Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor

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Program on Science and Global Security
Princeton University

13 December 2006

Revision 10

“Bhabha’s Vision”

The three-stage program as outlined in 1958

STAGE 1

Pressurized heavy-water reactors using natural uranium fuel

Rationale: simple technology, produce plutonium, no access to enriched uranium needed

STAGE 2

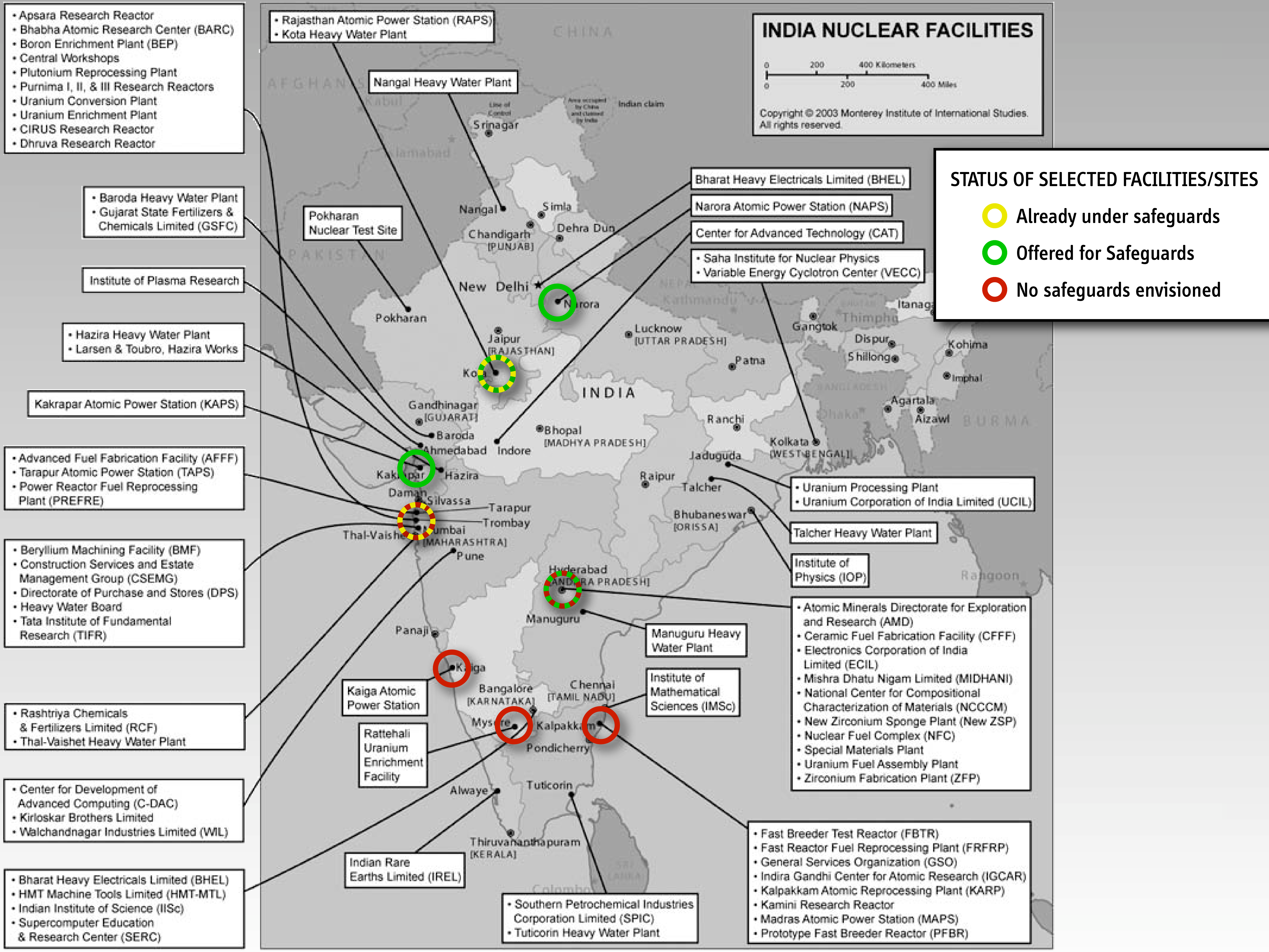
Fast-neutron (breeder) reactors using plutonium from PHWRs for initial cores

Rationale: increase plutonium stockpile, while reducing uranium-ore requirements

STAGE 3

Advanced thorium reactors (thermal and fast, Pu/U-233 as fissile isotopes)

Rationale: finally use large domestic thorium-resources, achieve self-sufficient large nuclear program

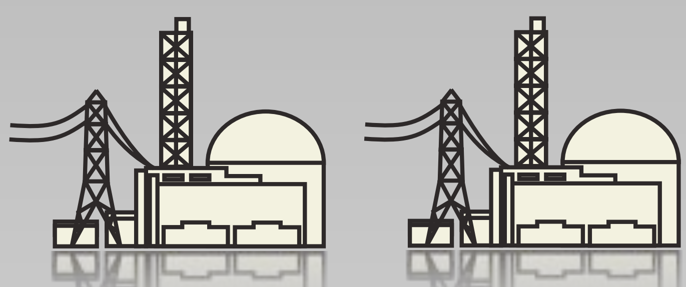

INDIA NUCLEAR FACILITIES
0 200 400 Kilometers
0 200 400 Miles
Copyright © 2003 Monterey Institute of International Studies. All rights reserved.
STATUS OF SELECTED FACILITIES/SITES
Already under safeguards
Offered for Safeguards
No safeguards envisioned
• Apsara Research Reactor
• Bhabha Atomic Research Center (BARC)
• Boron Enrichment Plant (BEP)
• Central Workshops
• Plutonium Reprocessing Plant
• Purnima I, II, & III Research Reactors
• Uranium Conversion Plant
• Uranium Enrichment Plant
• CIRUS Research Reactor
• Dhruva Research Reactor
• Baroda Heavy Water Plant
• Gujarat State Fertilizers & Chemicals Limited (GSFC)
Institute of Plasma Research
• Hazira Heavy Water Plant
• Larsen & Toubro, Hazira Works
Kakrapar Atomic Power Station (KAPS)
• Advanced Fuel Fabrication Facility (AFFF)
• Tarapur Atomic Power Station (TAPS)
• Power Reactor Fuel Reprocessing Plant (PREFRE)
• Beryllium Machining Facility (BMF)
• Construction Services and Estate Management Group (CSEMG)
• Directorate of Purchase and Stores (DPS)
• Heavy Water Board
• Tata Institute of Fundamental Research (TIFR)
• Rashtriya Chemicals & Fertilizers Limited (RCF)
• Thal-Vaishet Heavy Water Plant
• Center for Development of Advanced Computing (C-DAC)
• Kirloskar Brothers Limited
• Walchandnagar Industries Limited (WIL)
• Bharat Heavy Electricals Limited (BHEL)
• HMT Machine Tools Limited (HMT-MTL)
• Indian Institute of Science (IISc)
• Supercomputer Education & Research Center (SERC)
• Rajasthan Atomic Power Station (RAPS)
• Kota Heavy Water Plant
Nangal Heavy Water Plant
Pokharan Nuclear Test Site
Bharat Heavy Electricals Limited (BHEL)
Narora Atomic Power Station (NAPS)
Center for Advanced Technology (CAT)
• Saha Institute for Nuclear Physics
• Variable Energy Cyclotron Center (VECC)
• Uranium Processing Plant
• Uranium Corporation of India Limited (UCIL)
Talcher Heavy Water Plant
Institute of Physics (IOP)
• Atomic Minerals Directorate for Exploration and Research (AMD)
• Ceramic Fuel Fabrication Facility (CFFF)
• Electronics Corporation of India Limited (ECIL)
• Mishra Dhatu Nigam Limited (MIDHANI)
• National Center for Compositional Characterization of Materials (NCCCM)
• New Zirconium Sponge Plant (New ZSP)
• Nuclear Fuel Complex (NFC)
• Special Materials Plant
• Uranium Fuel Assembly Plant
• Zirconium Fabrication Plant (ZFP)
Manuguru Heavy Water Plant
Institute of Mathematical Sciences (IMSc)
Kaiga Atomic Power Station
Rattehali Uranium Enrichment Facility
Indian Rare Earths Limited (IREL)
• Southern Petrochemical Industries Corporation Limited (SPIC)
• Tuticorin Heavy Water Plant
• Fast Breeder Test Reactor (FBTR)
• Fast Reactor Fuel Reprocessing Plant (FRFRP)
• General Services Organization (GSO)
• Indira Gandhi Center for Atomic Research (IGCAR)
• Kalpakkam Atomic Reprocessing Plant (KARP)
• Kamini Research Reactor
• Madras Atomic Power Station (MAPS)
• Prototype Fast Breeder Reactor (PFBR)
CHINA
AFGHANISTAN
PAKISTAN
INDIA
BURMA
Srinagar
Nangal
Simla
Chandigarh [PUNJAB]
Dehra Dun
New Delhi
Narora
Pokharan
Jaipur [RAJASTHAN]
Lucknow [UTTAR PRADESH]
Patna
Gangtok
Thimphu
Itanagar
Dispur
Shillong
Kohima
Imphal
Agartala
Aizawl
Gandhinagar [GUJARAT]
Baroda
Ahmedabad
Indore
Bhopal [MADHYA PRADESH]
Ranchi
Kolkata [WEST BENGAL]
Jaduguda
Raipur
Talcher
Hazira
Daman
Silvassa
Tarapur
Trombay
Thal-Vaishet
Mumbai [MAHARASHTRA]
Pune
Bhubaneswar [ORISSA]
Hyderabad [ANDHRA PRADESH]
Manuguru
Panaji
Kaiga
Bangalore [KARNATAKA]
Chennai [TAMIL NADU]
Mysore
Kalpakkam
Pondicherry
Alwaye
Tuticorin
Thiruvananthapuram [KERALA]
Rangoon
Colombo
Indian claim
Line of Control
Area occupied by China and claimed by India


Kalpakkam / IGCAR Site
Kalpakkam Reprocessing Plant
(KARP)
Heavy-water reactors
(Madras-1 and -2)
© 2006 Europa Technologies
Image © 2006 DigitalGlobe
©2006 Google™
Pointer 12°34'12.86" N 80°10'09.64" E elev 17 ft
Streaming 100%
Eye alt 15566 ft


Prototype Fast Breeder Reactor
(PFBR) construction site

View of reactor vault (Source: www.bhavini.nic.in)

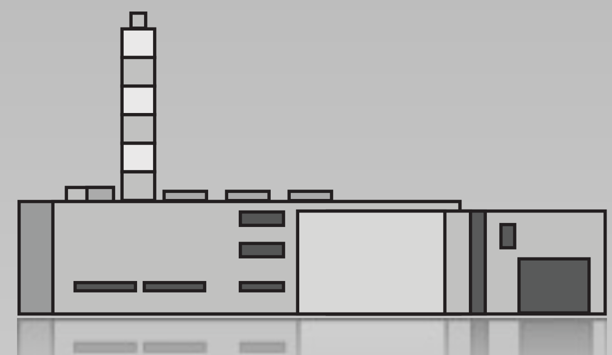
Nuclear Facilities and Materials at the Kalpakkam / IGCAR Site



Madras-1
(170 MWe)

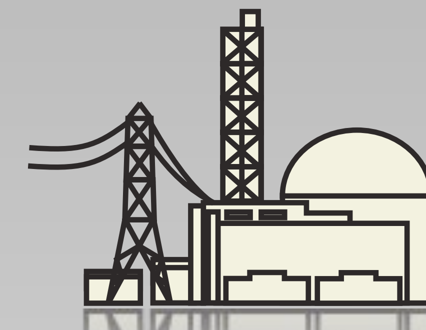
Madras-1
(220 MWe)

About 170 kg of plutonium per year
Fissile fraction: about 77%



Kalpakkam Reprocessing Plant (KARP)
100 MT(HM)/yr

Fast Reactor Fuel Reprocessing Plant (FRFRP)
in planning stages
(capacity on the order of 10-15 MT(HM)/yr)



PFBR
(500 MWe)

Plutonium requirements
for operation in
civilian and military mode?

Cumulative local plutonium production by 2010: *more than 4000 kg*
Reprocessed fraction: *unknown (but presumably high)*

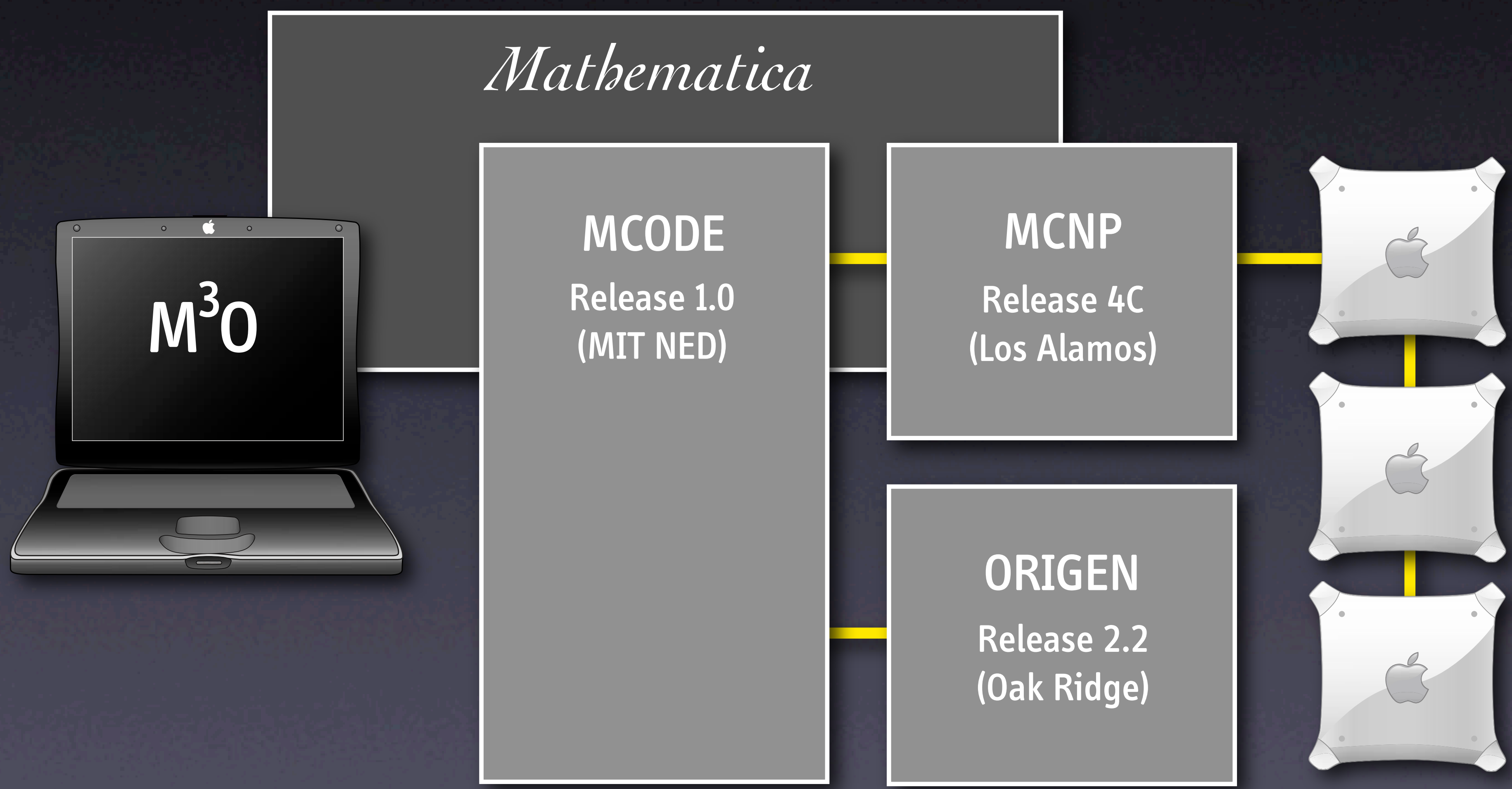
Local plutonium stockpile is likely to be (much) higher due to spent fuel transfers from other sites
Spent fuel from the Kaiga-1 and -2 reactors would add about 2000 kg of plutonium

KARP could separate more than 10,000 kg of plutonium by 2010

Reactor Model and Simulations

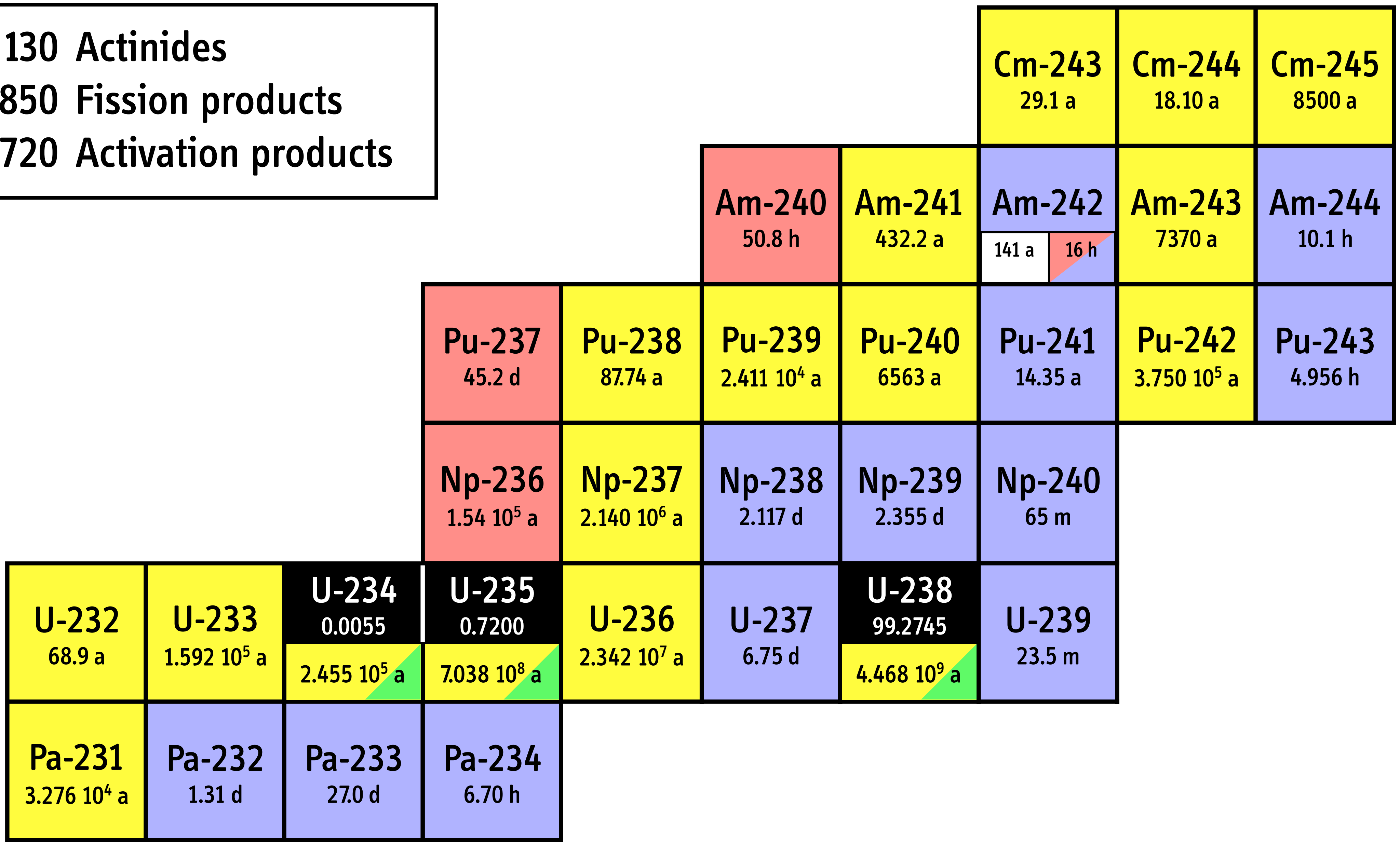
for the Prototype Fast Breeder Reactor (PFBR)

Computational System for Neutronics Calculations



Nuclides in Burnup Calculations

130 Actinides
850 Fission products
720 Activation products

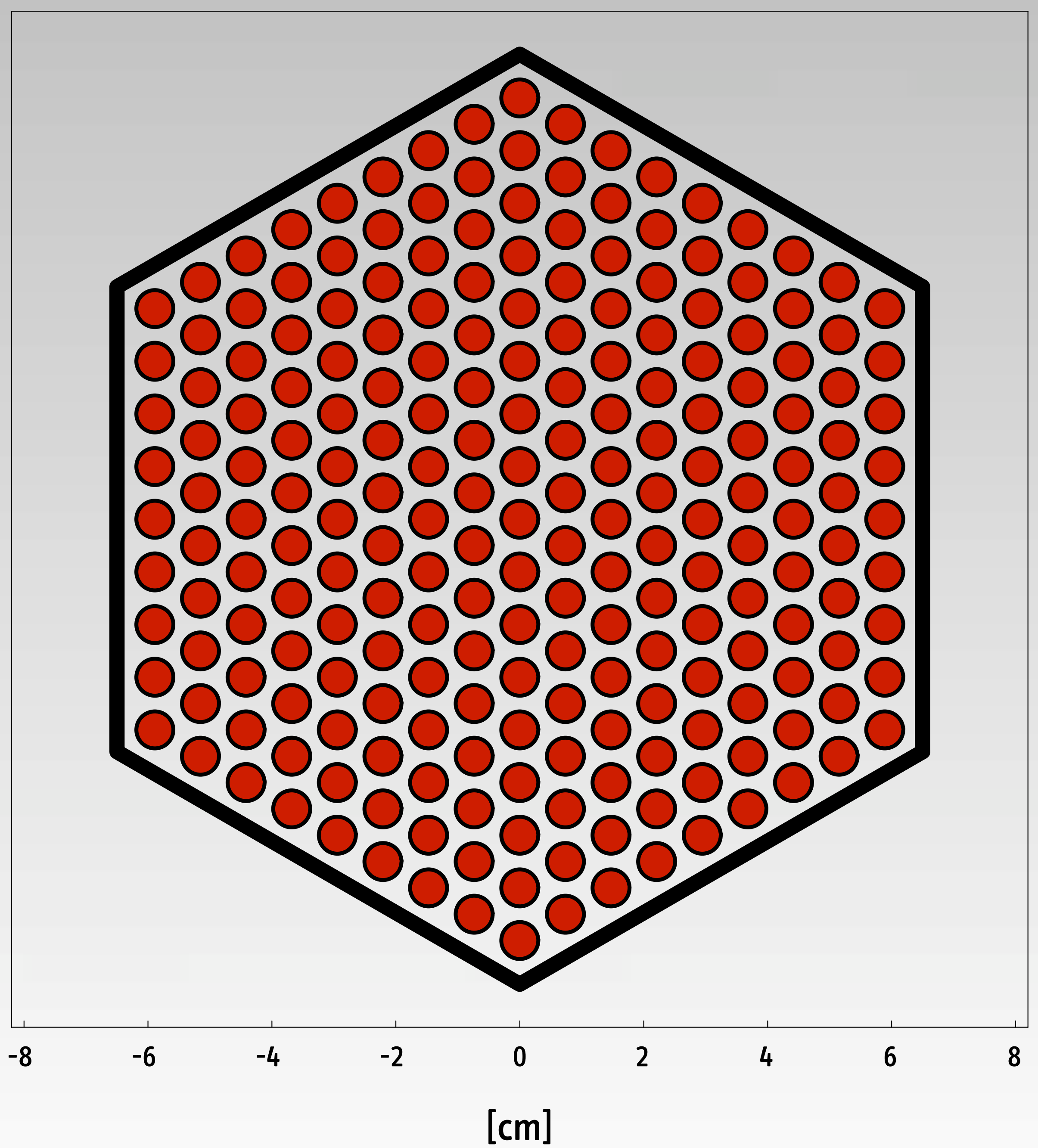


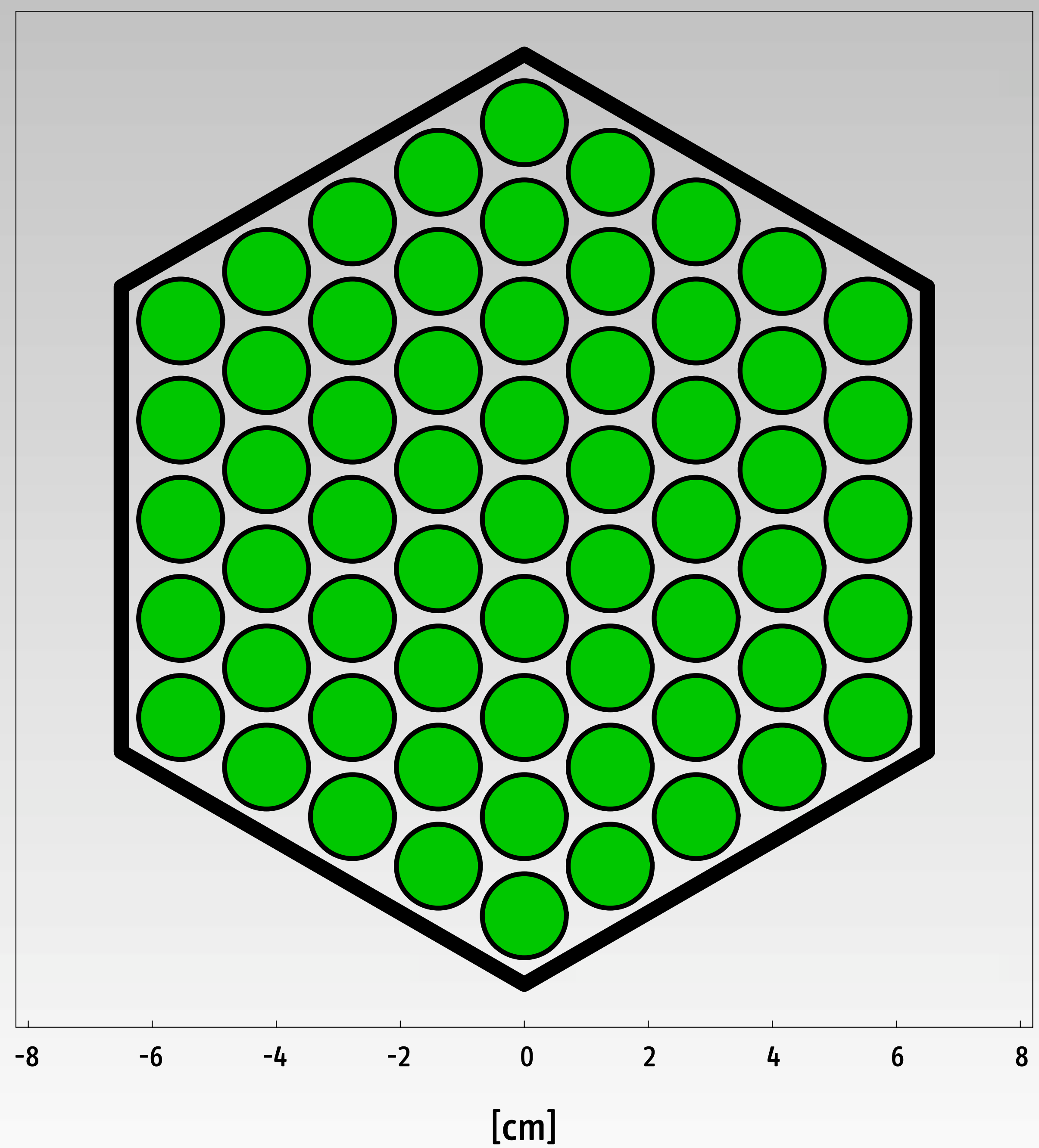
Fuel Pin and Assembly Characteristics

	Core and axial blanket	Radial blanket
Pellet diameter:	5.330 mm	12.760 mm
Gap thickness:	0.185 mm	0.185 mm
Cladding thickness:	0.450 mm	0.600 mm
Outer diameter of fuel pin:	6.600 mm	14.330 mm
Fuel pins per assembly:	217	61
Lattice pitch:	13.50 cm	
Outer width across flats:	13.16 cm	
Thickness of hexcan:	0.32 cm	
Inner width across flats:	12.52 cm	
Available volume in assembly:	135.75 cc per cm	
Fuel fraction:	35.66%	57.46%
Void fraction:	5.13%	3.38%
Cladding fraction:	13.90%	11.63%
Sodium fraction:	45.31%	27.53%

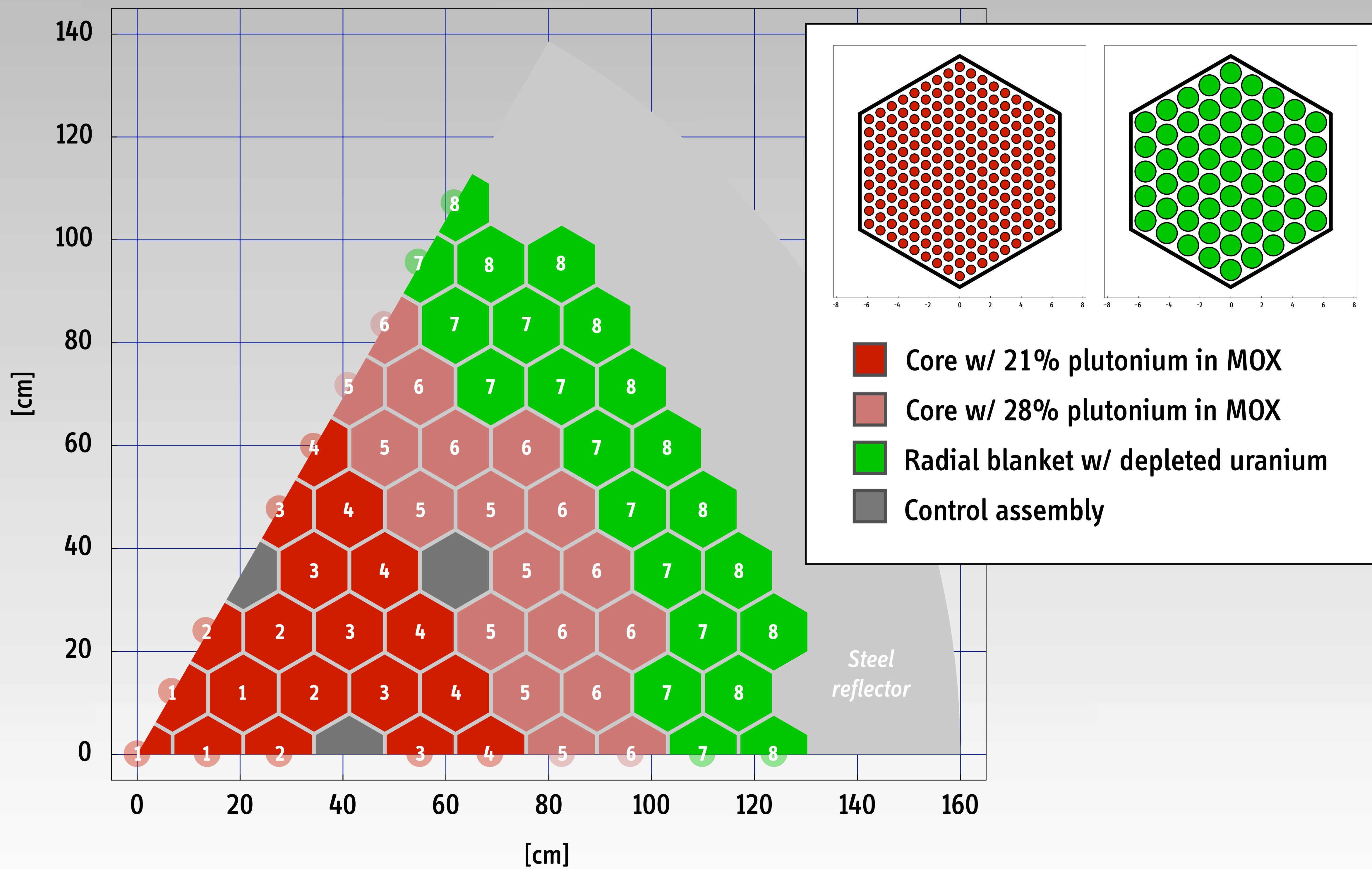
Data retrieved or inferred from the IAEA Fast Reactor Database (www-frdb.iaea.org)
Also: S. C. Chetal et al., *The Design of the Prototype Fast Breeder Reactor*, Nuclear Engineering and Design, 236 (2006), 852-860

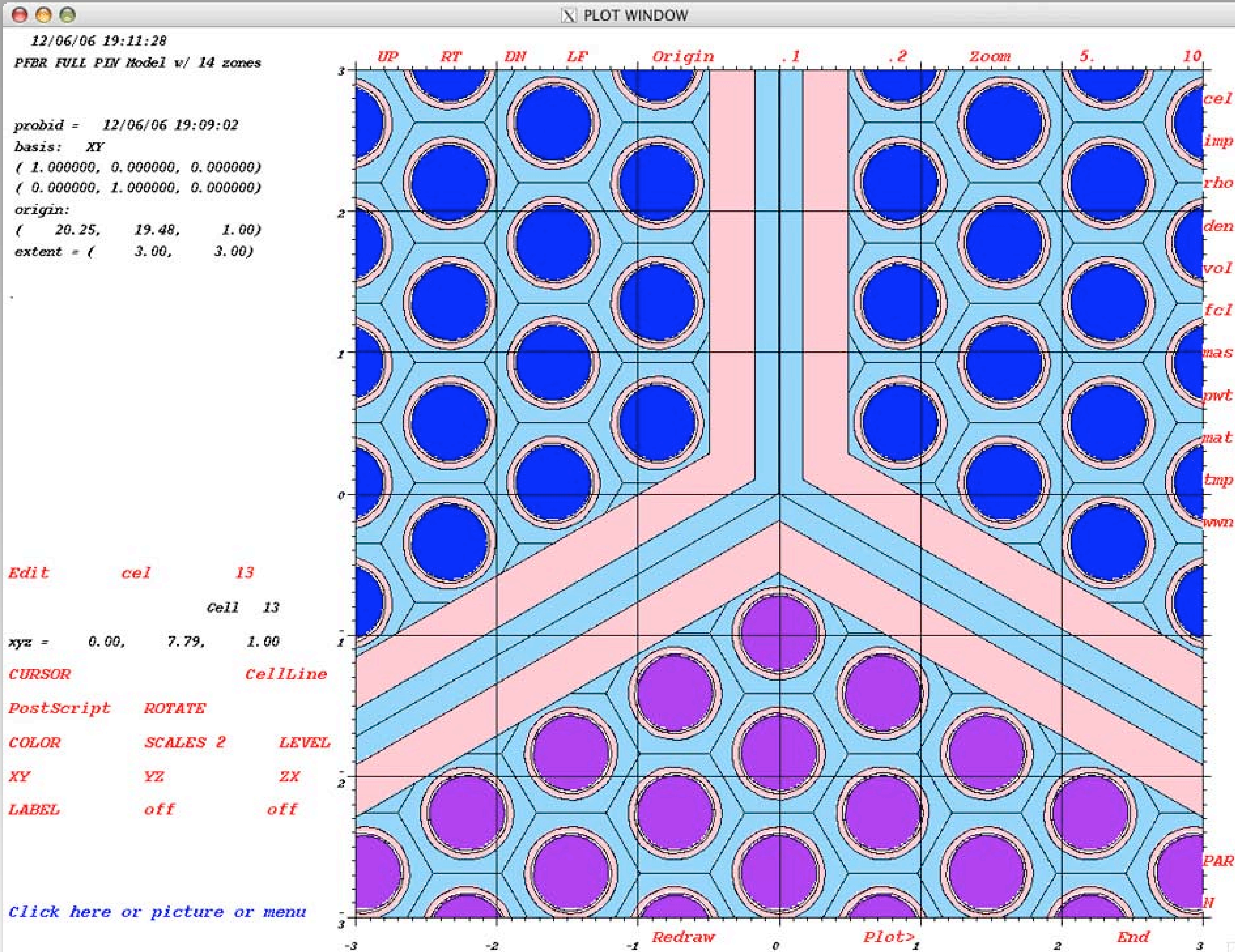
Fuel and Radial Blanket Assemblies

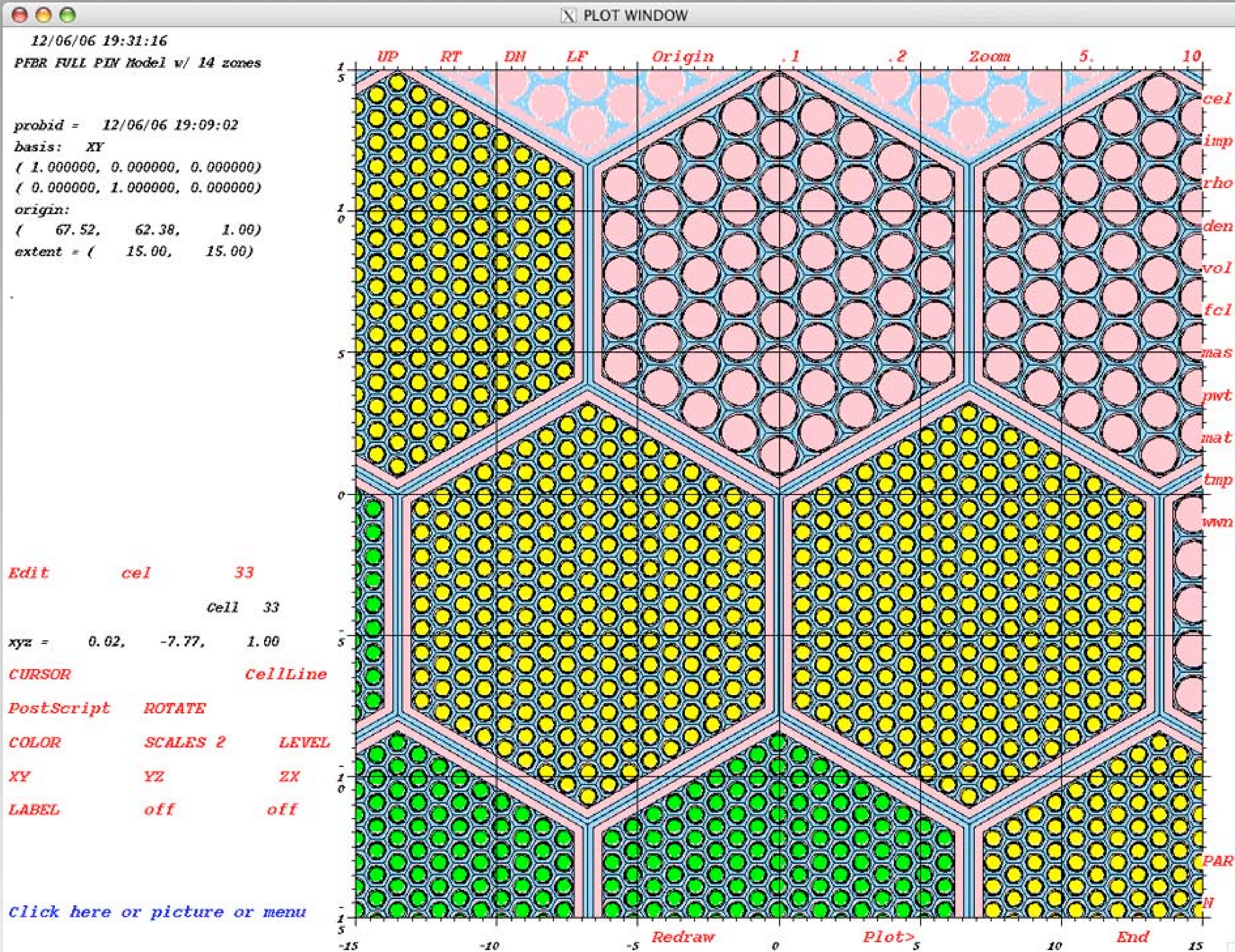




PFBR Core Layout




PLOT WINDOW
12/06/06 19:11:28
PFBR FULL PIN Model v/ 14 zones
probid = 12/06/06 19:09:02
basis: XY
(1.000000, 0.000000, 0.000000)
(0.000000, 1.000000, 0.000000)
origin:
(20.25, 19.48, 1.00)
extent = (3.00, 3.00)
Edit cel 13
Cell 13
xyz = 0.00, 7.79, 1.00
CURSOR CellLine
PostScript ROTATE
COLOR SCALES 2 LEVEL
XY YZ ZX
LABEL off off
Click here or picture or menu
UP RT DN LF Origin .1 .2 Zoom 5. 10
cel
imp
rho
den
vol
fcl
mas
pwt
mat
tmp
wwn
PAR
N
Redraw Plot> End


PLOT WINDOW
12/06/06 19:31:16
PFBR FULL PIN Model w/ 14 zones
probid = 12/06/06 19:09:02
basis: XY
(1.000000, 0.000000, 0.000000)
(0.000000, 1.000000, 0.000000)
origin:
(67.52, 62.38, 1.00)
extent = (15.00, 15.00)
Edit cel 33
Cell 33
xyz = 0.02, -7.77, 1.00
CURSOR CellLine
PostScript ROTATE
COLOR SCALES 2 LEVEL
XY YZ ZX
LABEL off off
Click here or picture or menu
UP RT DN LF Origin .1 .2 Zoom 5. 10
cel imp rho den vol fcl mas pwt mat tmp wwn
PAR N
Redraw Plot> End
-15 -10 -5 0 5 10 15

Main Operational Characteristics

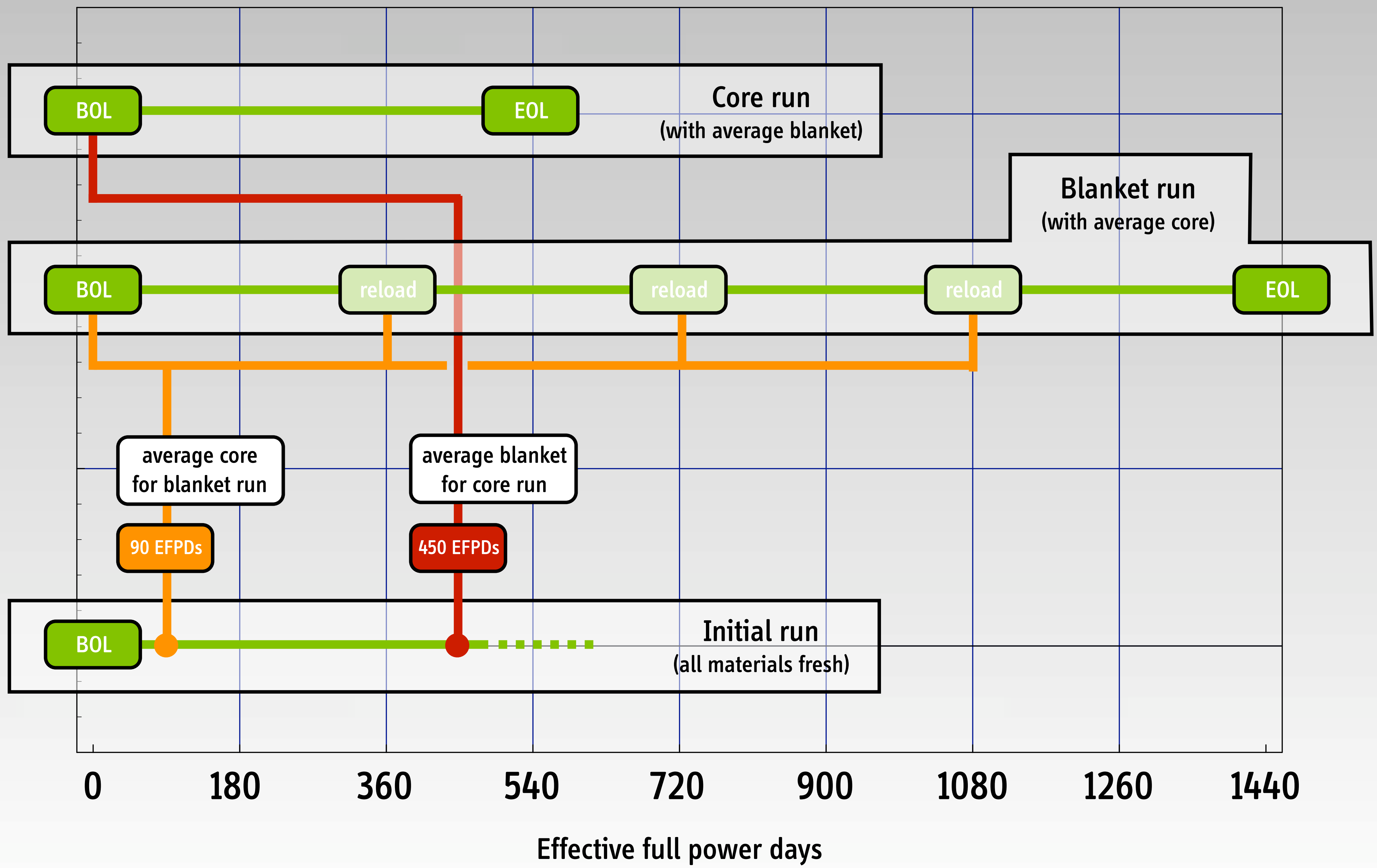
Power level:	500 MWe 1250 MWth (40% thermal to electric efficiency)

Cycle length:	180 effective full power days (EFPDs)
Reloading pattern:	1/3 of the core and 1/8 of the radial blanket
	on average: about 60 plus 15 elements, respectively
	540 EFPDs for average fuel element in core 1440 EFPDs for average fuel element in the radial blanket

Capacity factor:	75% on average: 1.52 reloads per year

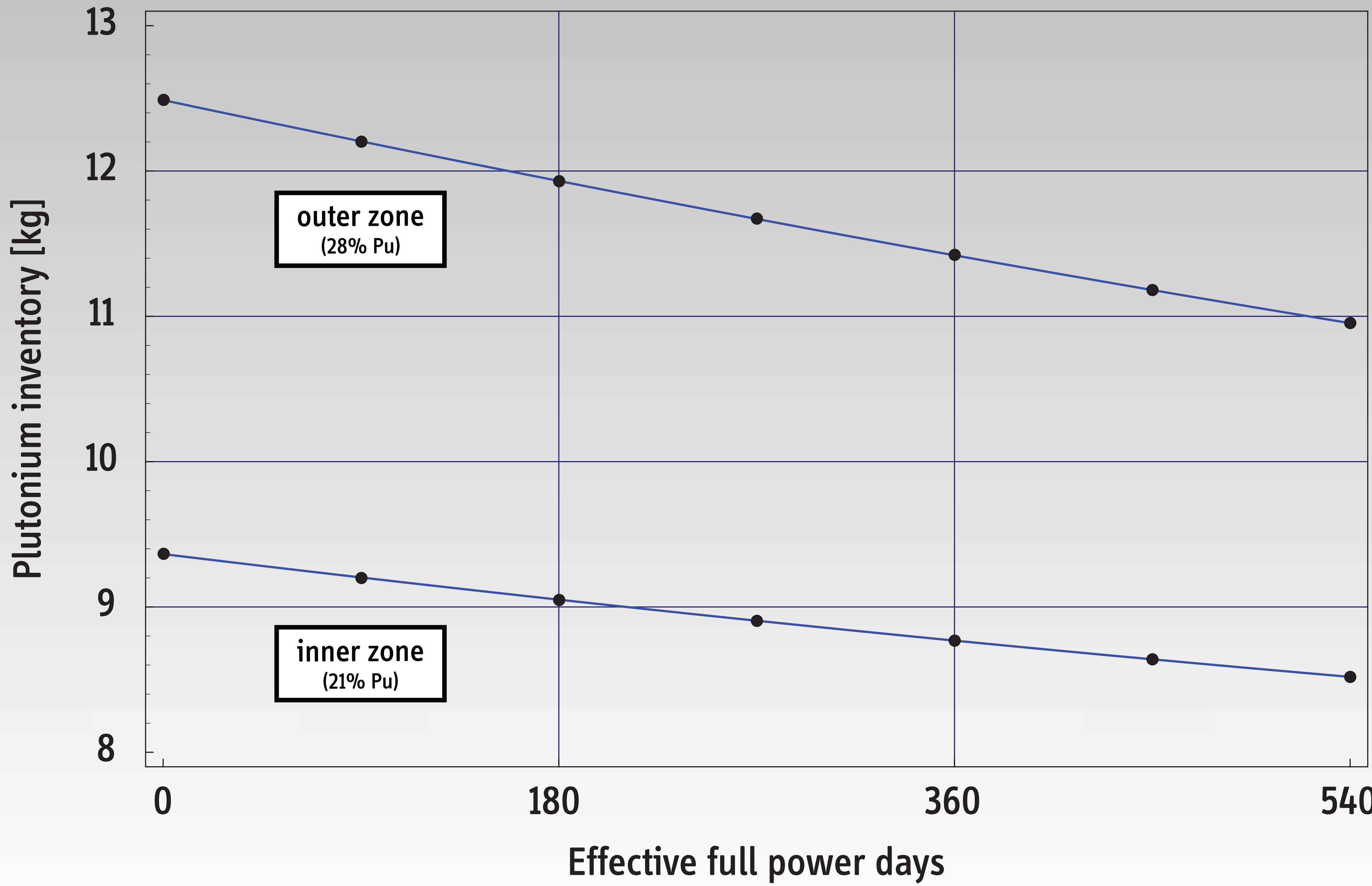
Data retrieved or inferred from the IAEA Fast Reactor Database (www-frdb.iaea.org)

Methodology

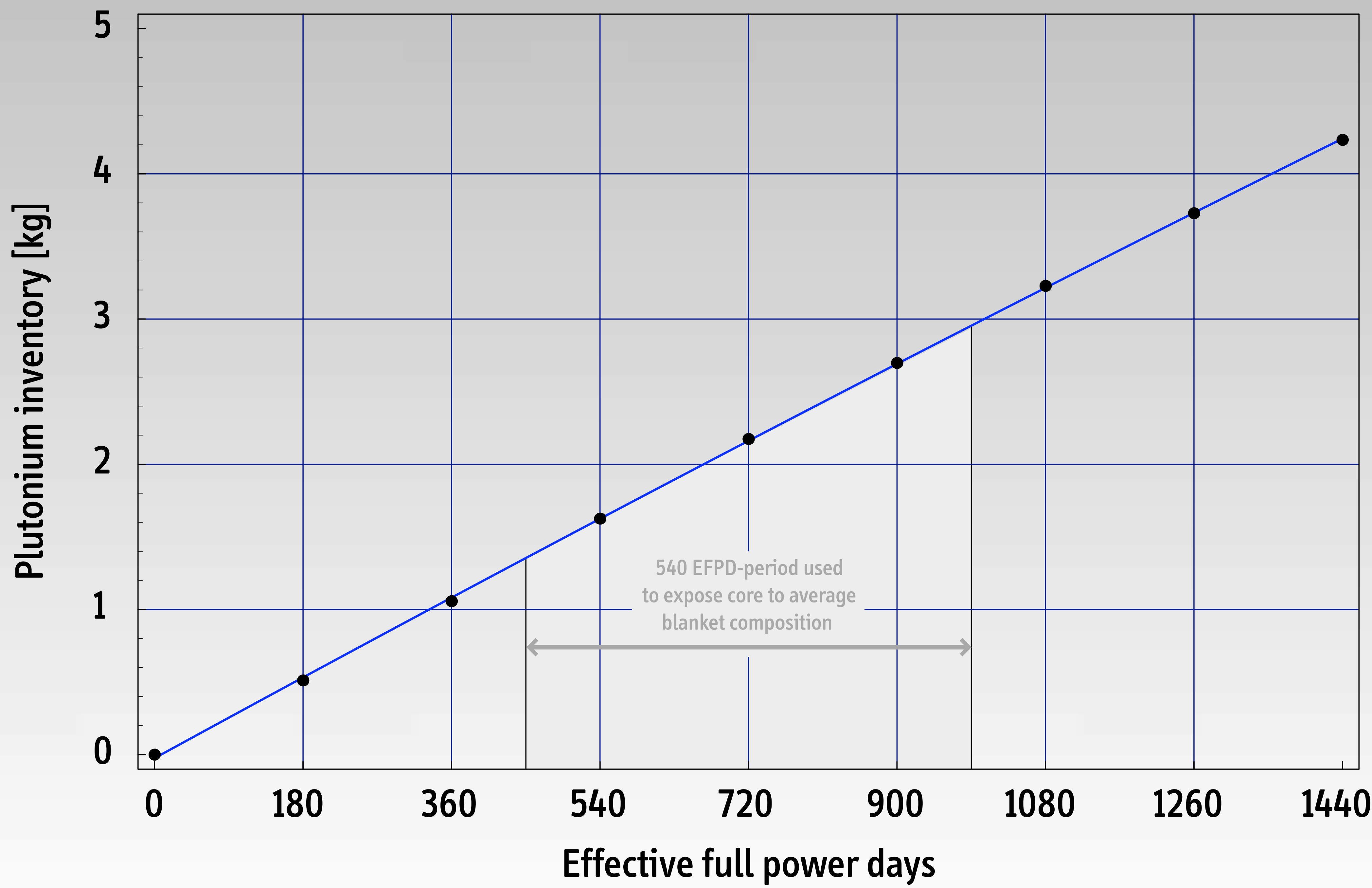


Results

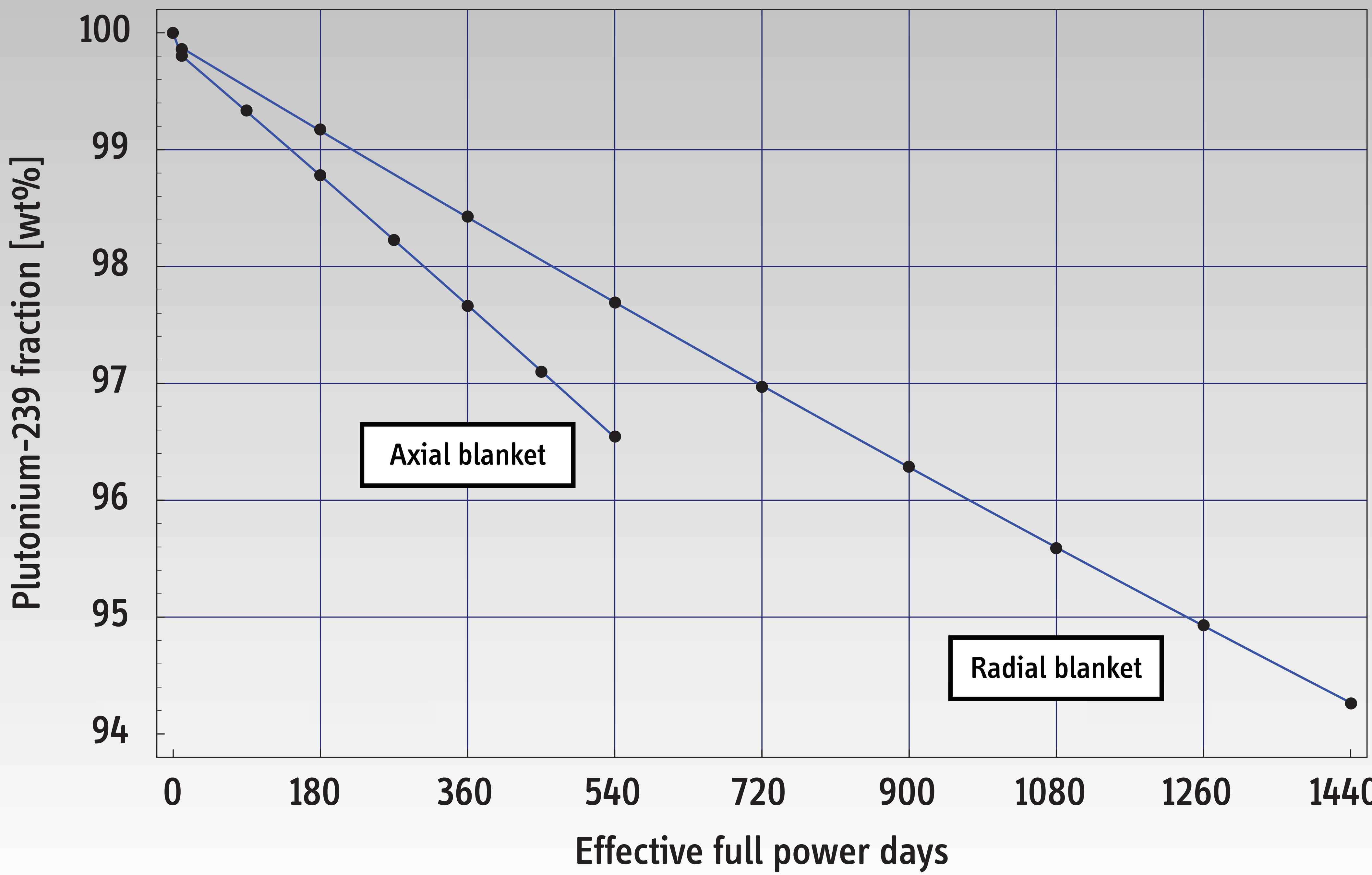
Average Plutonium Inventory in the Fuel Elements of the Core



Average Plutonium Inventory in a Fuel Element of the Radial Blanket



Plutonium Isotopics in the Blankets



Plutonium Isotopics in the Blankets of a Fast Neutron Reactor

(Why is it weapon-grade?)

		Heavy water reactor	Fast neutron reactor
U-238	Fission x-section	0.064 b	0.023 b
	Capture x-section	1.111 b	0.257 b
Pu-239	Fission x-section	253 b	1.815 b
	Capture x-section	112 b	0.505 b
Fissions per absorption in Pu-239		69%	78%
Assume 1% Pu-239 in 99% U-238			
Absolute absorption in plutonium		75.8%	7.7%

Annual Reload/Discharge Analysis

ANNUAL RELOAD

	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Core	4.0 kg	3.1 kg	3074.5 kg	2.7 kg	655.4 kg	279.4 kg	47.5 kg	26.5 kg
Axial Blanket	3.1 kg	2.4 kg	2449.8 kg	0.0 kg	0.0 kg	0.0 kg	0.0 kg	0.0 kg
Radial Blanket	3.4 kg	2.6 kg	2617.1 kg	0.0 kg	0.0 kg	0.0 kg	0.0 kg	0.0 kg
Total	10.5 kg 0.13%	8.1 kg 0.10%	8141.4 kg 99.77%	2.7 kg 0.3%	655.4 kg 64.8%	279.4 kg 27.6%	47.5 kg 4.7%	26.5 kg 2.6%
Overall Total	8160 kg			1012 kg				
Fissile Fraction	0.13%			69.5%				

ANNUAL DISCHARGE

	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Core	2.4 kg 0.08%	3.1 kg 0.11%	2862.5 kg 99.81%	2.2 kg 0.2%	541.6 kg 60.2%	284.7 kg 31.6%	44.9 kg 5.0%	26.6 kg 3.0%
Axial Blanket	2.5 kg 0.10%	2.5 kg 0.10%	2388.7 kg 99.80%	0.016 kg 0.030%	51.76 kg 96.543%	1.78 kg 3.323%	0.055 kg 0.103%	0.001 kg 0.001%
Radial Blanket	2.2 kg 0.09%	2.6 kg 0.11%	2500.2 kg 99.80%	0.056 kg 0.058%	91.04 kg 94.265%	5.26 kg 5.449%	0.215 kg 0.222%	0.005 kg 0.006%
Total	7.1 kg 0.09%	8.2 kg 0.11%	7751.4 kg 99.80%	2.3 kg 0.2%	684.4 kg 65.2 %	291.7 kg 27.8%	45.2 kg 4.3%	26.6 kg 2.5%
Overall Total	7767 kg			1050 kg				
Fissile Fraction	0.09%			69.5%				

Annual Reload/Discharge Analysis

	ANNUAL DISCHARGE							
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Overall Total Fissile Fraction	7767 kg 0.09%			1050 kg 69.5%				

Blanket Subtotals	53.6 kg of plutonium with a fissile fraction of 96.6% contained in the axial blanket
	96.6 kg of plutonium with a fissile fraction of 94.5% contained in the radial blanket
	150.2 kg of plutonium with a fissile fraction of 95.3% contained in both blankets combined

Annual Reload/Discharge Analysis

ANNUAL DISCHARGE

	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Core	2.4 kg 0.08%	3.1 kg 0.11%	2862.5 kg 99.81%	2.2 kg 0.2%	541.6 kg 60.2%	284.7 kg 31.6%	44.9 kg 5.0%	26.6 kg 3.0%
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Total	7.1 kg 0.09%	8.2 kg 0.11%	7751.4 kg 99.80%	2.3 kg 0.2%	684.4 kg 65.2 %	291.7 kg 27.8%	45.2 kg 4.3%	26.6 kg 2.5%
Overall Total Fissile Fraction	7767 kg 0.09%			1050 kg 69.5%				

ANNUAL MAKEUP

	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
	1.4 kg 0.25%	0.4 kg 0.07%	551.2 kg 99.68%					
Total Fissile Fraction	393 kg + 160 kg 0.25%							
Makeup + Discharge	8.5 kg 0.10%	8.6 kg 0.10%	8302.6 kg 99.80%					
Total Fissile Fraction	8320 kg 0.10%							

Breeding Ratio

$$BR = 1 + \frac{M_{\mathrm{DISC}} - M_{\mathrm{LOAD}}}{M_{\mathrm{DEST}}}$$

Only fissile isotopes are considered for the determination of the breeding ratio
For uranium-plutonium fuel, these are U-235, Pu-239 and Pu-241

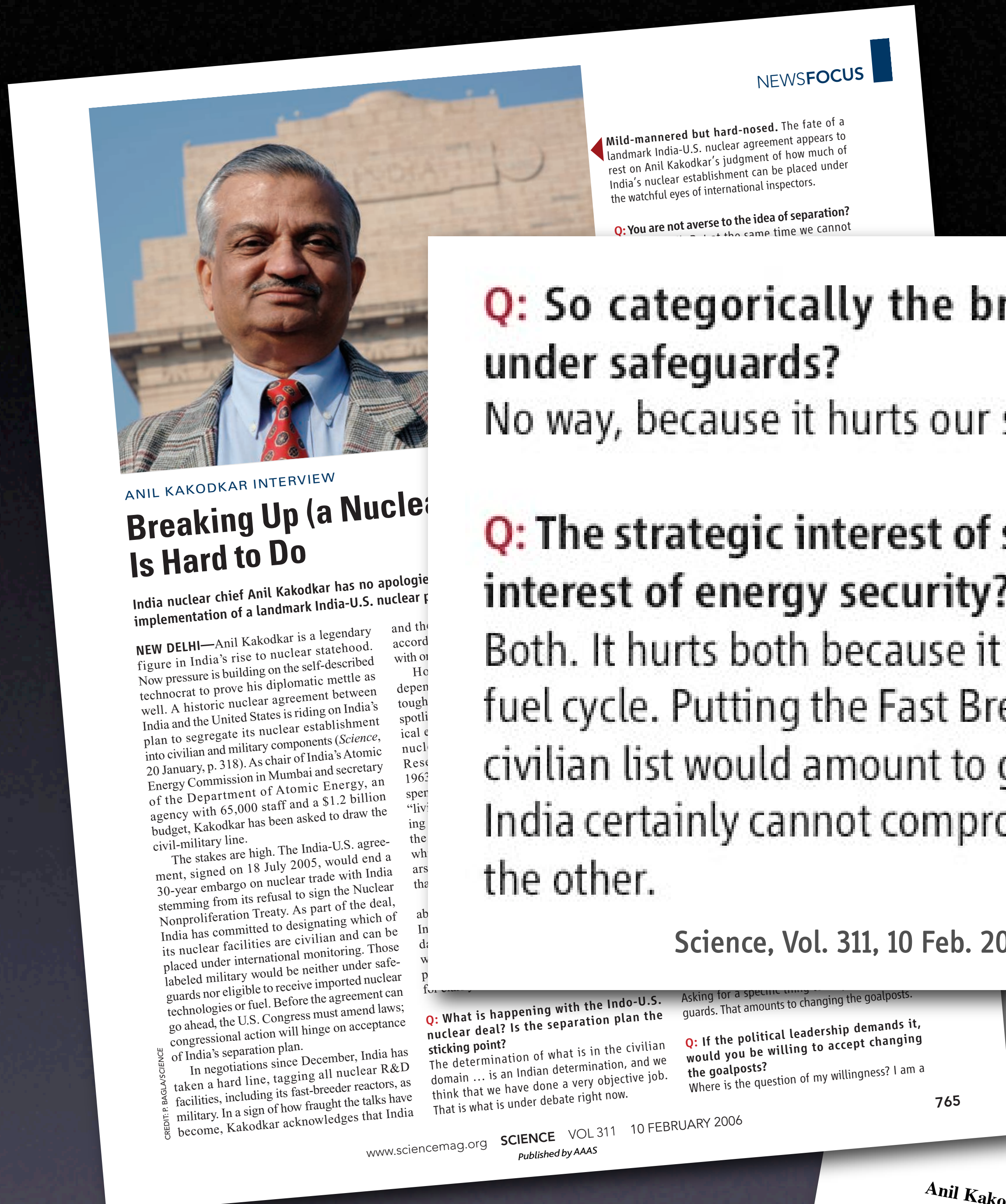
Fissile material is consumed by fission or neutron capture

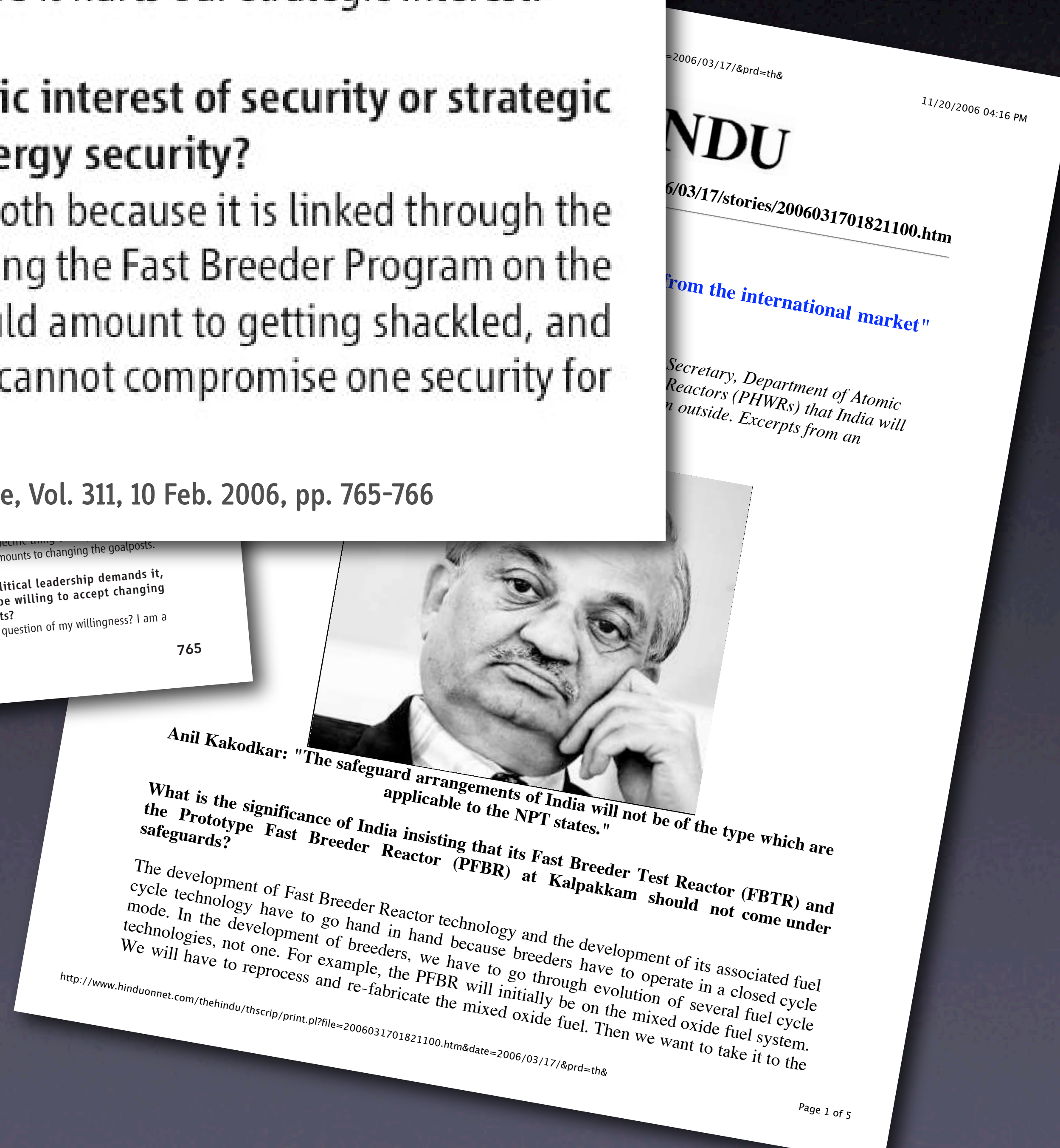
$$BR = 1 + \frac{738\ \mathrm{kg} - 711\ \mathrm{kg}}{440\ \mathrm{kg}} \approx 1.06$$

Values quoted in the literature: 1.05-1.10

Gretchenfrage

“Will India use the weapon-grade plutonium generated with the PFBR for its nuclear weapons program?”





Q: So categorically the breeders will not go under safeguards?

No way, because it hurts our strategic interest.

Q: The strategic interest of security or strategic interest of energy security?

Both. It hurts both because it is linked through the fuel cycle. Putting the Fast Breeder Program on the civilian list would amount to getting shackled, and India certainly cannot compromise one security for the other.

Science, Vol. 311, 10 Feb. 2006, pp. 765-766

Refueling Options for the PFBR

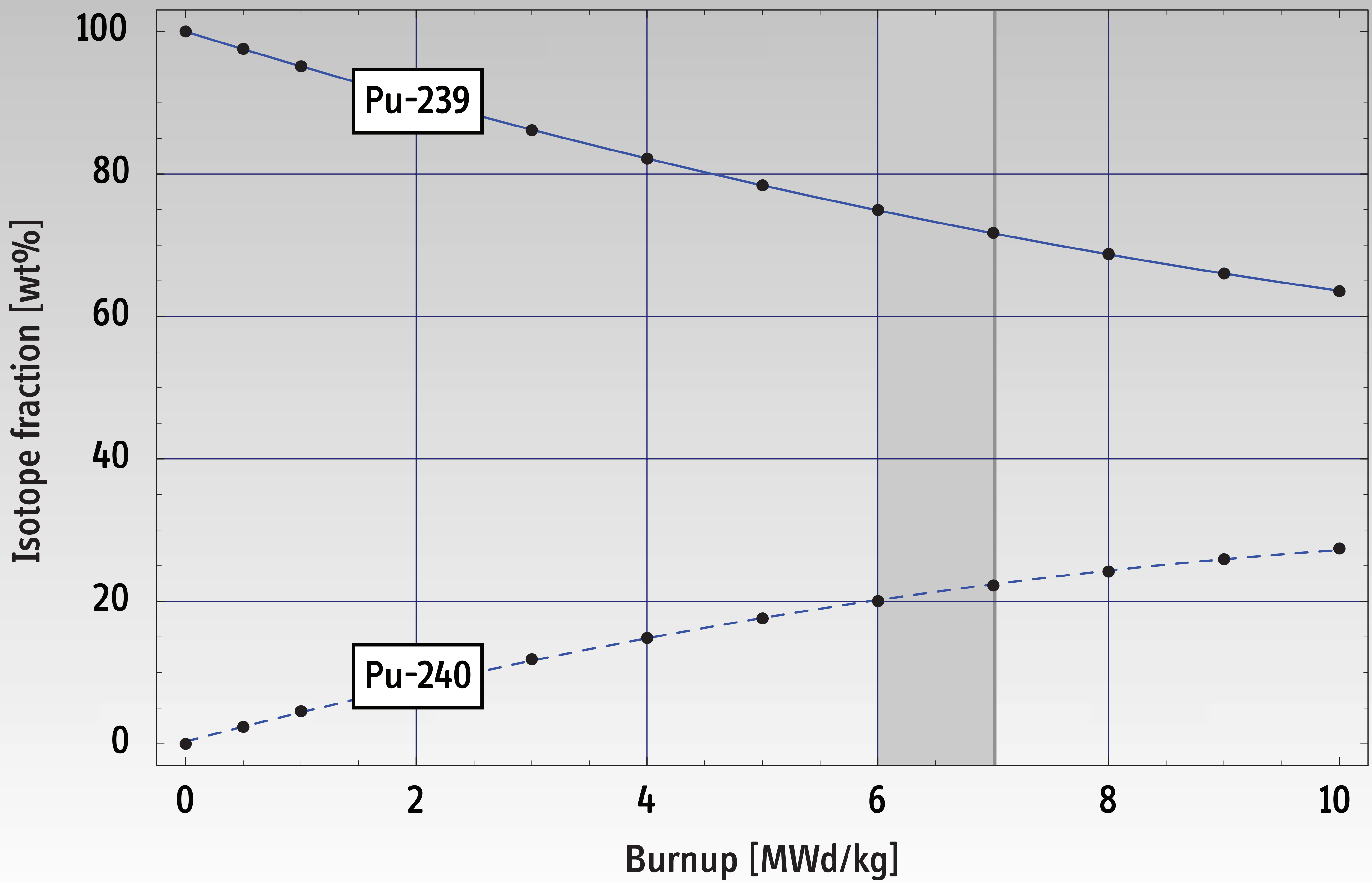
(Annual requirement: 1012 kg of plutonium with a Pu-FIS fraction of 69.5%)

	Core	Axial Blanket	Radial Blanket	CANDU
	900 kg 65.2% Pu-FIS	54 kg 96.6% Pu-FIS	97 kg 94.5% Pu-FIS	(unlimited supply) 77.1% Pu-FIS
Option 1	1012 kg (plus 38 kg surplus)			

Footnote

Isotopics of plutonium recovered from spent fuel of heavy water (CANDU) reactors

Plutonium Isotopics of Heavy Water Reactor Fuel

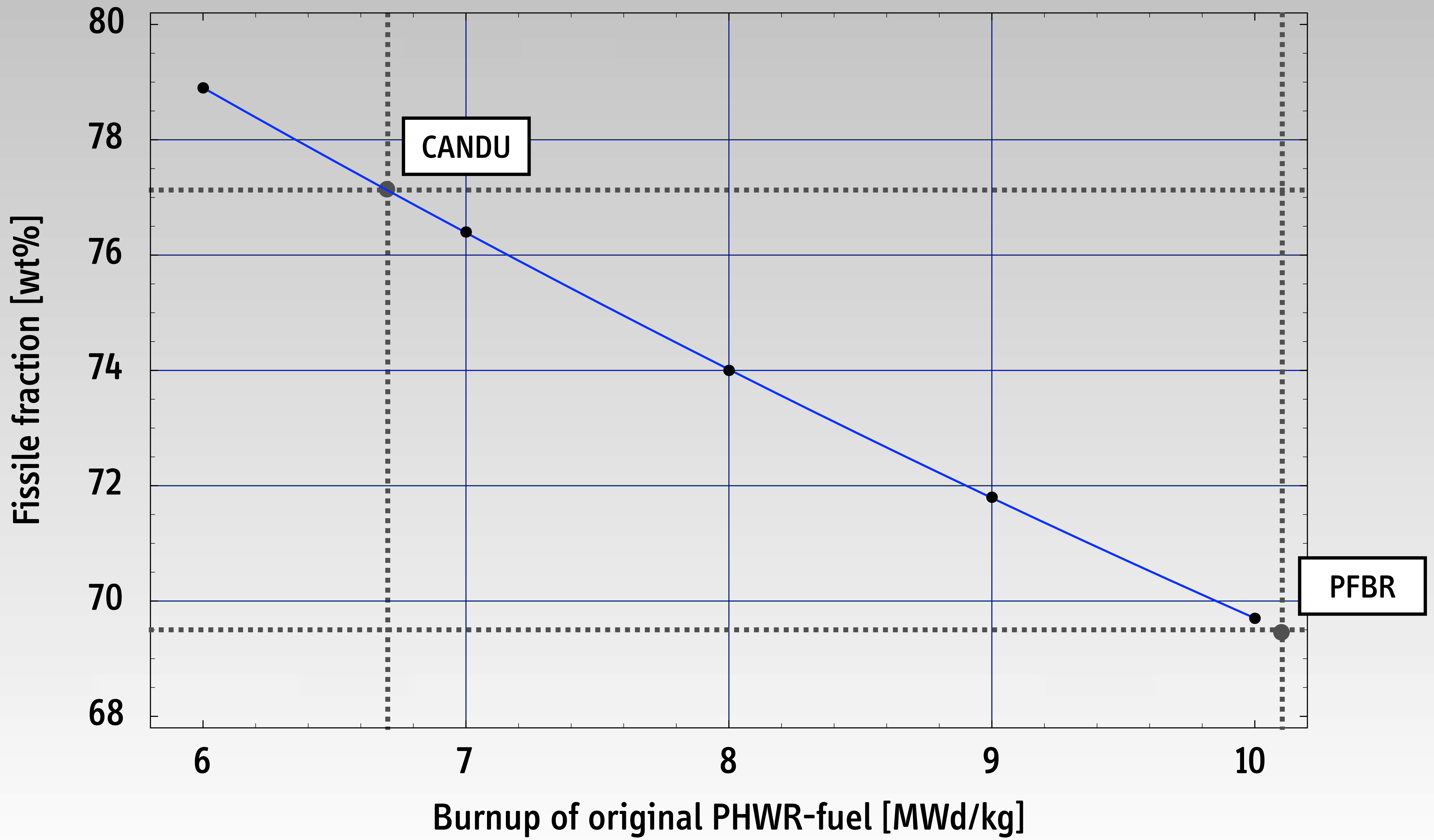


Plutonium Isotopics of Heavy Water Reactor Fuel

		Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
6.0 MWd/kg	at discharge	0.07%	74.92%	20.05%	4.19%	0.77%
	cooled	0.07%	75.60%	20.23%	3.32%	0.78%
7.0 MWd/kg	at discharge	0.09%	71.71%	22.23%	4.89%	1.08%
	cooled	0.09%	72.48%	22.46%	3.88%	1.09%
8.0 MWd/kg	at discharge	0.11%	68.75%	24.18%	5.52%	1.44%
	cooled	0.11%	69.58%	24.46%	4.39%	1.46%
9.0 MWd/kg	at discharge	0.13%	66.03%	25.90%	6.09%	1.85%
	cooled	0.13%	66.91%	26.24%	4.85%	1.87%
10.0 MWd/kg	at discharge	0.16%	63.52%	27.42%	6.61%	2.29%
	cooled	0.15%	64.44%	27.81%	5.27%	2.33%

Plutonium compositions in CANDU fuel irradiated to various discharge burnup levels.
Decay-corrected compositions are for a five-year storage period before reprocessing of the fuel.

Fissile Fraction of Plutonium Recovered from 5-Year-Cooled PHWR-Fuel

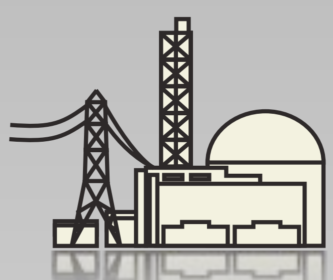


Refueling Options for the PFBR

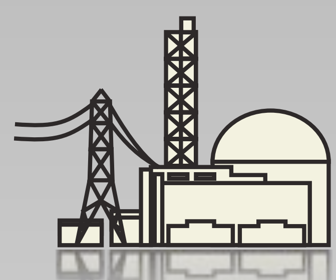
(Annual requirement: 1012 kg of plutonium with a Pu-FIS fraction of 69.5%)

	Core	Axial Blanket	Radial Blanket	CANDU
	900 kg 65.2% Pu-FIS	53.5 kg 96.6% Pu-FIS	96.5 kg 94.5% Pu-FIS	(unlimited supply) 77.1% Pu-FIS
Option 1	1012 kg (plus 38 kg surplus)			
Option 2	762 kg (plus 191.5 kg surplus)		not reused	250 kg
	requires chopping of core fuel and separation of axial blanket segments prior to reprocessing			
Option 3	646 kg (plus 254 kg surplus)	not reused	not reused	366 kg

Nuclear Facilities and Materials at the Kalpakkam / IGCAR Site

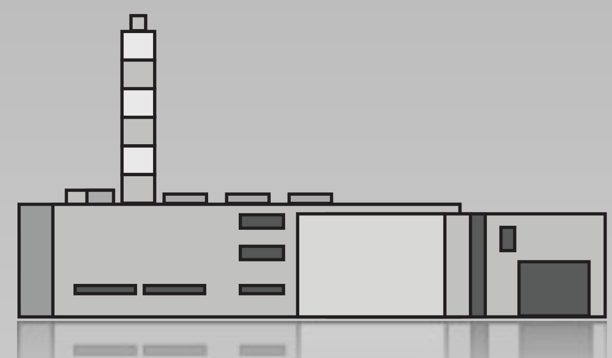


Madras-1
(170 MWe)



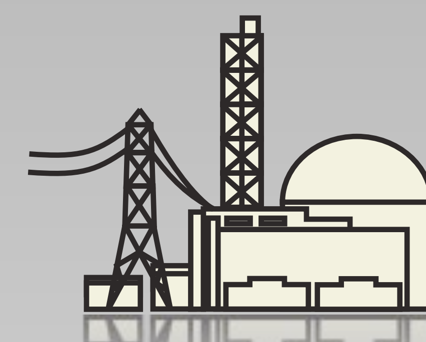
Madras-1
(220 MWe)

About 170 kg of plutonium per year
Fissile fraction: about 77%



Kalpakkam Reprocessing Plant (KARP)
100 MT(HM)/yr

Fast Reactor Fuel Reprocessing Plant (FRFRP)
in planning stages
(capacity on the order of 10-15 MT(HM)/yr)



PFBR
(500 MWe)

Plutonium requirements
for operation in
civilian and military mode?

2000 kg of Pu for initial core
1000 kg of Pu for initial reloads

1000 kg of Pu needed to produce
400 kg of weapon-grade Pu

plus 750 kg of extra core-Pu

Cumulative local plutonium production by 2010: *more than 4000 kg*
Reprocessed fraction: *unknown (but presumably high)*

Local plutonium stockpile is likely to be (much) higher due to spent fuel transfers from other sites
Spent fuel from the Kaiga-1 and -2 reactors would add about 2000 kg of plutonium

KARP could separate more than 10,000 kg of plutonium by 2010

What Does All That Mean?

Fissile Material Inventories and Production Capacities in South Asia

(military material only)

India		Pakistan	
Plutonium	HEU	Plutonium	HEU
Estimated Inventory (as of 2006, rounded)			
500 kg	(sub weapon-grade)	90 kg	1300 kg

Inventories are roughly comparable in terms of nuclear-weapon equivalents (about one hundred each)

Source: Mian et al., *Fissile Materials in South Asia and the Implications of the U.S.-India Deal*
Science and Global Security, 14: 117-143, 2006

Fissile Material Inventories and Production Capacities in South Asia

(military material only)

India		Pakistan	
Plutonium	HEU	Plutonium	HEU
Estimated Production Capacities (as of 2006)			
32 kg/yr	(20 kg/yr equivalent)	12 kg/yr	100 kg/yr
Potential Future Changes in Production Capacities (beyond 2010)			
-9 kg/yr after shutdown of CIRUS in 2010	(expandable)	--	(expandable)
PFBR		Khushab-2	
up to 150 kg/yr		10-40 kg/yr	

(The planned power level for the Khushab-2 reactor is unknown; the given range corresponds to a thermal power of 50-200 MW)

Conclusion

About 150 kg of weapon-grade plutonium will be generated annually
in the blankets of the Indian Prototype Fast Breeder Reactor

once the reactor is operated under equilibrium conditions
and achieves a capacity factor of 75%

Straightforward options exist that allow for
"diversion" of weapon-grade plutonium from the blankets
by topping-up the PBFR-core with CANDU-plutonium

(e.g. OLD CORE + 250 kg of CANDU-Pu → NEW CORE + 100 kg of WPu + 190 kg of PFBR-Core-Pu)

CANDU-plutonium will be needed for the initial cores of the PFBR anyway

Given the current dynamics of the South-Asian nuclear weapon programs,
it seems implausible that the DAE would *not* consider/exercise this option *sooner or later*

(suspicions/allegations will arise *sooner or later* that the PFBR is used for weapons purposes)