Neutronic Studies for Thorium Utilization in Accelerator Driven Systems

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ADS Program Objectives: Th utilisation

- World Nuclear Scenario
  - Plenty of U available
  - Large fissile Pu availability
    - Little incentive for breeding
  - Large waste volumes
    - Strong incentive for waste transmutation
  - Little incentive for Th use

- Present Indian Scenario
  - Very limited U availability
  - Small fissile Pu base
    - Strong incentive for breeding
  - Small volumes of waste
    - Less incentive for waste transmutation immediately
    - Likely to change with expected large scale expansion nuclear power program
  - Large Th deposits
    - Strong incentive for Th use
    - Low transuranic waste generation.
  - Three stage program
    - PHWRs: Pu for fast reactors
    - FBRs: Pu and Th breeding
    - Th-U233 fuelled reactors
- ADS provides
  - Faster breeding
    - Extra neutrons
    - Absence of parasitic control rods
  - Flexibility in use of fuels
  - Simplification of Th fuel cycle

ADS Reactor Physics studies

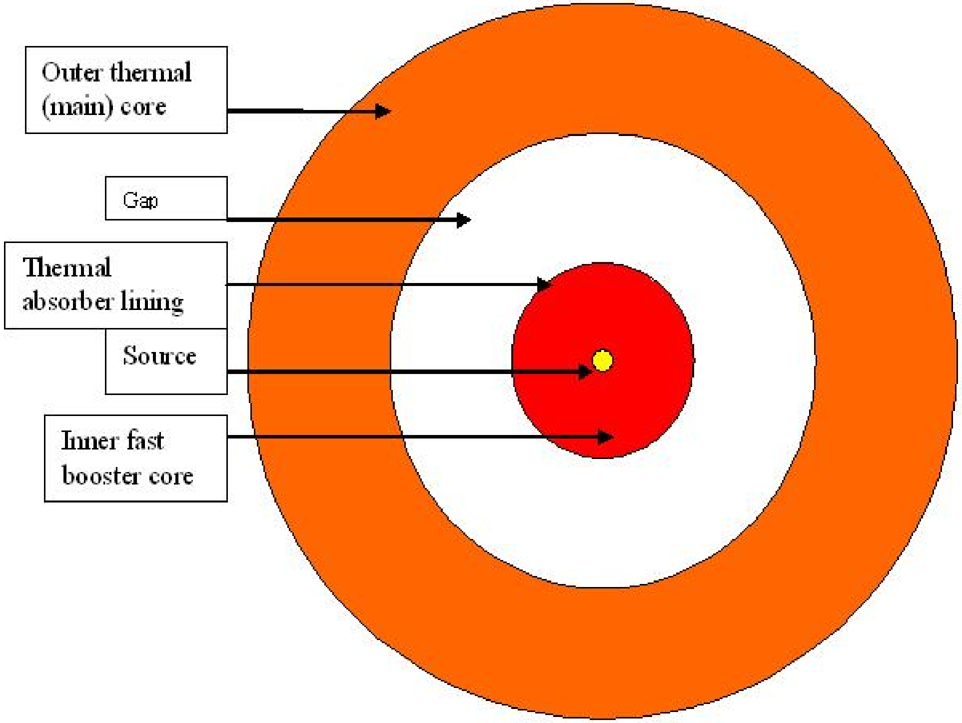
- Theoretical Studies
  - Development of Computer Codes
  - Theory of Reactor Noise in ADS
  - Methods for determining alpha modes
  - Noise simulator
- Experimental ADS facilities and studies
  - The Purnima Sub-critical facility
  - Critical facility
- One-way coupled ADS concept
- Studies on Th Utilisation in ADS
  - Studies on starting ADS with naturally available fuel
  - Enhanced Breeding in ADSs
  - Th Utilisation studies
    - Heavy Water Moderated ADSs
    - Fast ADS

Reactor Noise in ADS

- Reactor Noise analysis is an important tool for measurement of Reactor Physics parameters
- Similar techniques are likely to prove useful in ADS for sub-criticality measurement and monitoring
- Radioactive sources are Poisson sources due to
  - Large number of radioactive atoms
  - Relatively small number decay independently
- Accelerator sources are different
  - Pulsing
  - Cw accelerators
  - Fluctuations in intensity
    - Typically a few per cent
    - For Poisson source of 1e8 strength should be only 0.01%
  - Correlations in these fluctuations
- And are therefore non-Poisson sources
- The difference is likely to be important in the interpretation of noise based measurement / monitoring systems and require a new theory
- Such a theory has been worked out in BARC

ADS using low power accelerator One way coupled concept

- Power in ADS is inversely proportional to sub-criticality and directly proportional to neutron source strength
- In the control rod free concept, the operating k_{eff} is limited to the range 0.95-0.98
- This requires accelerator beam power of about 10 MW
- The one-way coupled booster-reactor concept can reduce this requirement five fold
  - Inner fast core with source at centre boosts the neutron source
  - These neutrons leak into the outer thermal (PHWR/AHWR) core where they undergo further multiplication
  - This cascade multplication gives very high energy gain
  - Due to the absorber lining and the gap very few neutrons return to the booster – i.e. there is a one way-coupling between the two
  - The one-way coupling ensures that the overall k_{eff}
  - is limited to the desired value
  - Consequently, accelerator power requirement for 750 MW(t) is ~ 1-2 MW
- As an example, there is a recent proposal for a waste transmuting ADS driven by an electron accelerator



Th utilisation options

- MSR
  - Completely different technology, little or no experience
- Once through cycles in thermal reactors
  - Do not significantly reduce requirement of mined uranium
  - They may reduce actinide waste burden
- Recycling options
    - Development of Th recycling technology
      - Associated difficulties and costs of Reprocessing and refabrication
  - Fast reactor
    - Self sustaining cycle possible
    - Little or no breeding likely
  - Thermal reactors
    - Breeding and self sustaining cycles difficult
    - Converters will require fissile material feed
      - This could come from fast breeders
- ADS as Th utilisation option
  - First CERN EA proposals were for generating power using Th
  - No constraint of maintaining criticality
    - Extra neutrons from the source

Indian Nuclear Power Reactor mix

Reactor type	No of units	Power MWe	Total MWe
Pressurised heavy water reactor (PHWR)	10 2	220 500	~3000
Boiling water reactor (BWR)	2	160	320
Pressurised water reactor (VVER)	2	1000	2000
Fast breeder FBR	1	500	500

Enhanced Breeding in ADS

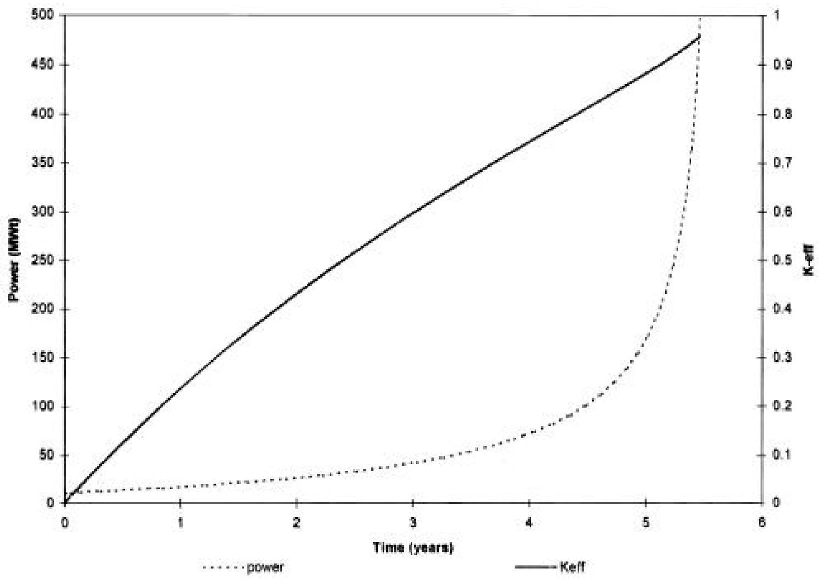
- Extra neutrons from the spallation source give enhanced breeding in ADS
  - How large is this effect?
  - Is it enhanced by sub-critical multiplication?
- We have shown that enhancement in rate of U-233 formation in ADS over critical reactors is exactly equal to the external source strength
- Further enhancement due to absence of parasitic absorption in control rods
- For typical accelerator currents proposed, enhanced breeding not very large
  - can be considered significant for self sustaining or near self sustaining cycles(eg U-Th).
  - In ADS mode these could become self sustaining or breeding cycles respectively

Th utilisation in fast ADS

- Three stage program
  - First stage PHWRs
  - Second stage: Pu from PHWR discharge in fast reactors
    - Breed Pu and U233 from Th
    - Expand capacity
  - Third stage: use and if possible breed U233
- Fast reactors: long doubling times
- Improve with advanced fuels for PuU cycle
- Little or no improvement for U233-Th cycle
  - Self sustaining cycle
- Growth is possible with ADS
- Reinvestment of about 5% electrical power gives an incremental growth of 1% of installed capacity

Starting ADS with pure Th

- MSR ADS concepts studied for long at Los Alamos by C.D.Bowman and coworkers
- One such scheme starts with pure Th fuel driven by a modest power (~10MW) proton beam on Pb
- They expected that such a reactor will reach full power of 200 MWe in about one year
- Our studies showed that actually it will take more than 5 years
- If however we use a mixture of Th and U we can get full power from day one
- In heavy water reactors the time required to breed the necessary U-233 is much longer ~ 20 years
- Hence using a mixture of Th and another fuel with a fissile species (say) natural U is more appropriate



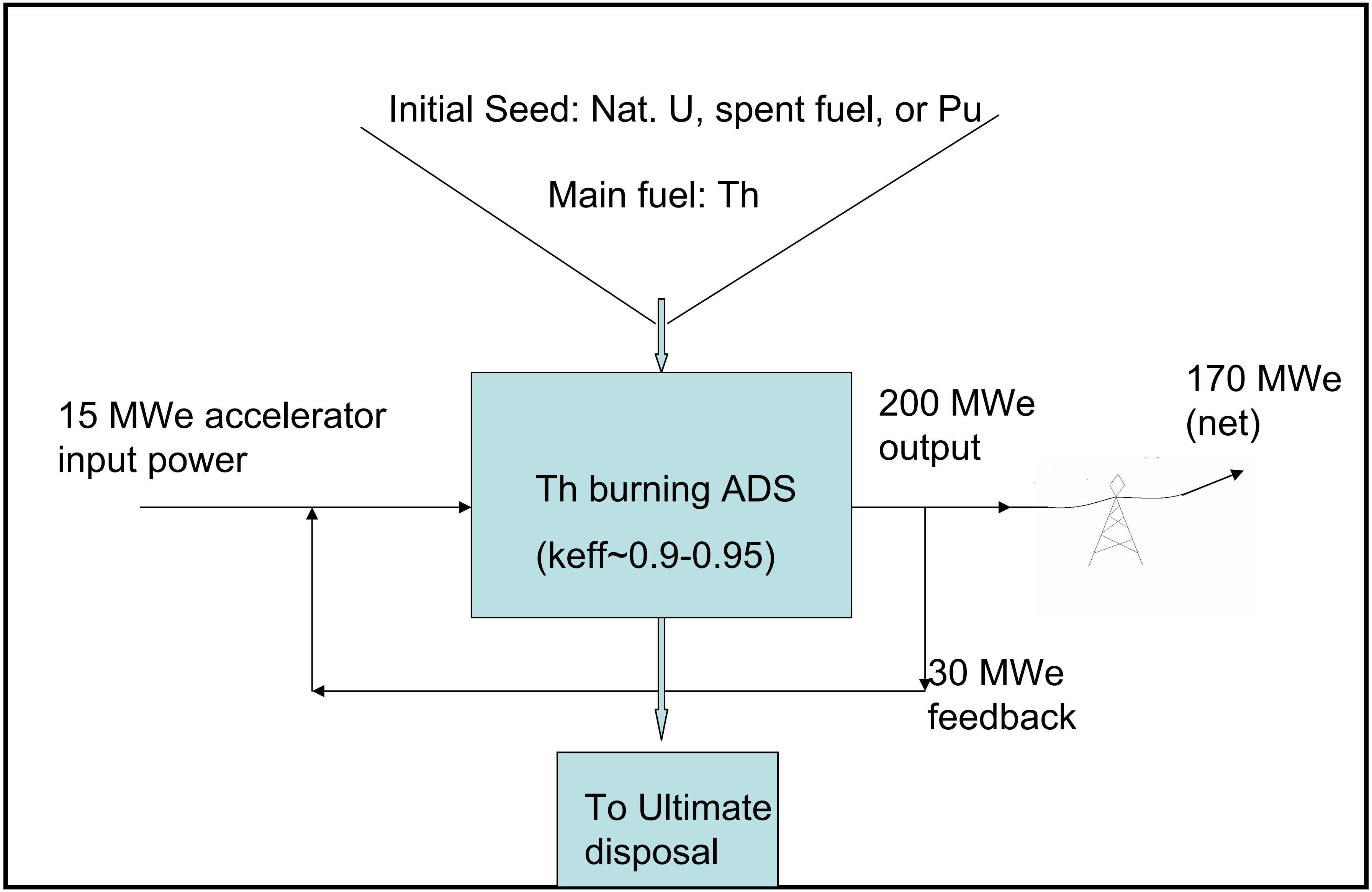
$$t = \frac{1}{s}\left[(\eta - 1)x + \left((\eta - 2)\xi - \lambda\right)\ln\left(1 - \frac{x}{\xi}\right)\right]$$

$$k = \frac{\eta x}{x + \xi + \lambda}$$

Th once through cycles

- Obviates the need for recycling with the attendant difficulties and costs
- Due to much lower minor actinide concentration, disposal does not prove much of a problem
- In critical reactors, driver fuel is needed
- In ADS this requirement can be relaxed
  - In-situ breeding and burning
    - Heavy Water moderated (PHWR) ADS
    - Fast ADS
    - Resonance region spectrum ADS

Th burning ADS concept



Initial Seed: Nat. U, spent fuel, or Pu

Main fuel: Th

15 MWe accelerator input power

Th burning ADS

(keff~0.9-0.95)

200 MWe output

170 MWe (net)

30 MWe feedback

To Ultimate disposal

Other In-situ breeding-burning concepts

- Travelling wave reactors (fast systems)
  - Wave can be sustained with U-Pu fuel
    - Metallic fuel required
      - Effect of density, spectrum
  - With Th-U fuel
    - Wave cannot sustain itself if
      - Capture in structures, coolant is accounted
        - » Lower density of Th metal
        - » Lower value of $\eta\varepsilon$
- Bowman’s MSR based Th burner
  - Removal of Xe, Kr
  - Maximum k~0.92
- Fusion fission hybrids

Th once through cycles: basics

$$L = 1 - \frac{k}{\eta'}\left(1 + \frac{1}{\beta}\right) - \frac{ek}{\beta\nu}\left(\frac{1000}{D} - 1\right)$$

$$k = (1 - L) / \left\{ \frac{1}{\eta'}\left(1 + \frac{1}{\beta}\right) - \frac{e}{\beta\nu}\left(\frac{1000}{D} - 1\right) \right\}$$

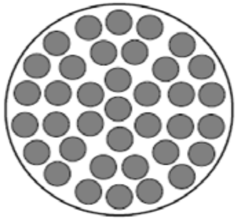
D : discharge burnup (GWd/t)

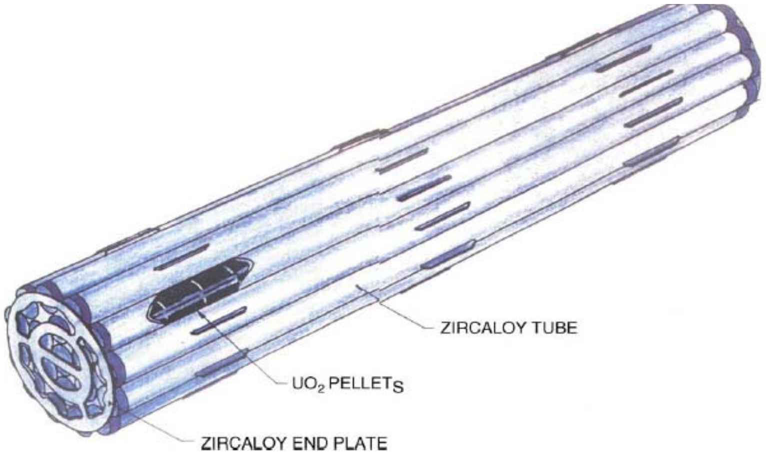
- e : equilibrium fraction of U-233 in the fuel
- k : operating k_{eff}
- L : loss in structures, FP, leakage

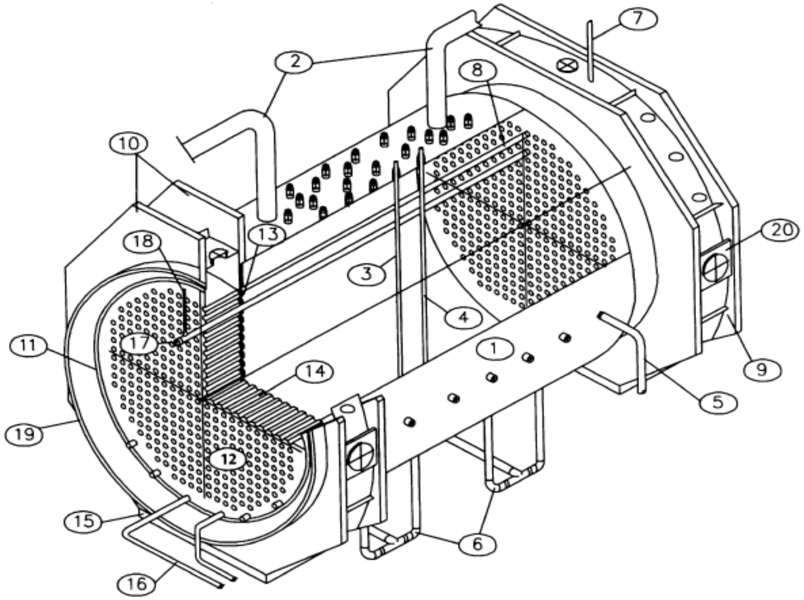
$$\eta' = \eta\varepsilon$$

$$\beta = \frac{\lambda_{Pa}}{\sigma_{Pa}\phi + \lambda_{Pa}}$$

PHWR:Reactor vessel and fuel bundle

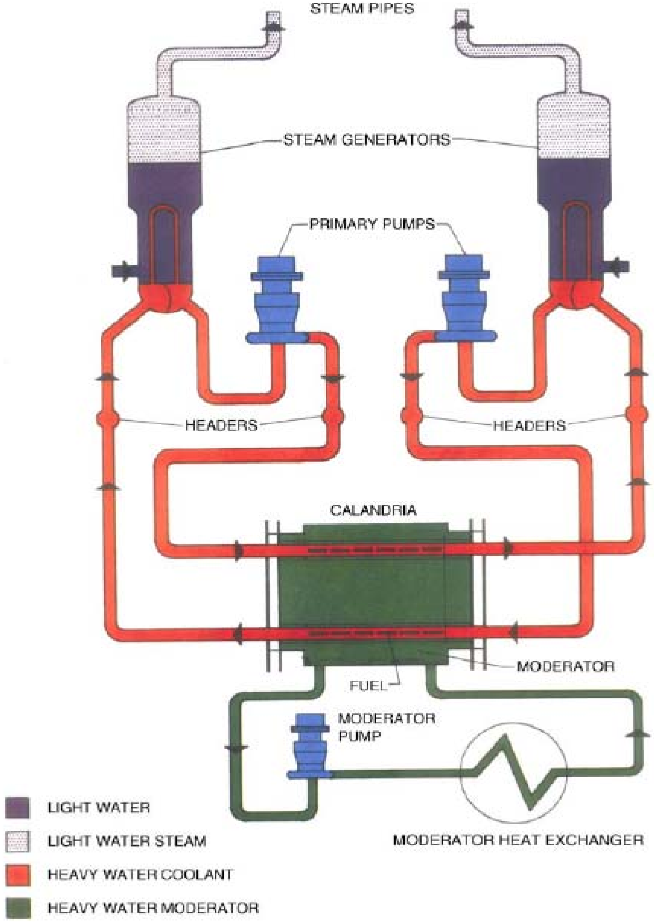


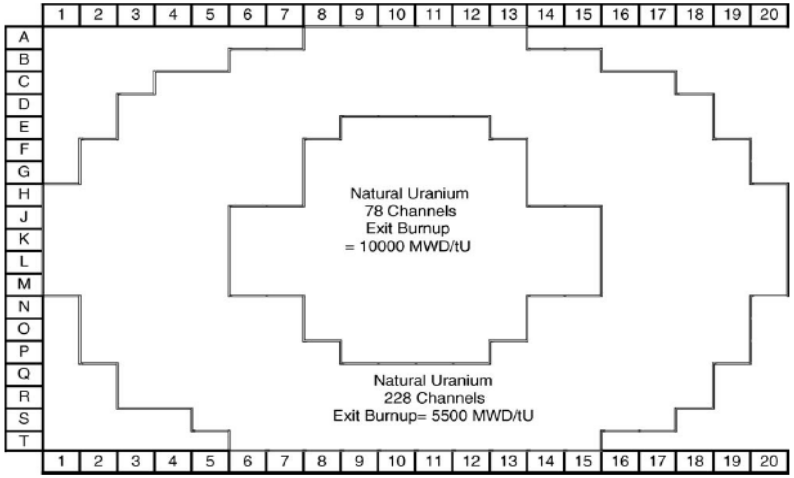




1. CALANDRIA SHELL
2. OVER PRESSURE RELIEF DEVICE
3. SHUT DOWN SYSTEM #1
4. SHUT DOWN SYSTEM #1
5. MODERATOR INLET
6. MODERATOR OUTLET
7. VENT PIPE
8. COOLANT CHANNEL ASSEMBLY
9. END SHIELD
10. END SHIELD SUPPORT STRUCTURE ASS'Y
11. MAIN SHELL ASS'Y
12. TUBE SHEET F/M SIDE
13. TUBE SHEET CAL SIDE
14. LATTICE TUBE
15. END SHIELD SUPPORT PLATE
16. END SHIELD COOLING INLET PIPES
17. END FITTING ASS'Y
18. FEEDER PIPES
19. OUTER SHELL
20. SUPPORT LUG

PHWR Layout


STEAM PIPES
STEAM GENERATORS
PRIMARY PUMPS
HEADERS
HEADERS
CALANDRIA
MODERATOR
FUEL
MODERATOR PUMP
MODERATOR HEAT EXCHANGER
LIGHT WATER
LIGHT WATER STEAM
HEAVY WATER COOLANT
HEAVY WATER MODERATOR


1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
A B C D E F G H J K L M N O P Q R S T
Natural Uranium
78 Channels
Exit Burnup
= 10000 MWD/tU
Natural Uranium
228 Channels
Exit Burnup= 5500 MWD/tU

Once through Th cycle PHWR ADS

- Initial fuel: Nat. U & Th
- Normal refuelling of U bundles (say 7 GWd/t)
- Th will reside longer
  - U-233 generation adds reactivity
  - Compensate by replacing some U by Th
- Th increases and U decreases
- Ultimately fully Th core
  - In situ breeding and burning Th
- Advantages
  - Use of natural fuels only
  - 140 tons U consumption during reactor life
  - High burnup of Th ~ 100 GWd/t
- Disadvantage
  - Low K ~0.9 and gain < 20 with Pb target
  - Accelerator power ~ 30 MW for a 200 MWe ADS
- Use of denatured Zr and better D2O purity can increase K to 0.93

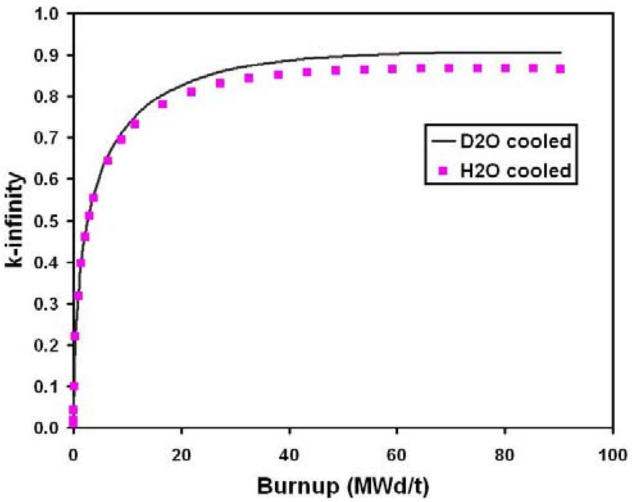
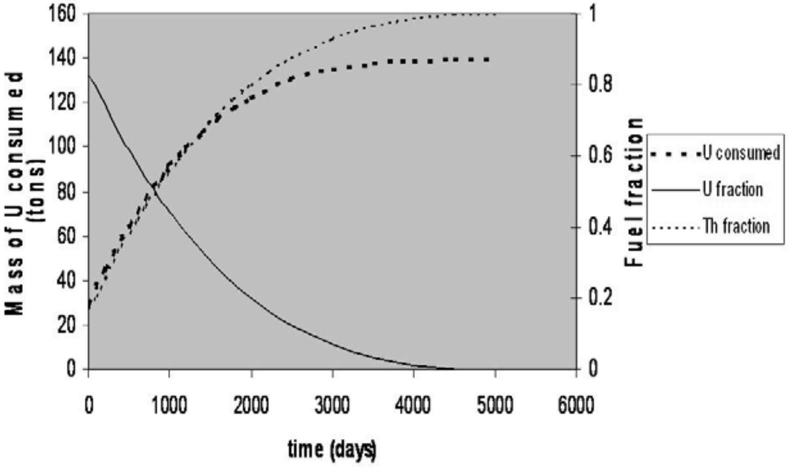


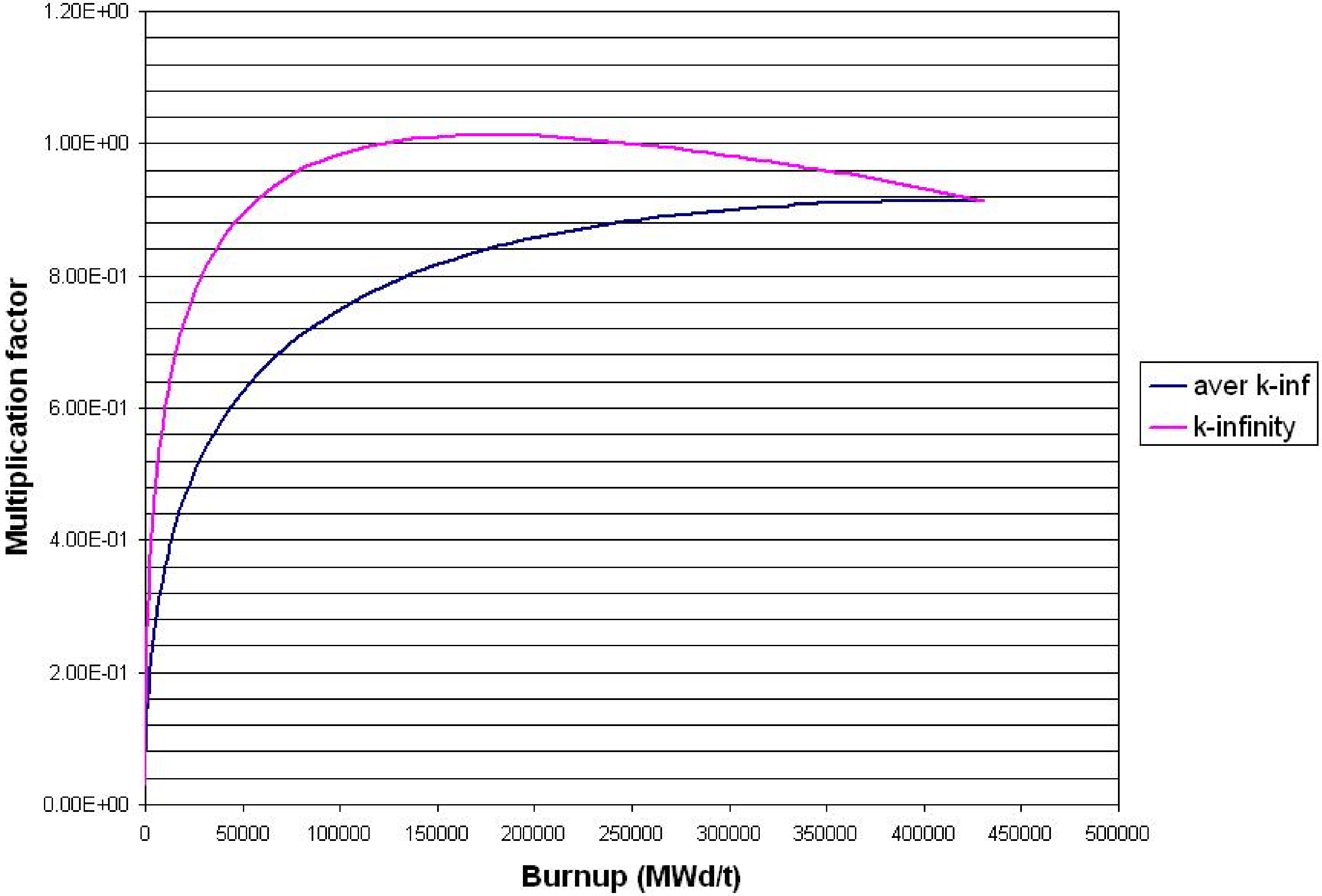
Fig. 4 U and Th fractions in ADSS for 7 GWd/t U burnup



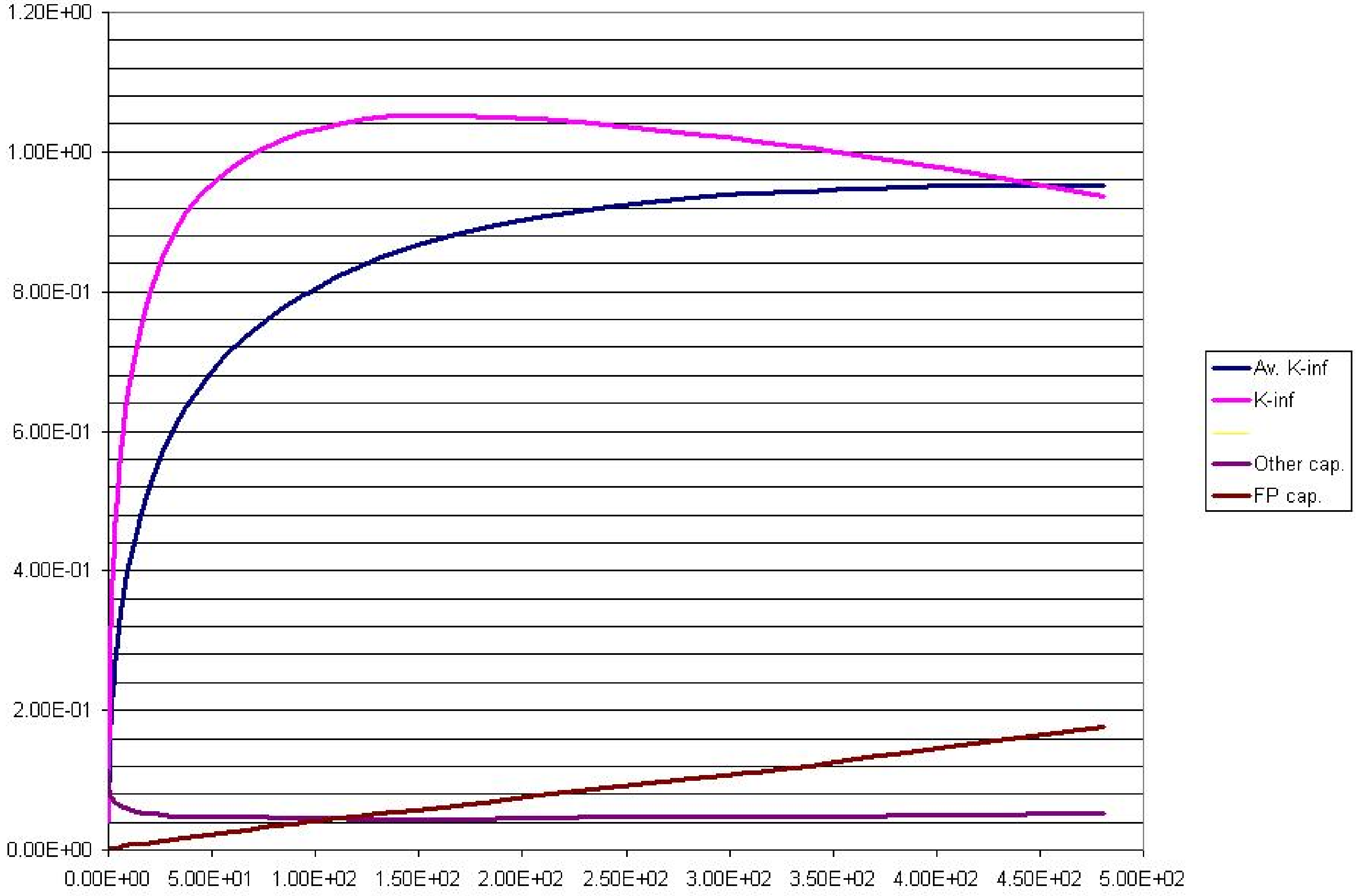
Once through Th cycle fast ADS

- Advantages
  - Good breeding properties of fast reactors
    - Lower parasitic capture on FPs and structures
    - Higher value of η ε
- Disadvantages
  - Higher U-233/Th ratio required ~ 0.1 [against 0.015]
    - Greater loss of U-233 when fuel is discharged needing higher breeding rate
    - Requires initial fissile charge of fissile material
  - Very long irradiation time and high fluence exposure
- Will need
  - Minimum possible absorption in structures and coolant
  - Higher discharge burnup ~ 400 GWd/t
  - On power fuelling facility with good shuffling
- Oxide fuelled systems give about the same k as thermal (PHWR)
- Metallic fuel gives higher value k~0.95
  - Coolant Na, Pb

ThO2 fuelled fast system: 40W/g

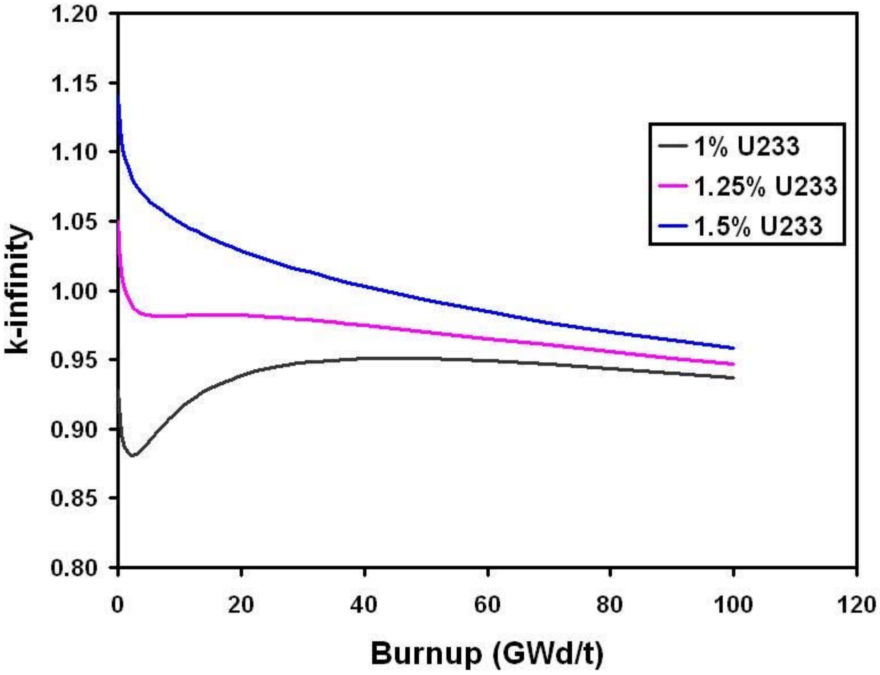


Th metal fuelled fast system: 40W/g



Th Utilisation in Heavy Water Moderated ADSs: Recycling

- Self sustaining cycles
  - Very difficult for critical reactors
    - Very low burn-ups
  - For ADS mode PHWR
  - With D2O coolant
    - K~0.95
    - burn-up 50 GWd/t
    - Energy Gain is ~ 40
    - 30 MW beam for 1200 MW(t) reactor
  - Boiling H2O coolant
    - Burnup ~ 23 GWd/t
    - Gain ~ 40
  - Power distribution



Conclusion

- Thorium utilisation by ADS routes shows some advantages over that in critical reactors
- These are due to extra neutrons from the source and the lack of constraint of maintaining criticality
- In heavy water moderated ADS
  - a once through cycle started with Nat. U and Th and ultimately fuelled with Th is possible but the gain is rather low
  - With recycling a self sustaining cycle is possible with an acceptable gain
- In fast ADS
  - an acceptable gain appears to be possible in once through cycle at very high discharge burnups

Thank You