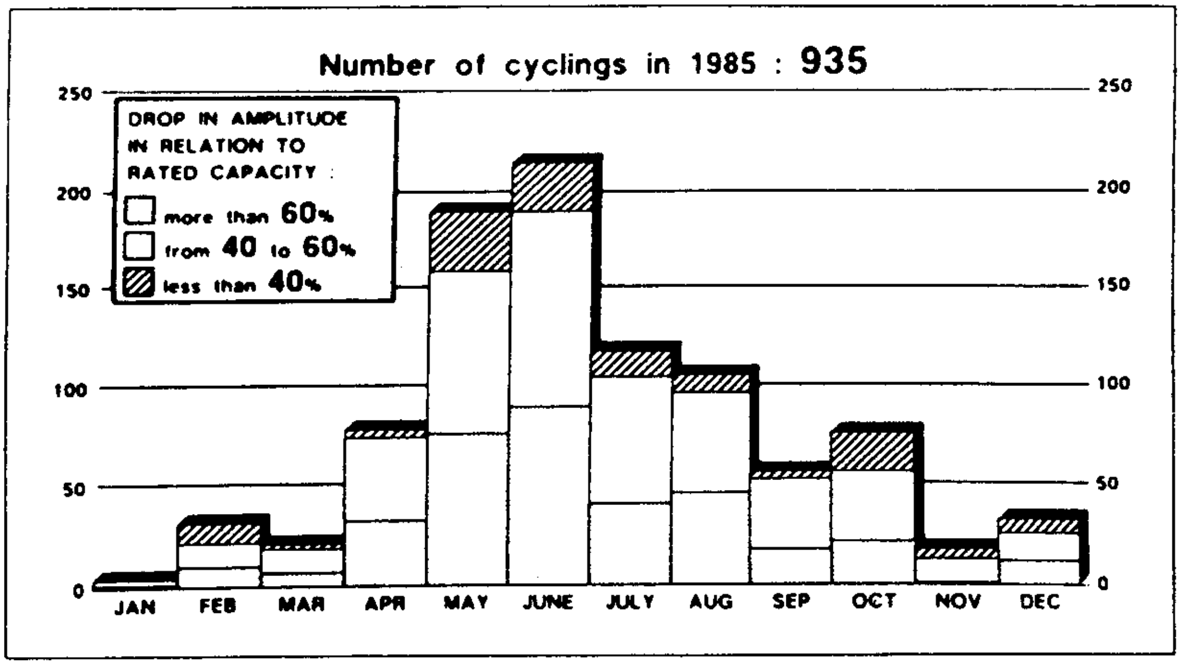
- THE "CLASSICAL" OUT -> IN
- THE "MODERN" IN -> OUT
- THE "HYBRID"
- THE "MIXED FUEL", (UO2 - MOX)

FUEL MANAGEMENT



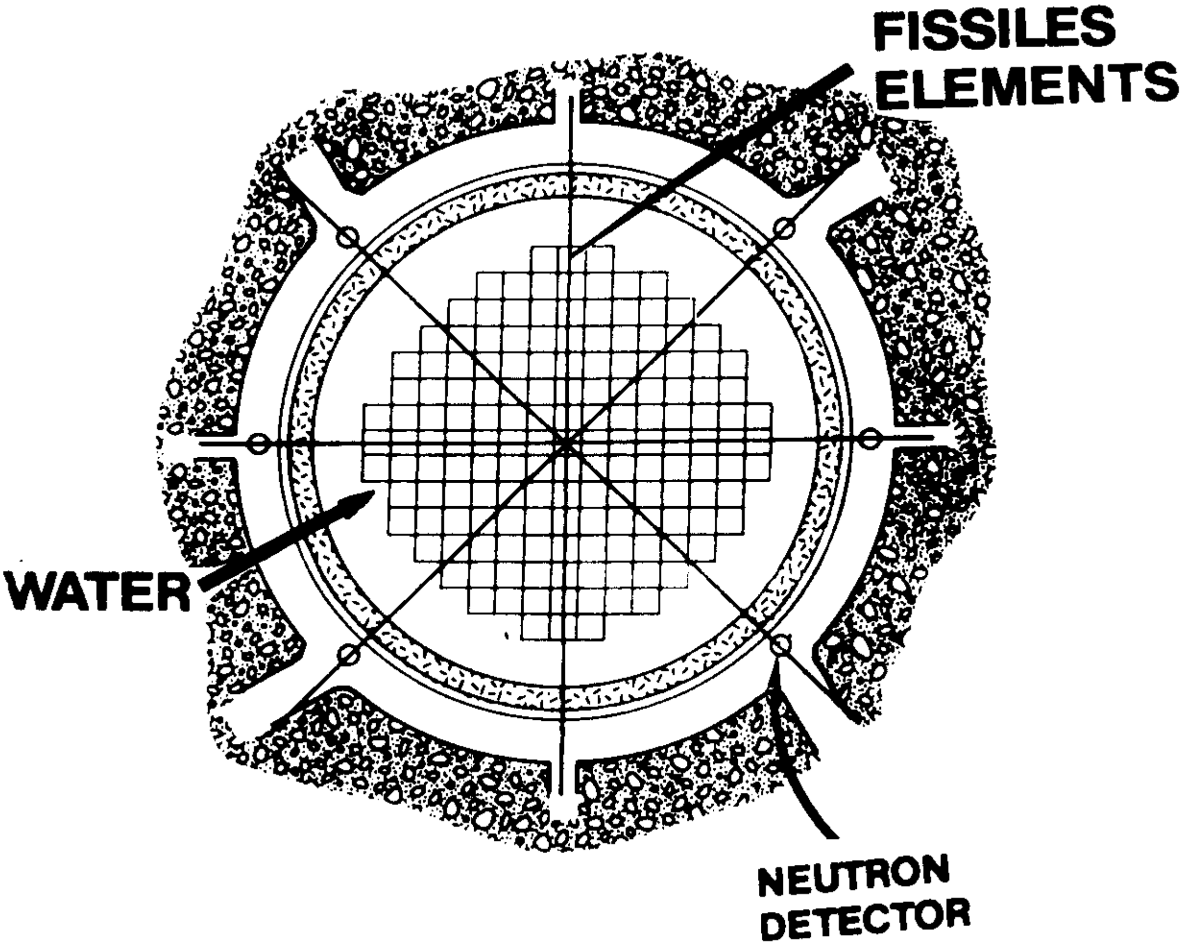
AVERAGE DISCHARGE BURNUP V S CYCLE LENGTH


(fraction of core reload)
by 1/2
by 1/3
by 1/4
by 1/5
by 1/6
30000 MWd/T
40000 MWd/T
50000 MWd/T
10 000 EFPH
7000 EFPH
enrichment(%)
2.4
2.8
3.2
3.6
4
4.4
4.8
5.2
5.6
Fuel cycle cost (%)
16
14
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
−12



CONTRIBUTION OF FRENCH PWR UNITS TO ANNUAL LOAD FOLLOW (TYPICAL FIGURES, YEAR 1985)

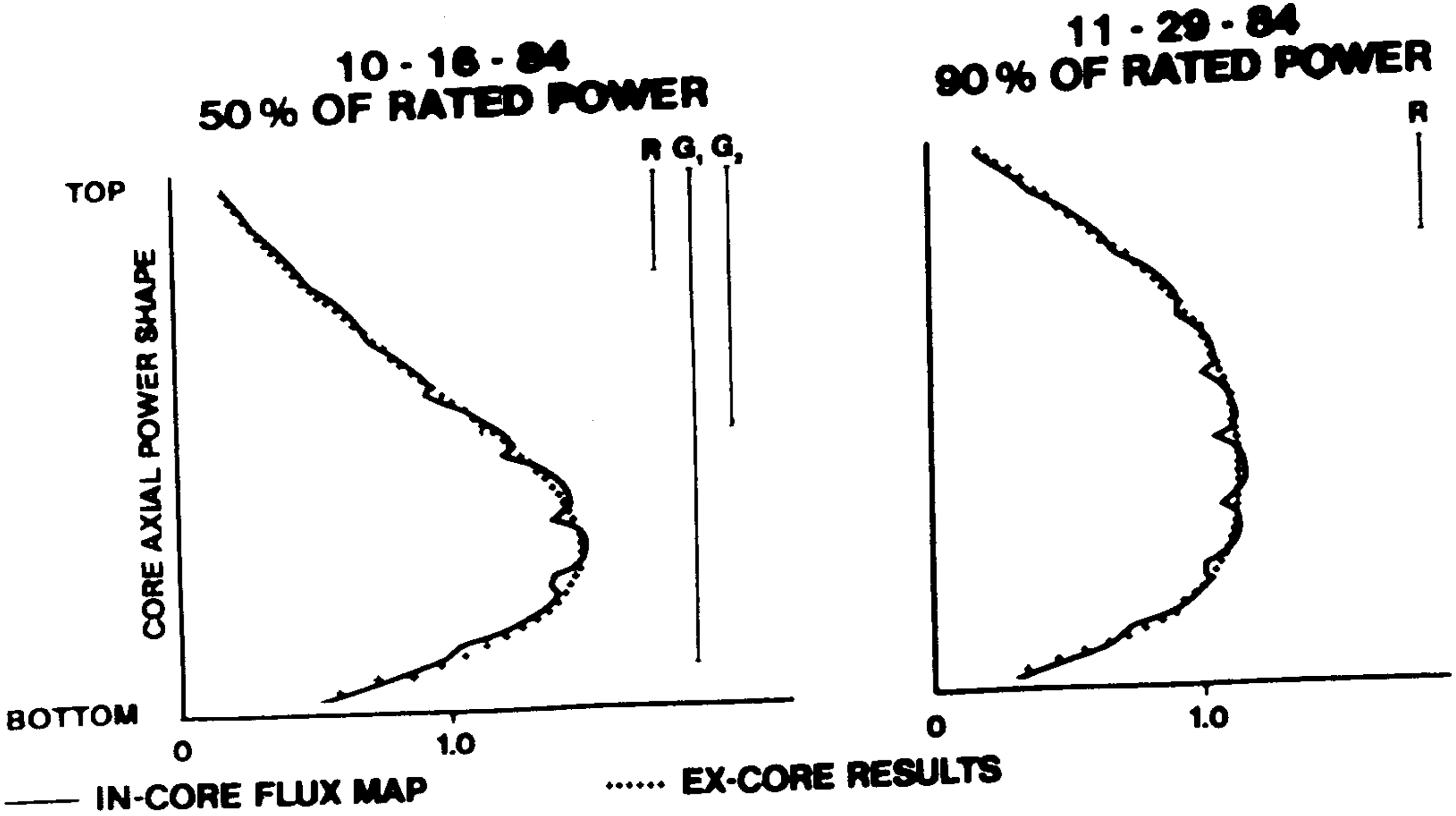
FRAMATOME



SIMPLIFIED CORE LAY-OUT

78

PALUEL UNIT1 - STARTUP TEST
MULTISECTION EX-CORE DETECTOR MEASUREMENT

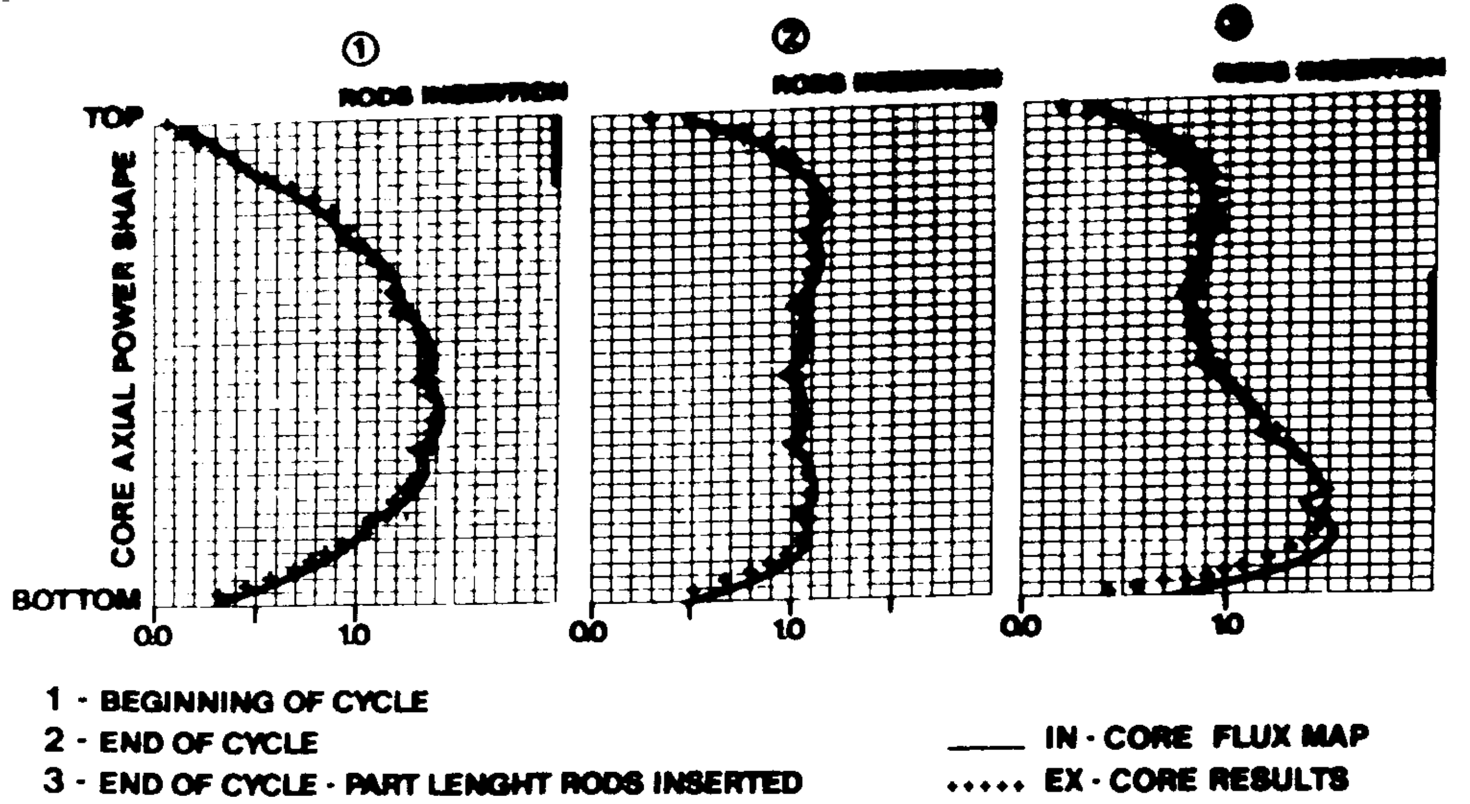

10 - 16 - 84
50 % OF RATED POWER

11 - 29 - 84
90 % OF RATED POWER

- the startup tests and operation of several (8) 1300 MWe plants of the PALUEL type now under commercial operation.

FRAMATOME

BUGEY UNIT 2 - MULTISECTION EX-CORE DETECTOR TESTS MEASUREMENT OF AVERAGE AXIAL POWER DISTRIBUTION



1 - BEGINNING OF CYCLE
2 - END OF CYCLE
3 - END OF CYCLE - PART LENGHT RODS INSERTED

\- the BUGEY-2 special tests, beginning in 1978, involving use of the full and part-length rods in order to generate adverse power distributions,

DIGITAL CORE CONTROL
AND PROTECTION SYSTEMS
FOR N4 PLANTS

CORE CONTROL AND PROTECTION

CORE CONTROL SYSTEM

- ADAPTATION OF CORE POWER TO TURBINE POWER
- AXIAL POWER SHAPE CONTROL
    - PREVENTION OF XENON OSCILLATIONS
    - CONTROL OF CORE SAFETY MARGINS (DNBR, POWER DENSITY)

86

CORE PROTECTION

1. PROTECTION SYSTEM

- REACTOR TRIP
- ACTUATION OF SAFEGUARD SYSTEM

2. CORE SURVEILLANCE UNIT

ONLINE VERIFICATION OF COMPLIANCE WITH THE LIMITING CONDITIONS OF OPERATION (INITIAL CONDITIONS POSTULATED IN ACCIDENT ANALYSES)

CORE CONTROL

1. FRENCH GRID HISTORICAL BACKGROUND

2. MAIN EDF MANEUVERABILITY REQUIREMENTS FOR THE N4 PROJECT

3. MODE X CORE CONTROL PRINCIPLES

4. EXAMPLE OF LOAD FOLLOW TRANSIENT

CORE CONTROL

1. FRENCH GRID HISTORICAL BACKGROUND

1975 **ESSENTIALLY BASE LOAD OPERATION**

IMPLEMENTED ON 6 OLDER 3-LOOP PLANTS

- SLOW LOAD FOLLOW TRANSIENTS : ±2% RP/MIN
- LOCAL FREQUENCY CONTROL : ±2% RP
- REMOTE FREQUENCY CONTROL : ±3% RP

1985 **EXTENSIVE LOAD FOLLOW**

IMPLEMENTED ON 3-LOOP 900 MWe & 4-LOOP 1300 MWe UNITS (48)

- FAST LOAD FOLLOW TRANSIENTS : ±5% RP/MIN
- LOCAL FREQUENCY CONTROL : ±3% RP
- REMOTE FREQUENCY CONTROL : ±5% RP
- CAPABILITY TO RETURN TO FULL POWER AT 5% RP/MIN WITHOUT NOTICE

1995 **IDEM + IMPROVED FLEXIBILITY**

TO BE IMPLEMENTED ON THE NEW GENERATION OF 4-LOOP 1450 MWe UNITS (N4 SERIES)

SUCCESSFULLY TESTED AT THE SAINT-ALBAN 1300 MWe UNIT IN 1991

- HIGHER AUTOMATION DEGREE
- HIGHER FLEXIBILITY IN LIQUID WASTE MANAGEMENT

2. MAIN EDF REQUIREMENTS FOR THE N4 PROJECT

- **DAILY LOAD FOLLOW CAPABILITY**

  . 16-8 TYPICAL TRANSIENT
  . BETWEEN 100 & 30%RP
  . DURING 80% OF CYCLE LENGTH
  . POWER RATE : UP TO 5% RP/MIN

- **FREQUENCY CONTROL SUPERIMPOSITION**

  . LOCAL (short term limitation of frequency deviations) ±3% RP
  . REMOTE (return to nominal frequency) ±5% RP
  . POSSIBLE AT ANY POWER LEVEL BETWEEN 30 & 100% RP WITHOUT BORON CHANGES

- **ROD POSITIONING AT PART POWER LEVEL**

  CHOICE AVAILABLE BETWEEN DIFFERENT STRATEGIES:
  . MINIMISATION OF WASTE : XENON FOLLOWING BY RODS
  . CAPABILITY TO RETURN RAPIDLY TO FULL POWER WITHOUT NOTICE : XENON FOLLOWING BY BORON
  . INTERMEDIATE STRATEGIES

3. MODE X CORE CONTROL PRINCIPLES

MAIN OBJECTIVES :

- TO MEET THE EDF REQUIREMENTS FOR N4 PLANTS
- TO FACILITATE PLANT OPERATION BY ENSURING A FULLY AUTOMATED TEMPERATURE AND AXIAL POWER SHAPE CONTROL
- TO MAINTAIN THE AXIAL POWER SHAPE CLOSE TO A REFERENCE SHAPE IN ORDER TO PREVENT ANY RISKS OF XENON OSCILLATION
- TO LIMIT BORON CONCENTRATION CHANGES AT THE COMPENSATION OF LONG TERM REACTIVITY EFFECTS (XENON, FUEL BURNUP)
- TO ALLOW AN EASY IMPLEMENTATION OF DIFFERENT STRATEGIES OF ROD POSITIONING AT PART POWER LEVELS

3. MODE X CORE CONTROL PRINCIPLES (contd.)

MODE X PRINCIPLES :

- BASED ON THE FOLLOWING OBSERVATION : WHEN AT LEAST TWO ROD BANKS ARE PARTIALLY INSERTED AT DIFFERENT ELEVATIONS IN THE CORE, IT IS POSSIBLE, BY VARYING THE OVERLAPS BETWEEN THESE BANKS, TO CONTROL THE CORE REACTIVITY AND THE AXIAL POWER SHAPE SIMULTANEOUSLY

- TWO INTERLINKED CONTROL LOOPS :
  - REACTOR COOLANT AVERAGE TEMPERATURE CONTROL LOOP
  - AXIAL OFFSET (AO) CONTROL LOOP

- ROD SPEED IS A FUNCTION OF TEMPERATURE DEVIATION ONLY

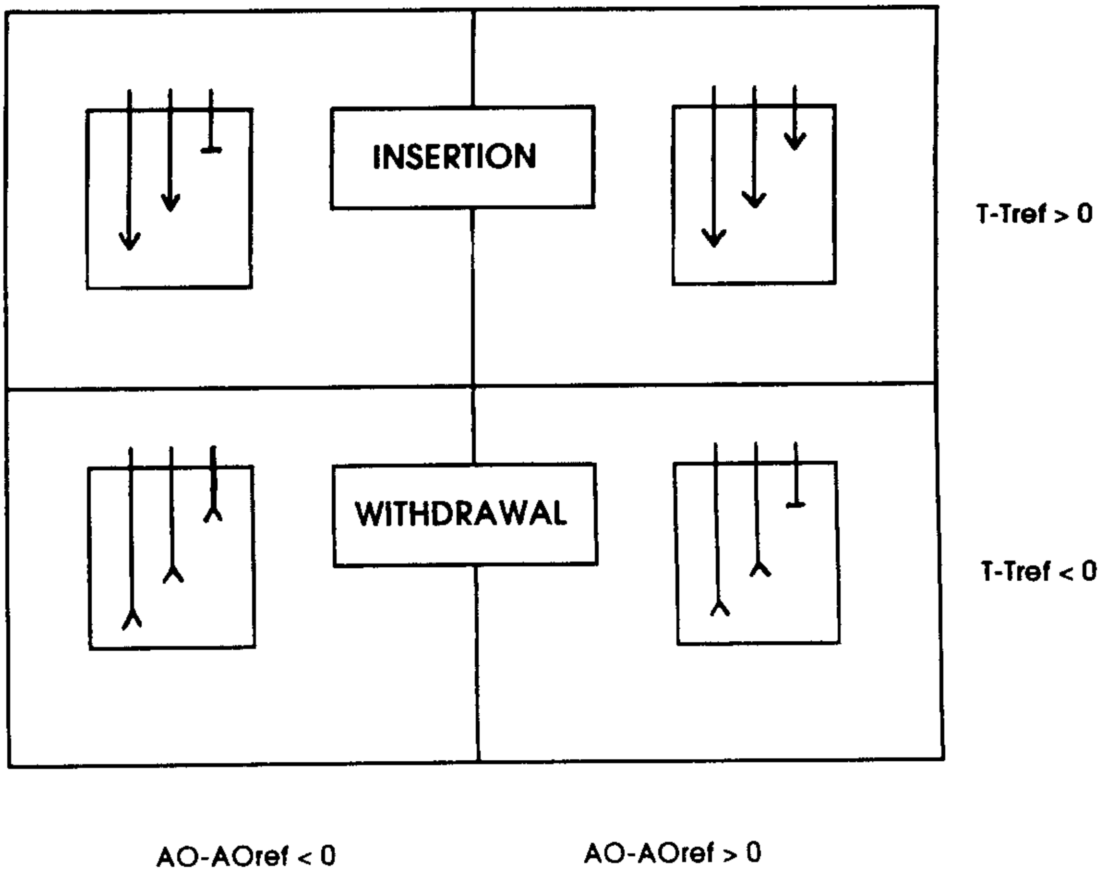
- THE SAME SPEED SIGNAL IS APPLIED TO ALL BANKS

- VARIATIONS OF OVERLAPS ARE OBTAINED BY BLOCKING SOME ROD BANKS MOMENTARILY, DEPENDING ON THE AO DEVIATION

- THE BLOCKED RODS ARE PRIORILY THOSE LOCATED IN THE TOP OR THE BOTTOM OF THE CORE

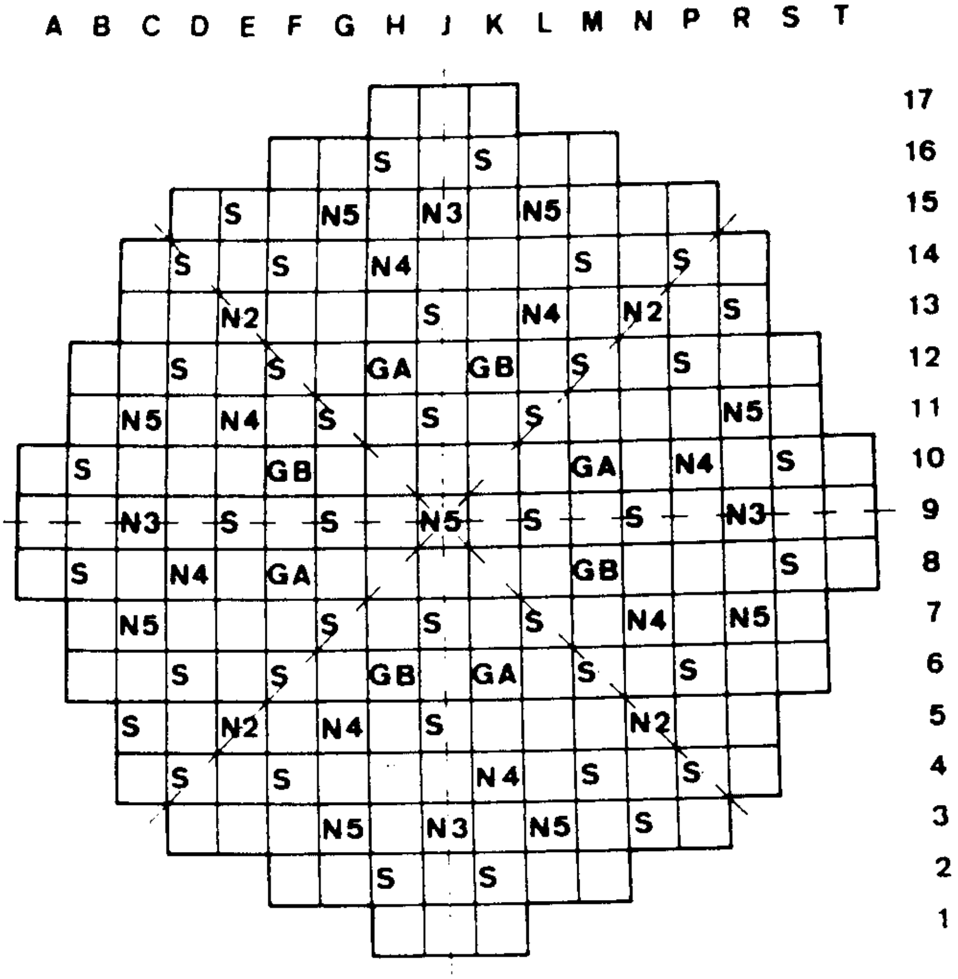
3. MODE X CORE CONTROL PRINCIPLES (contd.)

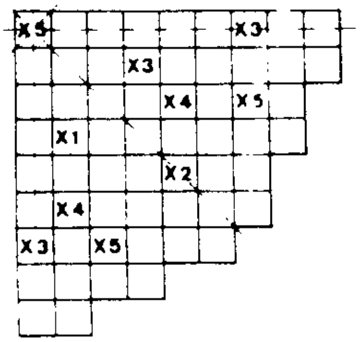
PHYSICAL PRINCIPLES FOR ROD MOTION

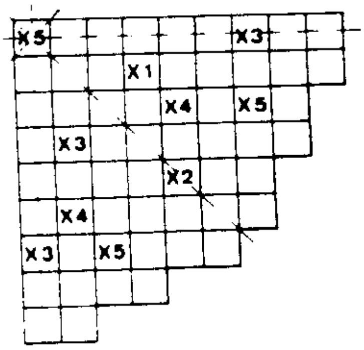


CORE CONTROL

3. MODE X CORE CONTROL PRINCIPLES (contd.)







CONTROL BANKS	X1 4	GREY RCCA
	X2	4 BLACK RCCA
	X3	4 GREY + 4 BLACK RCCA
	X4	8 BLACK RCCA
	X5	9 BLACK RCCA
SHUTDOWN BANKS		40 BLACK RCCA

CORE CONTROL

3. MODE X CORE CONTROL PRINCIPLES (contd.)

SHUTDOWN MARGIN ONLINE MONITORING

BANK OVERLAPS NOT CONSTANT

⇒ CLASSICAL INSERTION LIMITS IN FUNCTION OF THE POWER LEVEL ARE NOT ADEQUATE TO ENSURE COMPLIANCE WITH THE SAFETY REQUIREMENTS ON MINIMUM SHUTDOWN MARGIN

⇒ IMPLEMENTATION OF A SHUTDOWN MARGIN MONITORING SYSTEM

- REAL TIME CALCULATION OF THE ROD "OVERINSERTION"
  - INSERTED ANTIREACTIVITY IN EXCESS OF WHAT IS STRICTLY NECESSARY TO COMPENSATE THE POWER DEFECT BETWEEN FULL POWER AND THE CURRENT CORE STATE
- SIMPLE ALGORITHMS TO CALCULATE INDIVIDUAL REACTIVITY EFFECTS (DOPPLER, MODERATOR, ROD INSERTION, AXIAL POWER SHAPE)
- MAIN INPUT DATA :
  - POWER LEVEL
  - COOLANT TEMPERATURE
  - ROD POSITIONS
  - AXIAL POWER DISTRIBUTION (measured by multi-section excore detectors)
- BORATION IS ACTUATED WHEN THE COMPUTED OVERINSERTION REACHES THE LIMIT VALUE TAKEN INTO ACCOUNT IN THE SAFETY REPORT

3. MODE X CORE CONTROL PRINCIPLES (contd.)

BENEFITS OF THE SDM MONITORING SYSTEM COMPARED WITH USUAL INSERTION LIMITS :

1. ROD INSERTION LIMITS ARE CALCULATED TAKING INTO ACCOUNT THE REAL CORE CONDITIONS (NO PENALIZING ASSUMPTIONS)

   ⇒ LESS STRINGENT LIMITS

   ⇒ MORE FLEXIBILITY FOR CORE CONTROL

2. THE INDICATIONS DELIVERED BY THE SYSTEM ARE PARTICULARLY SUITABLE TO CONTROL THE BORON CONCENTRATION IN FUNCTION OF THE DESIRED ROD POSITIONING STRATEGY :

   - THE MAXIMUM POWER LEVEL (PMAX) THE PLANT MUST BE ABLE TO REACH IF REQUIRED BY THE DISPATCHING IS TRANSLATED INTO A REFERENCE VALUE FOR ROD OVERINSERTION
   - THE GLOBAL ROD POSITIONING AT PART POWER IS PERFORMED BY DILUTION/BORATION OPERATIONS IN FUNCTION OF THE DEVIATION IN ROD OVERINSERTION

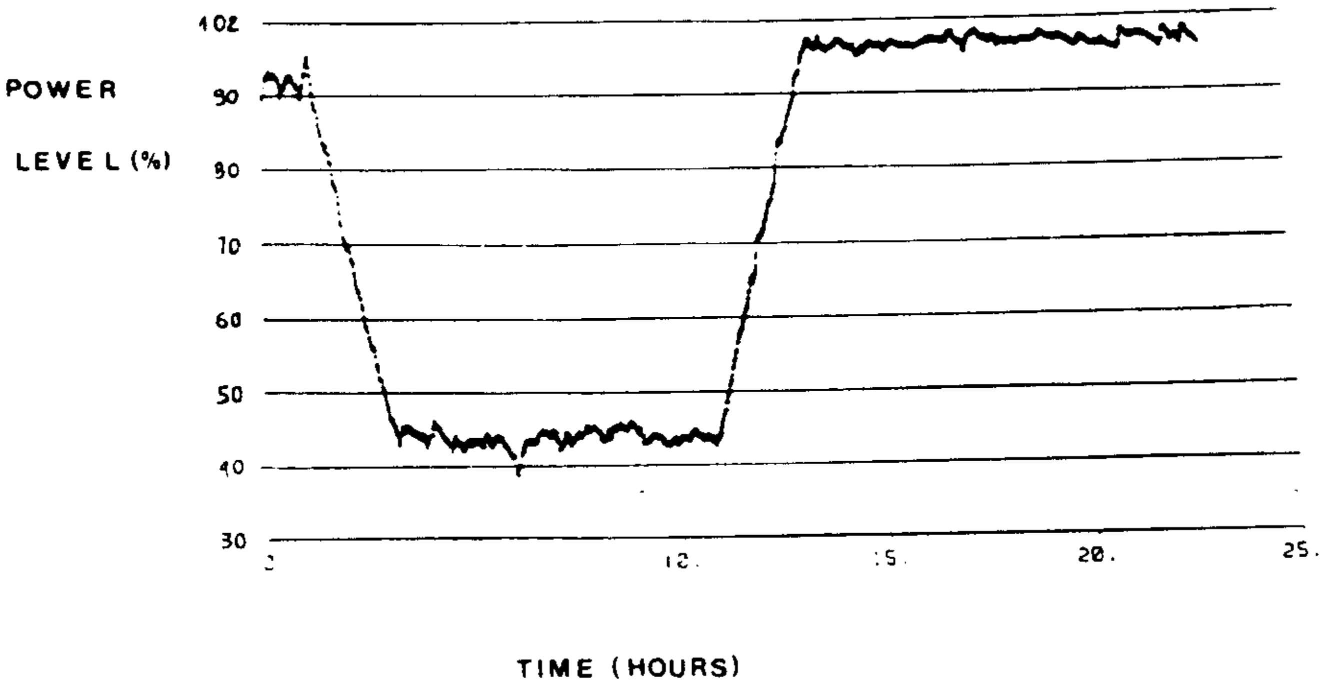
REMARK : THESE BENEFITS WOULD ALSO EXIST IN CASE OF A CORE CONTROL MODE WITH CONSTANT BANK OVERLAPS

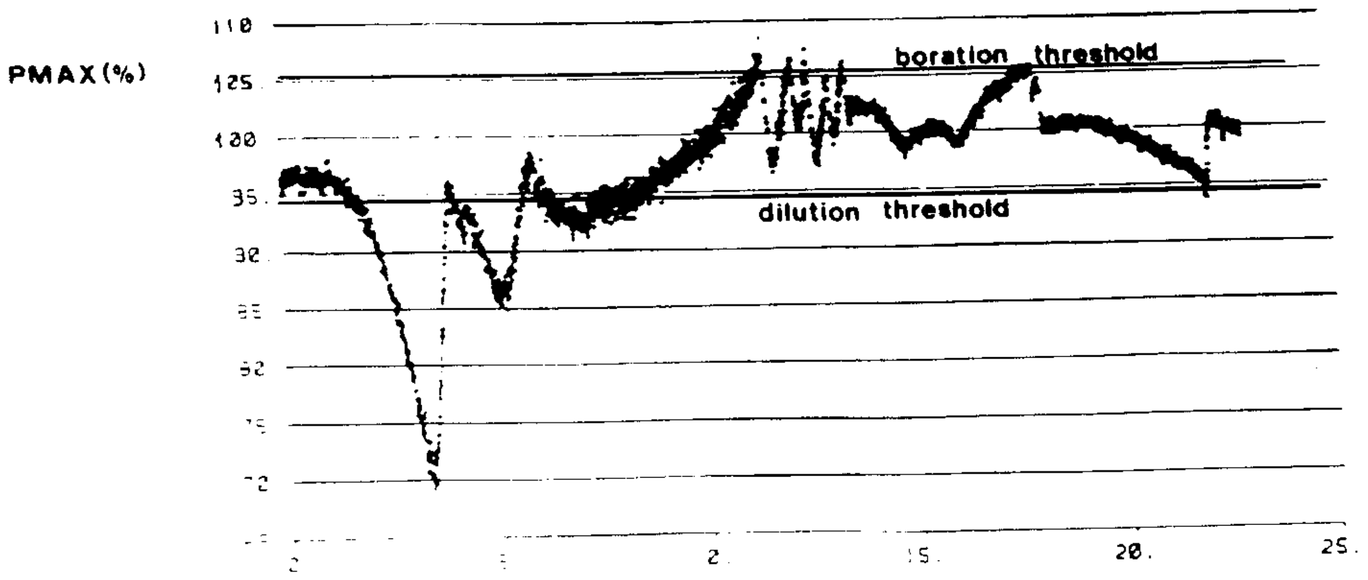
CORE CONTROL

4. EXAMPLE OF LOAD FOLLOW TRANSIENT

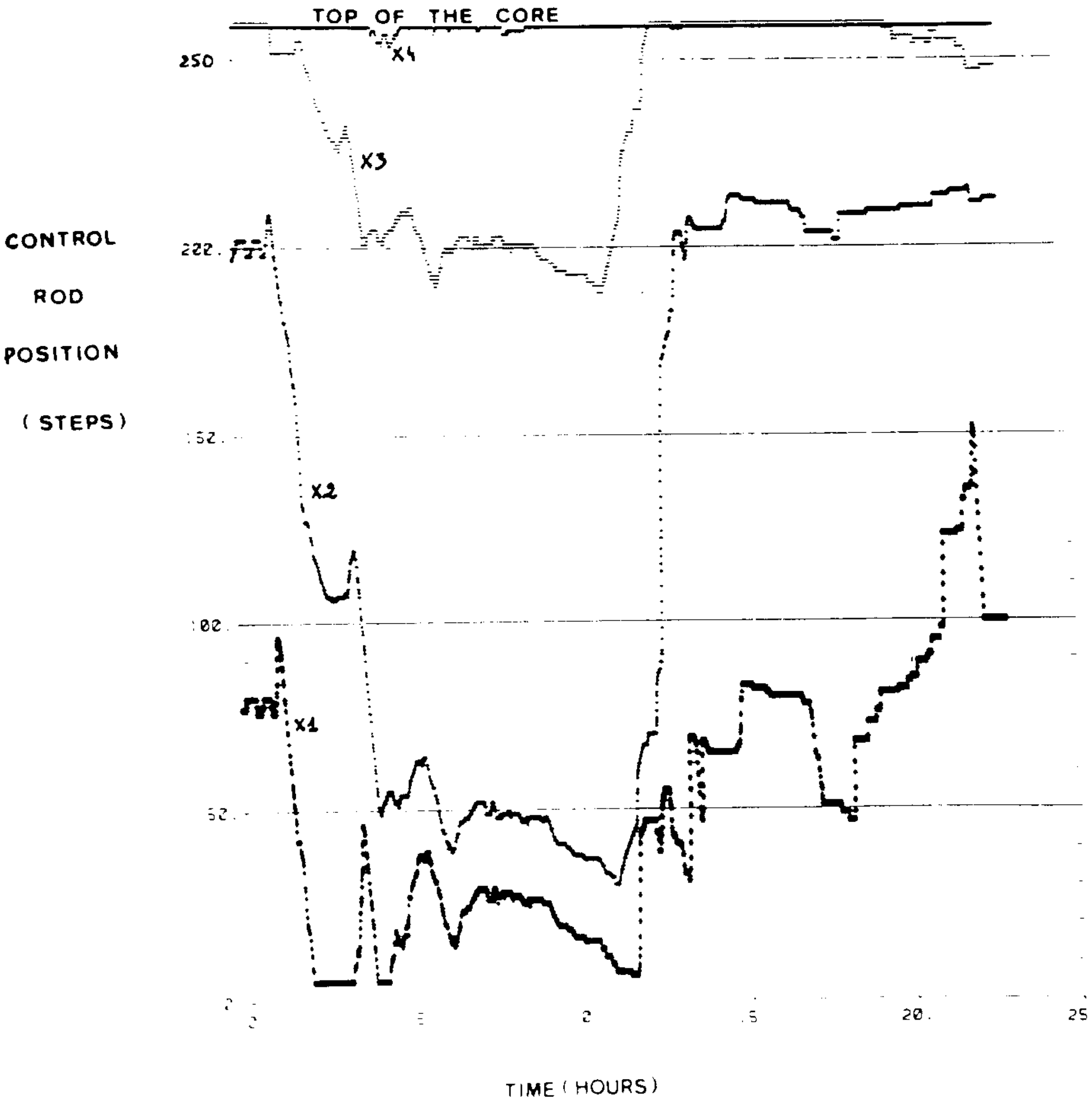
- SAINT-ALBAN 2 UNIT (4 LOOPS - 1300 MWe)
- THIRD CAMPAIGN OF MODE X TESTS (1991)
- TYPICAL DAILY LOAD FOLLOW WITH SUPERIMPOSITION OF FREQUENCY CONTROL (LOCAL AND REMOTE)
- STRATEGY AT PART POWER : CAPABILITY TO RETURN TO FULL POWER WITHOUT NOTICE

4. EXAMPLE OF LOAD FOLLOW TRANSIENT





4. EXAMPLE OF LOAD FOLLOW TRANSIENT



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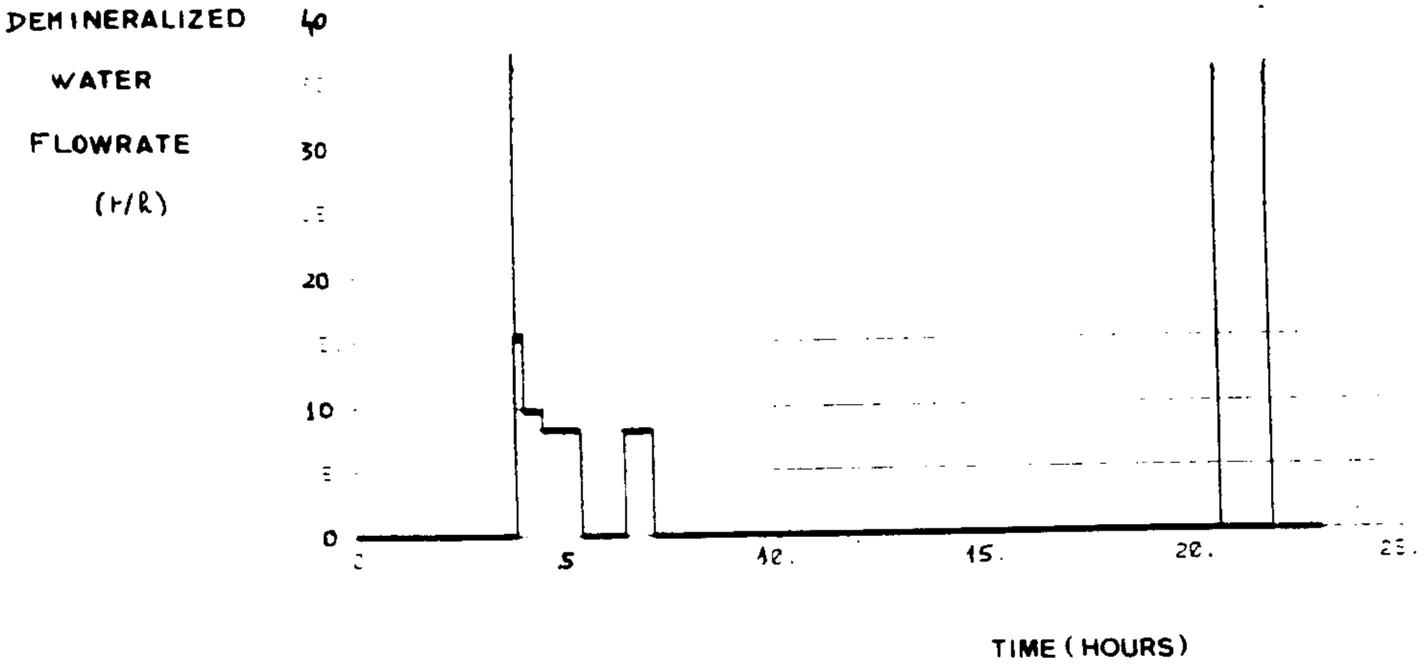
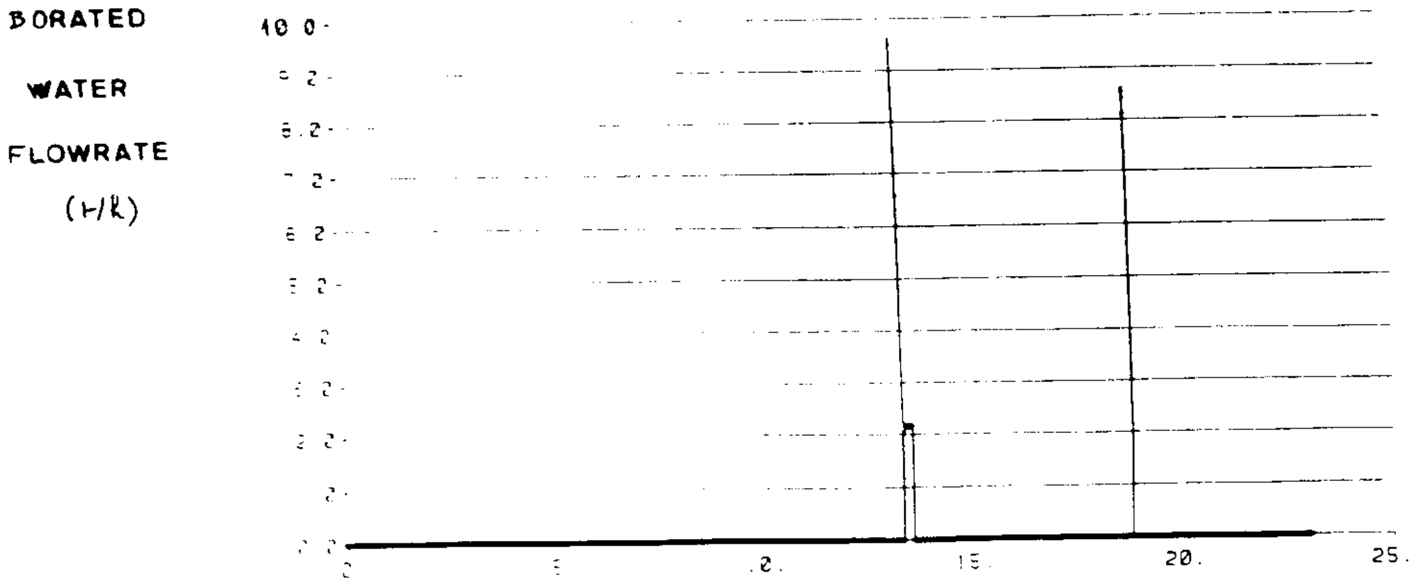




CORE PROTECTION

1. PROTECTION SYSTEM

ACTUATES REACTOR TRIP TO ENSURE COMPLIANCE WITH THE CORE RELATED SAFETY CRITERIA

- MINIMUM DEPARTURE FROM NUCLEATE BOILING RATIO
- PEAK FUEL TEMPERATURE

2. SURVEILLANCE UNIT

- VERIFIES DURING NORMAL OPERATION THE OBEYANCE WITH THE LIMITING HYPOTHESES CONSIDERED IN THE SAFETY ANALYSES
  - MINIMUM REQUIRED SHUTDOWN MARGIN
  - MAXIMUM LINEAR HEAT RATE / LOCA
  - ...
- GENERATES ALARMS FOR OPERATOR ACTION

⇒ TWO TYPES OF EQUIPMENT

- FOUR PROTECTION CHANNELS
  REACTOR TRIP THROUGH A 2 OUT OF 4 VOTING LOGIC
- TWO SURVEILLANCE UNITS
  ALARMS GENERATED THROUGH A 1 OUT OF 2 LOGIC

CORE PROTECTION

REACTOR TRIP CHANNELS FOR CORE PROTECTION

1. SPECIFIC PROTECTION CHANNELS

- HIGH NEUTRON FLUX
- HIGH NEUTRON FLUX RATE
- HIGH THERMAL POWER
- ROD POSITION VARIATION
- LOW COOLANT FLOW RATE
- LOW REACTOR COOLANT PUMP SPEED
- LOW PRESSURIZER PRESSURE
- HIGH PRESSURIZER PRESSURE

2. GENERIC PROTECTION CHANNELS

- LOW DNBR
- HIGH LINEAR POWER DENSITY
- HIGH CORE OUTLET ENTHALPY
- HIGH HOT CHANNEL OUTLET QUALITY

CORE PROTECTION

GENERIC PROTECTON

ON LINE CALCULATION OF MINIMAL DNBR AND MAXIMAL POWER DENSITY

⇒ ***SIMPLIFIED REPRESENTATION OF CORE POWER DISTRIBUTION BY USING SYNTHESIS METHOD***

- .6 CURRENTS FROM AN EXCORE CHAMBER ⇒ MEAN AXIAL POWER PROFILE $\overline{P}(z)$

- .PRETABULATED PEAK POWER BY ROD CONFIGURATION + CONTROL BANK POSITION } ⇒ RADIAL PEAK POWER Fxy(z)

- .THERMO-HYDRAULICAL MEASUREMENTS (Tin, Tout, P, Ω) ⇒ THERMAL POWER LEVEL

CORE PROTECTION

SURVEILLANCE UNIT

GENERIC PROTECTIONS ARE EFFICIENT WITHOUT ANY ASSUMPTION ON PRE-ACCIDENT VALUES OF DNBR AND POWER DENSITY

SPECIFIC PROTECTIONS ARE EFFICIENT IF LIMITS ARE RESPECTED FOR INITIAL DNBR AND POWER DENSITY

⇒ *LIMITING CONDITIONS OF OPERATION, COHERENT WITH ACCIDENT STUDIES*

→ A SURVEILLANCE UNIT VERIFIES ON-LINE THE L.C.O. :

- CALCULATION OF MARGINS :
  - . "LOW DNBR" ALARM
  - . "LOCA" ALARM
  - . "SHUTDOWN MARGIN" ALARM (SCRAM EFFICIENCY)
- SURVEILLANCE OF SPECIFIC PARAMETERS :
  - . RCCA BANK INSERTION (ROD EJCTION ACCIDENT;)
  - . QUADRANT POWER TILT
  - . ROD MISALIGNMENT

CORE PROTECTION

SURVEILLANCE UNIT

"LOW DNBR " ALARM :

- CALCULATION OF CURRENT DNBR WITH THE SAME METHOD AS FOR GENERIC PROTECTION BUT WITH A BETTER ACCURACY (MORE DETAILED MODEL)

  . A GREATER RESPONSE TIME IS ALLOWED

- LCO THRESHOLD DIMENSIONED BY THE MOST LIMITATIVE TRANSIENT NOT DETECTED BY GENERIC PROTECTION

  ⇒ *ROD DROP ACCIDENT*

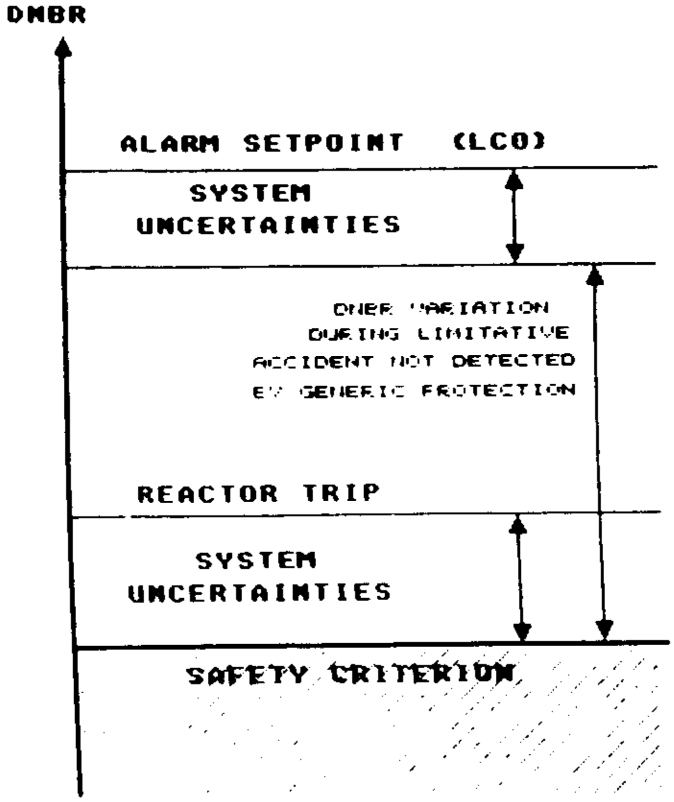
"LOCA" ALARM :

- CALCULATION OF CURRENT AXIAL DISTRIBUTION OF POWER DENSITY, WITH THE SYNTHESIS METHOD

  . GREATER RESPONSE TIME }
  . BETTER ACCURACY } THAN FOR GENERIC PROTECTION

- LCO THRESHOLD DIMENSIONED BY THE LOSS OF COOLANT ACCIDENT

CORE PROTECTION SURVEILLANCE UNIT



CORE PROTECTION

SURVEILLANCE UNIT

OTHER SURVEILLANCE FUNCTIONS

QUADRANT POWER TILT :

GENERIC PROTECTION CALCULATION ARE VALID FOR AZIUMTAL OSCILLATIONS UNTIL A DESEQULIBRIUM EQUAL TO 2 %

ROD MISALIGNEMENT :

RADIAL PEAK POWER PER ROD ZONE, PRETABULATED IN GENERIC PROTECTION, ARE NOT VALID IF A SINGLE ROD IS MISALIGNED FROM ITS BANK

CONTROL RODS INSERTION :

IN ORDER TO LIMIT CONSEQUENCES OF ROD EJECTION ACCIDENT, SPECIFIC ROD INSERTION LIMITS ARE DIMENSIONED BY SAFETY STUDIES

SHUTDOWN MARGIN SURVEILLANCE :

(→ REACTIVITY CONTROL)