THORIUM UTILIZATION FOR SUSTAINABLE SUPPLY OF NUCLEAR ENERGY

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PLAN OF TALK

Introduction

Three Stage Nuclear Power Programme

Thorium Utilisation for sustainable Nuclear Energy

Related ongoing activities and plans

Summary

For Long Term Energy Security and Large Scale Utilization of Thorium Reserves in the country, India has a robust Three Stage Power Programme in place.

Development of Thorium Based Reactor Systems for sustainable Nuclear Energy belongs to the third stage

Indian nuclear energy policy

- Commitment to high economic growth rate by a populous country.
- Indigenous and largely home-grown nuclear power program.
- Limited resources of uranium- to be judiciously utilized.
- Vast and easily accessible thorium reserves- to be eventually harnessed.
- Commitment to closed fuel cycle for optimum resource utilization.
- Safety and energy security are vital.

THREE STAGE NUCLEAR POWER PROGRAMME

Nat U , HEAVY WATER BASED PHWR - I Stage

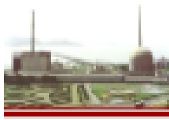
Pu FROM THE Ist STAGE USED IN THE
FAST BREEDER REACTOR, WHERE 232Th IS ALSO
COVERTED TO 233U - II Stage

233U FROM SECOND STAGE IS USED IN THE THIRD
STAGE ALONG WITH 232Th (Pu MAY BE USED IN
ADDITION) - III Stage

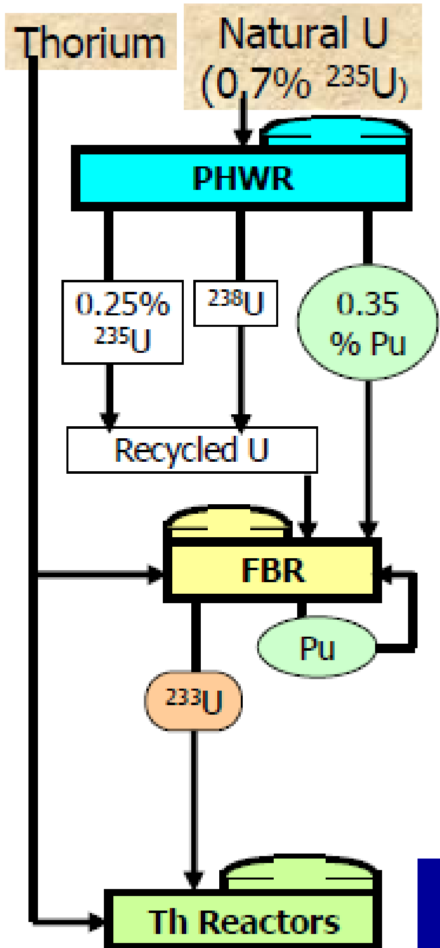
Reduces the volumes of waste to be handled
With the closed fuel cycle , Nuclear is near renewable

courtesy: Dr. R. Chidambaram

BARC

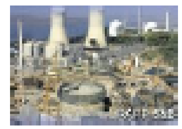


Current Indian nuclear power programme.



Indigenous Fuel

17 PHWRs under operation (4240 MWe)



1 PHWR under construction (220 MWe)

PHWRs Planned

(5540 MWe)

Total 10000 MWe

Imported Fuel

2 BWRs under operation (320 MWe)

2 LWRs under construction (2000 MWe)

Total 2320 MWe

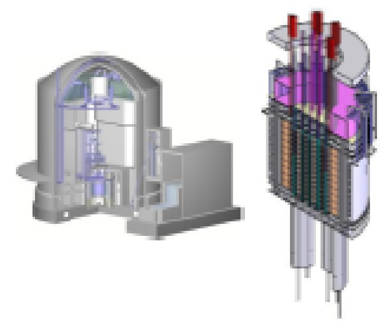
FBR under construction (500 MWe)

FBRs currently Planned

(2000 MWe)

Future FBRs

Fastest growth consistent with Pu availability



Thorium to be deployed on a large scale when enough growth in installed nuclear capacity has been achieved

Indian Nuclear Power Programme - 2020

REACTOR TYPE AND CAPACITIES	CAPACITY (MWe)	CUMULATIVE CAPACITY (MWe)
> 19 reactors at 6 sites in operation Tarapur, Rawatbhata, Kalpakkam, Narora, Kakrapar and Kaiga	4,560	4,560
¬ 1 PHWR under construction at RAPP-6(220 MWe)	220	4,780
¬ 2 LWRs under construction at Kudankulam(2x1000 MWe)	2,000	6,780
¬ PFBR under construction at Kalpakkam (1 X 500 MWe)	500	7,280
> Projects planned till 2020 PHWRs(8x700 MWe), FBRs(4x500 MWe), AHWR(1x300 MWe)	7,900	15,180
¬ Additional LWRs through international cooperation	~ 20000	~ 35000

Nuclear fuel resources : India

Uranium: up to 60,000 metric tons

(deposits require elaborate mining operations for extraction)

Natural Uranium contains 0.7% isotope U-235 for use as fuel (with or without enrichment).

Thorium: ~ 1000,000 metric tons

(Available in beach sands -requiring minimum mining operations for extraction)

Thorium contains no fissile isotope, but it can breed into U-233 by absorbing a spare neutron available in a nuclear reactor, which fissions on subsequent neutron absorption.

Attributes of Thorium

- Significantly more abundant than uranium
- Better Performance Characteristics
  - Higher melting point
  - Better thermal conductivity
  - Lower fission gas release
  - Good radiation resistance and dimensional stability
- Better Chemical Stability
  - Reduced fuel deterioration in the event of failure
  - No oxidation during permanent disposal in repository
  - Poses problem in dissolution during reprocessing

Attributes of thorium

- **Better self sustainability**

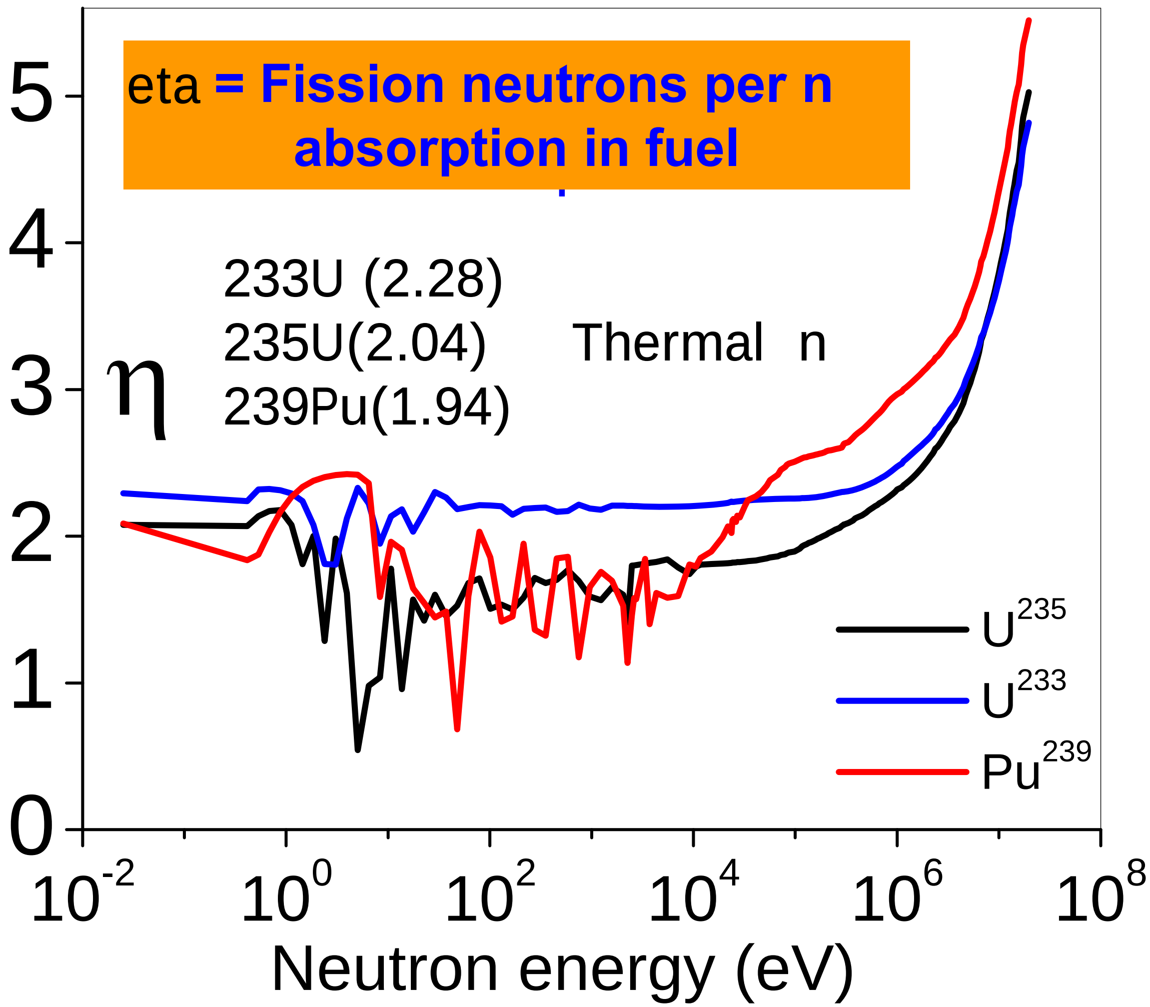
[σ_a of ^{232}Th (7.4 barns) is three times that of ^{238}U (2.7 barns)]

Lower levels long lived minor actinide generation

Presence of ^{232}U in ^{233}U

[Acts as proliferation resistant but poses problem in fuel fabrication]

Fission neutrons availability in breeder reactors



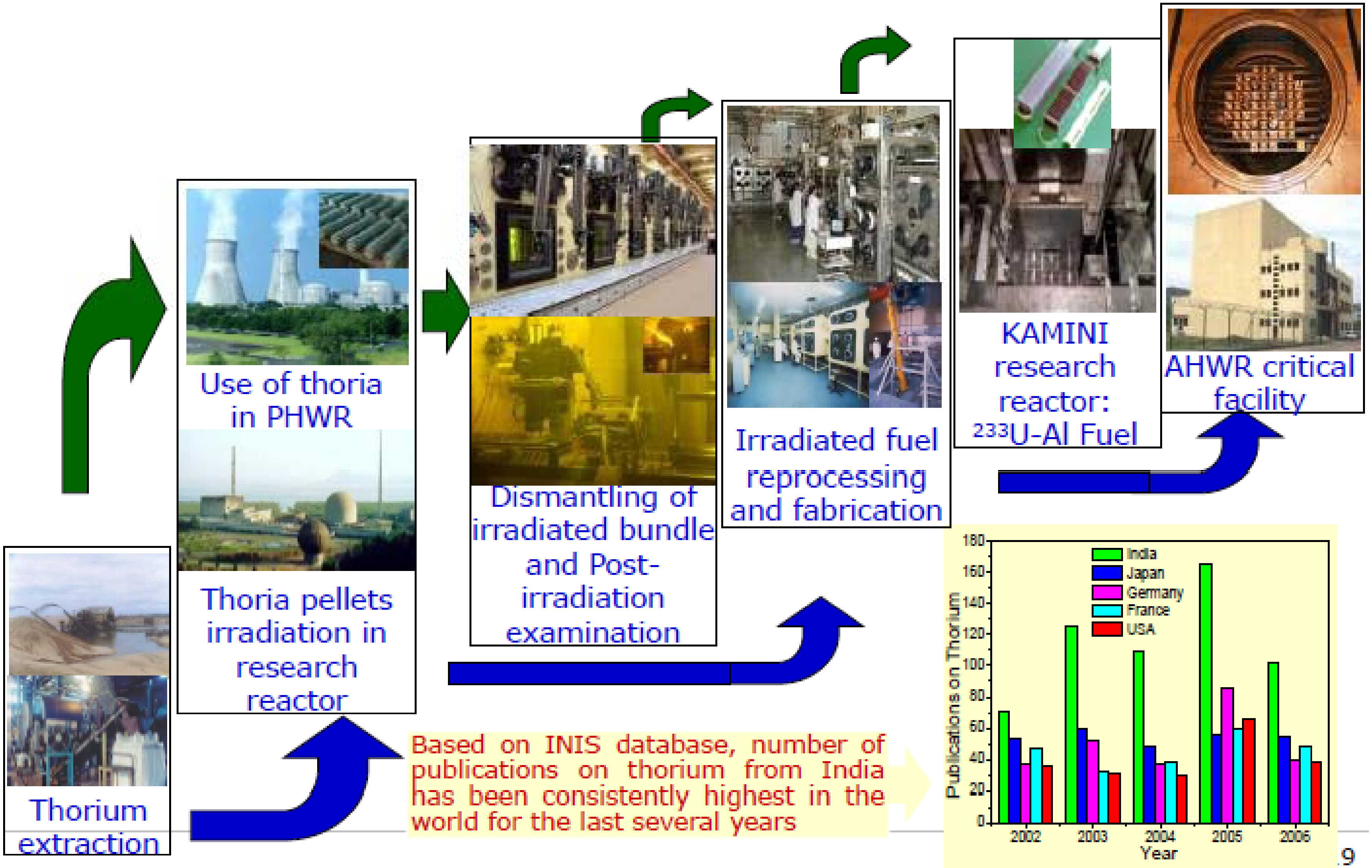
- **Fuel doubling time depends on: surplus neutrons per absorption in the reactor fuel.**

  (However, all neutron surpluses to be suitably absorbed for safe reactor operation.)

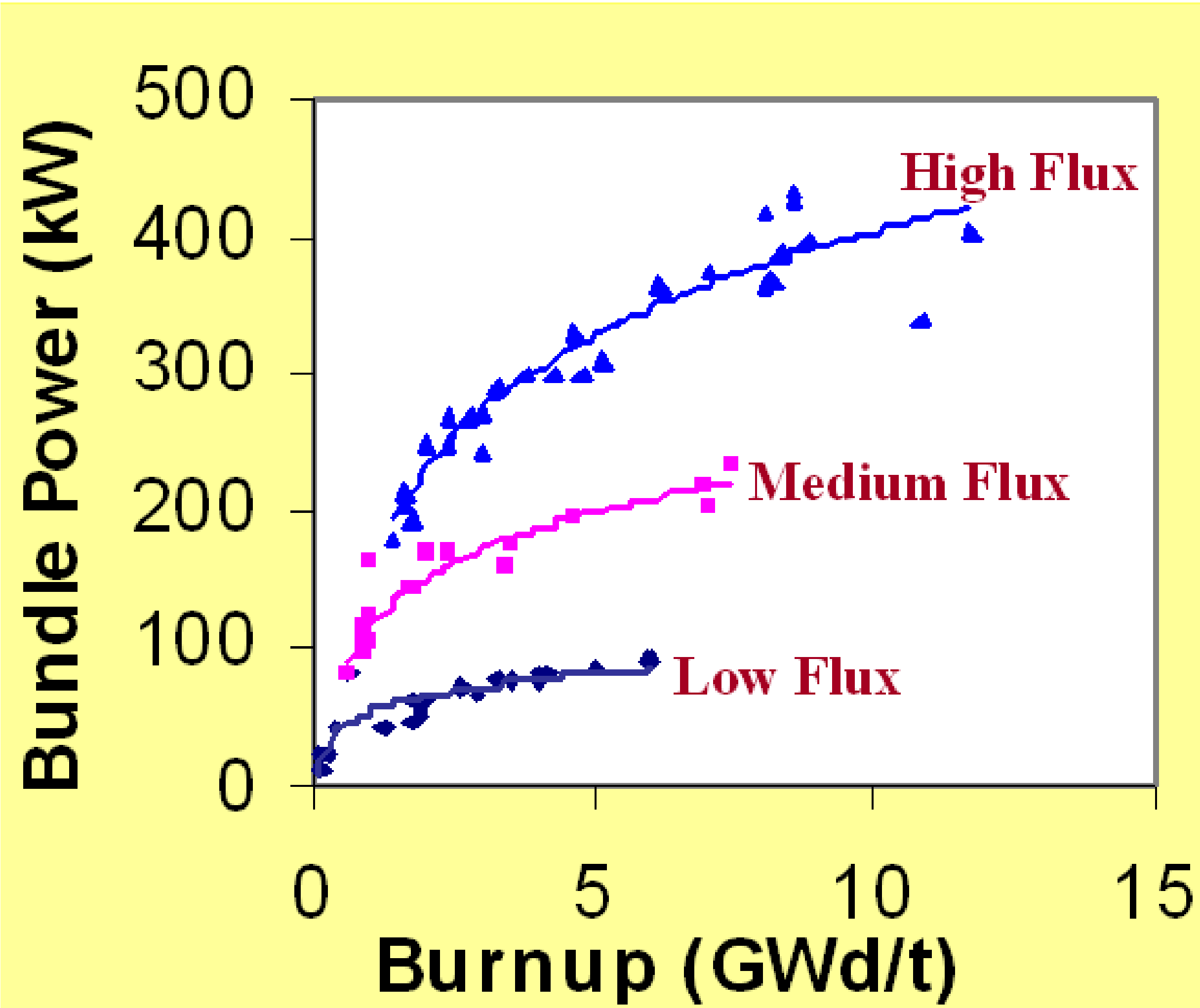
- **^{239}Pu-fuel : has surplus neutrons only in fast spectrum.**

- **^{233}U-fuel : has similar neutron surpluses in fast & thermal spectra.**

Evolution of thorium fuel cycle development in India



Use of Thoria bundles in PHWR



Reactor	Number of bundles
Madras- I	4
Kakrapar-I	35
Kakrapar-II	35
Rajasthan- II	18
Rajasthan -III	35
Kaiga-II	35
Rajasthan-IV	35
Kaiga-I	35
Tarapur-III	12
Tarapur-IV	12

[Also irradiated in pile loops in Research Reactor]

Post Irradiation Examination

- **Power Peaking in the central elements**
- **Atom % fission = 1.25%**

Isotopic Composition of Discharged Uranium (%)						
	^{232}U	^{233}U	^{234}U	^{235}U	^{236}U	^{238}U
Mass Spectrometric Analysis	0.0459	88.78	9.95	1.0	0.085	0.14
Theoretical Prediction *	0.0491	90.556	10.945	1.07	0.0918	-

- **Fission products measured were ^{125}Sb, ^{134}Cs, ^{137}Cs, ^{144}Ce-^{144}Pr, ^{154}Eu, ^{155}Eu, ^{90}Sr.**
- **Gross activity of the bundle measured.**

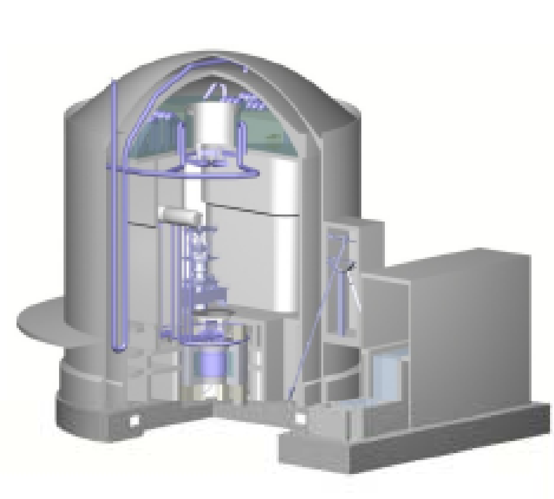
Radiological concerns during storage

- **Radioactivity levels much higher for the reprocessed thoria compared to that of mined thoria due to higher concentration of ^{228}Th (concentration is in ppm instead of ppb)**
- **A storage period of 16-20 years brings down the radio-activity levels to that of mined thoria.**
- **Requires suitable ventilation for large releases of thoron.**

Thoria can be recycled in the remote fabrication of (Th-^{233}U) MOX fuel without any storage period after reprocessing

The Indian Advanced Heavy Water Reactor (AHWR)

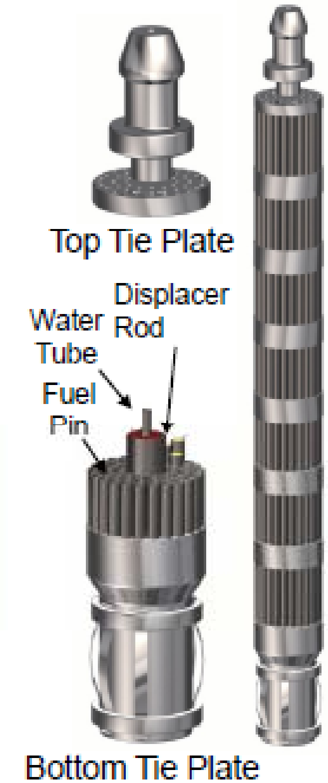
AHWR is a 300 MWe vertical pressure tube type, boiling light water cooled and heavy water moderated reactor using ^{233}U-Th MOX and Pu-Th MOX fuel.



AHWR can be configured to accept a range of fuel types including enriched U, U-Pu MOX, Th-Pu MOX, and ^{233}U-Th MOX in full core

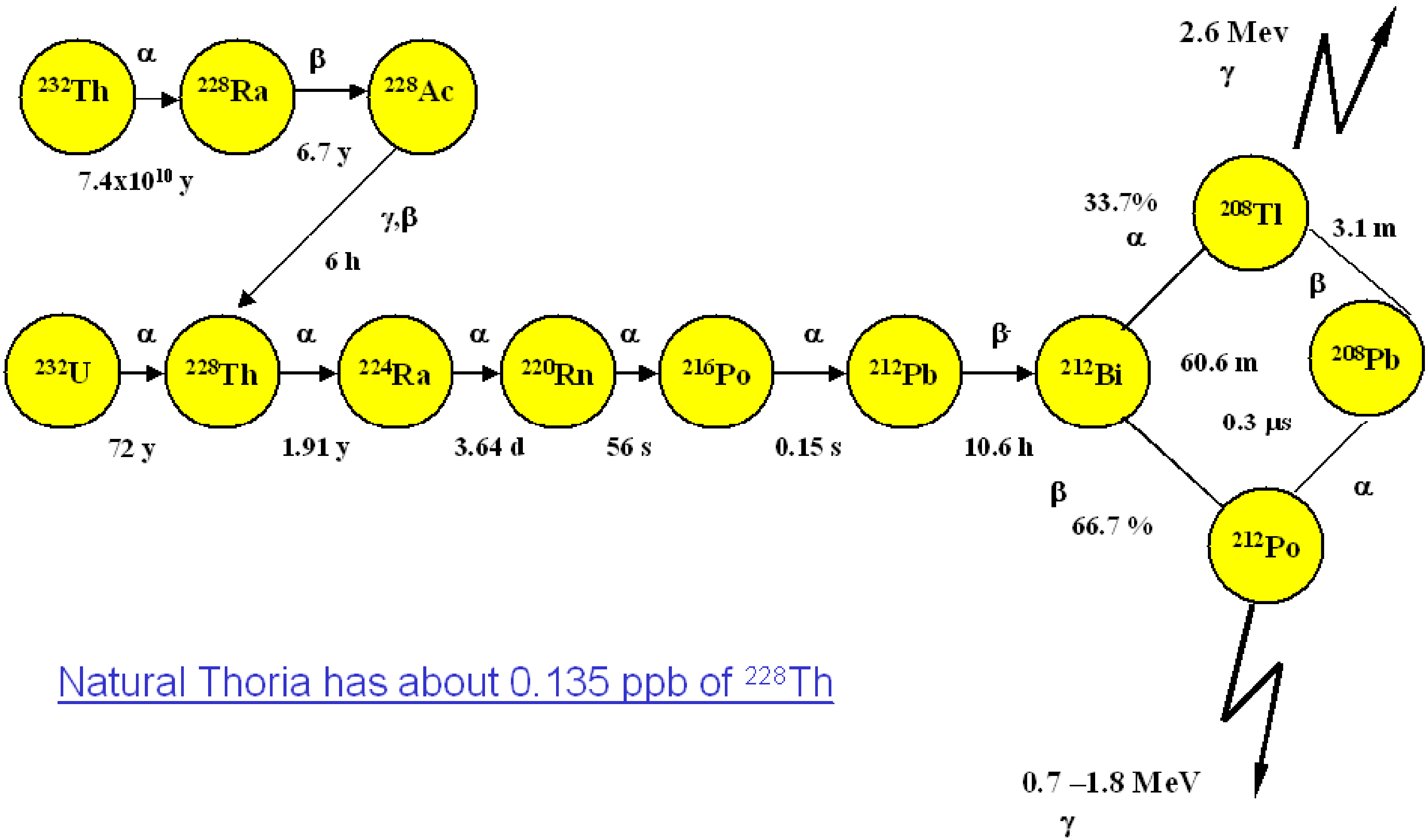
Major design objectives

- 65% of power from Th
- Several passive features
  - 3 days grace period
  - No radiological impact
- Passive shutdown system to address insider threat scenarios.
- Design life of 100 years.
- Easily replaceable coolant channels.



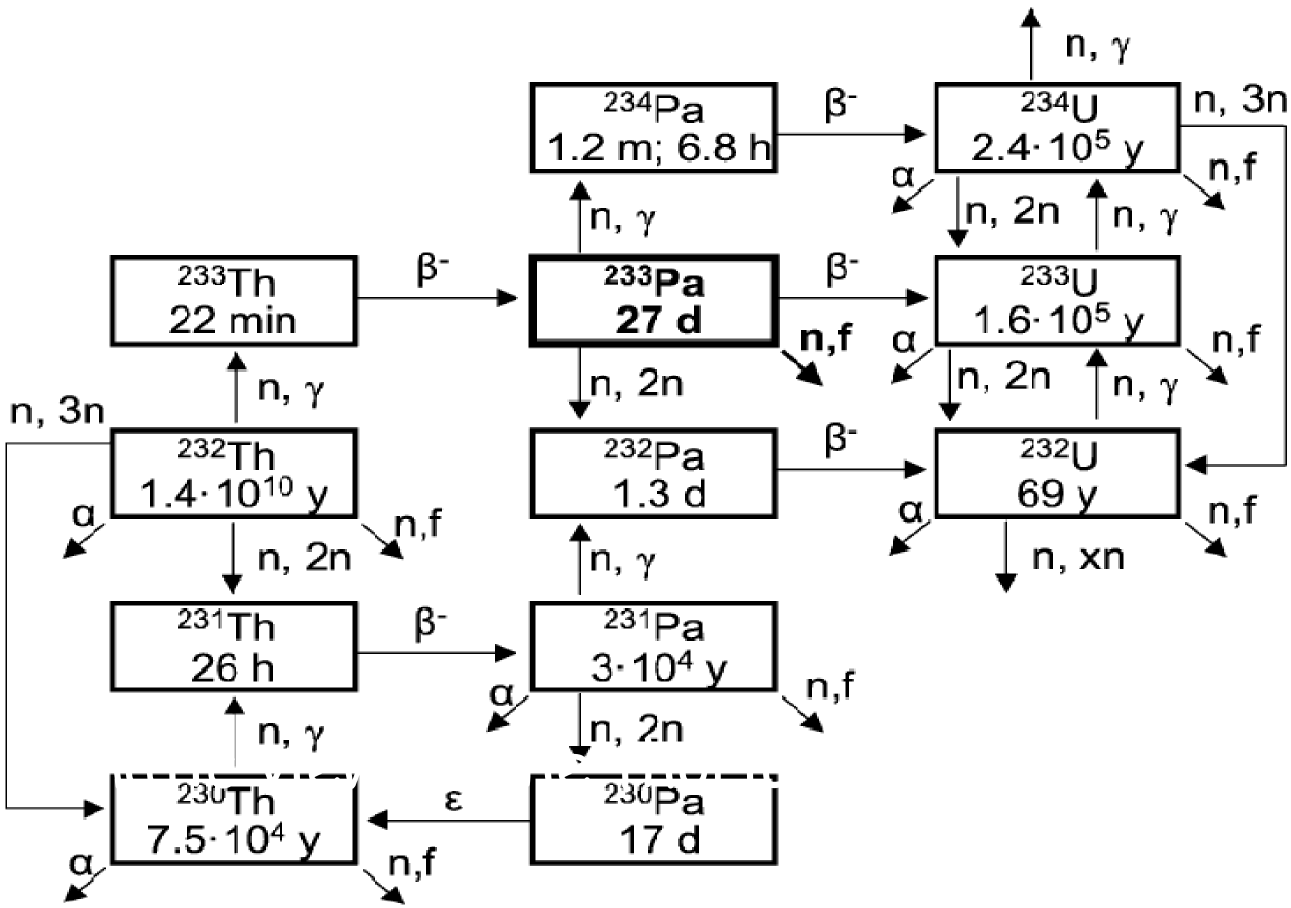
AHWR Fuel assembly

^{232}Th and ^{232}U decay chain



Natural Thoria has about 0.135 ppb of ^{228}Th

Isotopes in the Th-U fuel cycle



NEUTRON DATA of Interest to ADS programme

Need for more and improved quality data(abs, fiss, fissprod, n mult) for Th – U Cycle Nuclei (231-233 Pa, 232,233U)- radioactive target

Data for Minor Actinides required (Np, Am, Cm)

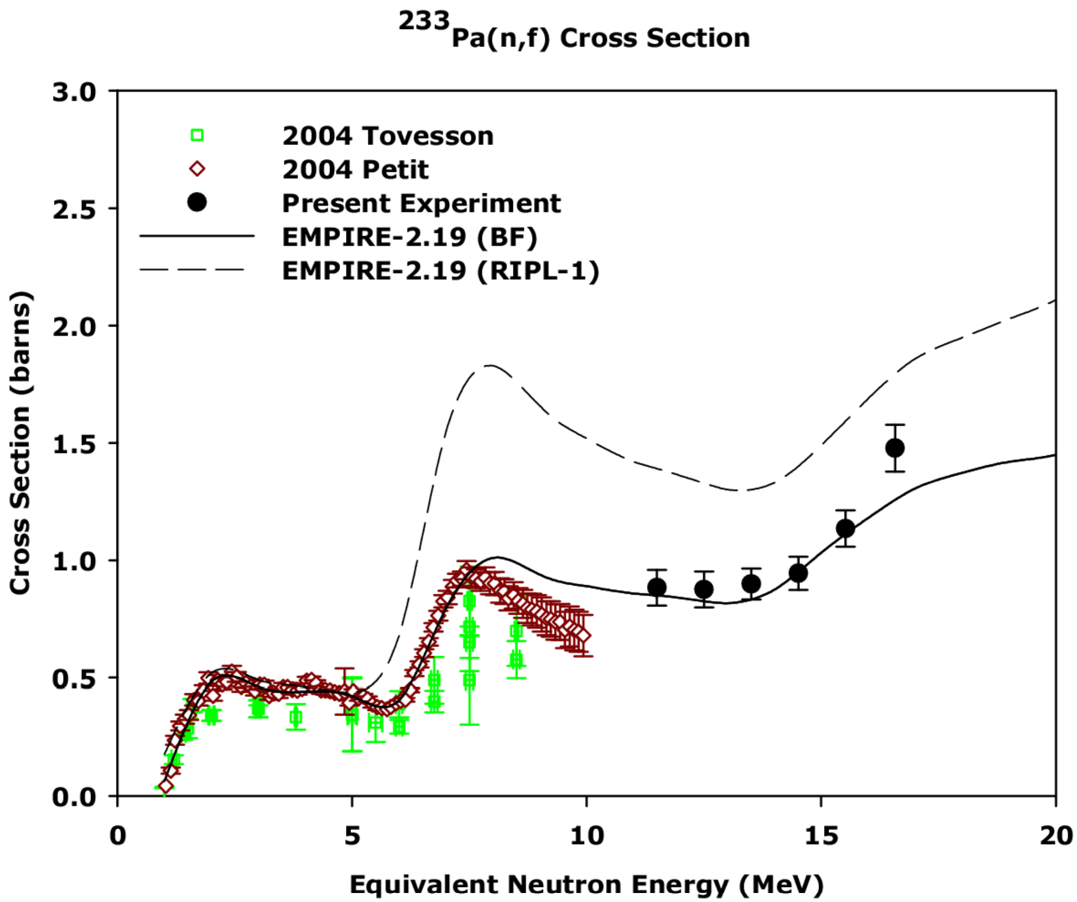
Need for data for Pb, Bi , Structural Materials at energies Higher than 20 MeV

Prediction and Measurement of Rare Earth Alpha Emitters Produced in LBE spallation target

Production of Light Radioactive/toxic nuclei like 7Be

Neutron capture data for long lived FF –
129I, 135Cs,107Pd,93Zr

Determination of the ^{233}Pa(n, f) reaction cross-section from 11.5 to 16.5 MeV neutron energy by hybrid surrogate ratio approach



232Th+6Li

232Th+4He (235U+n)

232Th+2H (233Pa+n)

B.K.Nayak(Phys Rev. C (2009)rapid

Thorium Utilization Strategies for the Third Stage

Addition of isotopes like U-235 and Pu-239
In the Thorium feed

Molten Salt Reactor where Fission products
Could be removed through on-line chemistry

Addition of external Neutrons into the Reactor
Environment – such as in ADS

Generating “External Neutrons”

These would be generated by non-fission events.

These could be knocked off from suitable nuclei by collision of energetic primary particles.

Examples:

Process	Example	Yield	Energy cost-on target only*
(D,T) fusion	400 KeV on T	4×10^{-5} n/D	10,000 MeV/n
Li (D,n) break up	35 MeV D on Li	2.5×10^{-3} n/D	14,000 MeV/n
U-238(γ,n) photo-nuclear	20 MeV e^- on U-238	1×10^{-2} n/e^-	2000 MeV/n
Spallation	800 MeV proton on U-238	~ 30 n/p	27 MeV/n

*** Plug –point power/energy to particle kinetic energy conversion efficiency will affect overall (real) energy cost per neutron.**

Basic functions of ADS sub-systems
Accelerator coupled to Reactor

- <u>Proton accelerator</u>
- intense beam of high energy accelerated particles (p)
- <u>Spallation Target</u>
- high-Z material is target
- neutrons emitted in nuclear reaction induced by high-energy protons.
- <u>Sub-critical reactor</u>
- operates through continuation of self-terminating fission chains, each triggered by spallation neutron or its derivative neutron.

WHY ADS ?

- Inherently safe
- Sub – critical ---self terminating fission chain
- No restriction on fuel type
- less dependence on delayed neutrons
- Ideally suited for long lived MA incineration

- (Note: Fast Reactor MA/Th > 3% not permitted)

- Better n per fission----Reduced Doubling time
Increased burnup – Less fissile material inventory
Fast / Thermal Reactor combination possible

- Large Scale utilisation of Th - complement AHWR

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
- Disavantage
  - Low k_{eff} ~0.9 and gain < 20 with Pb target
  - Accelerator power ~ 30 MW for a 200 MWe ADS

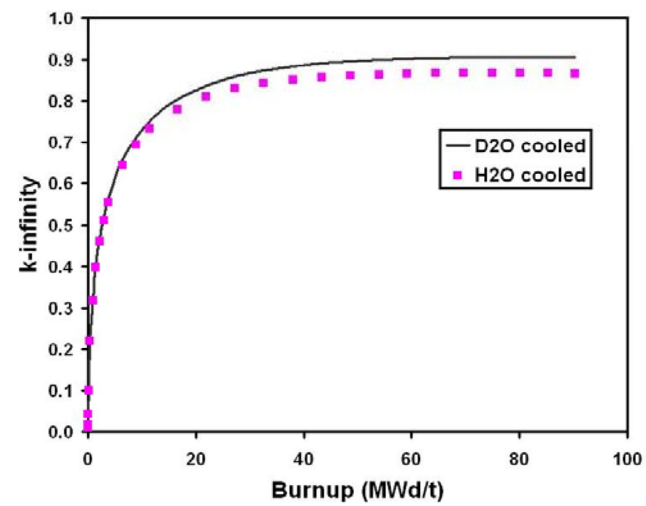
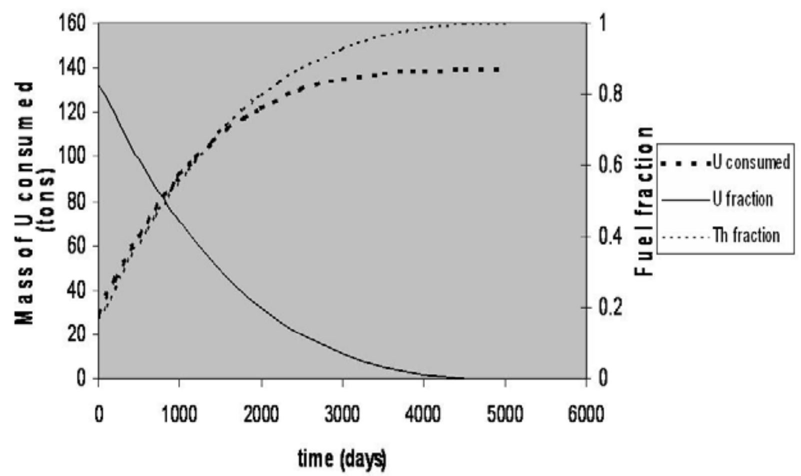


Fig. 4 U and Th fractions in ADSS for 7 GWd/t U burnup



Power in ADS is inversely proportional to sub-criticality and directly proportional to neutron source strength

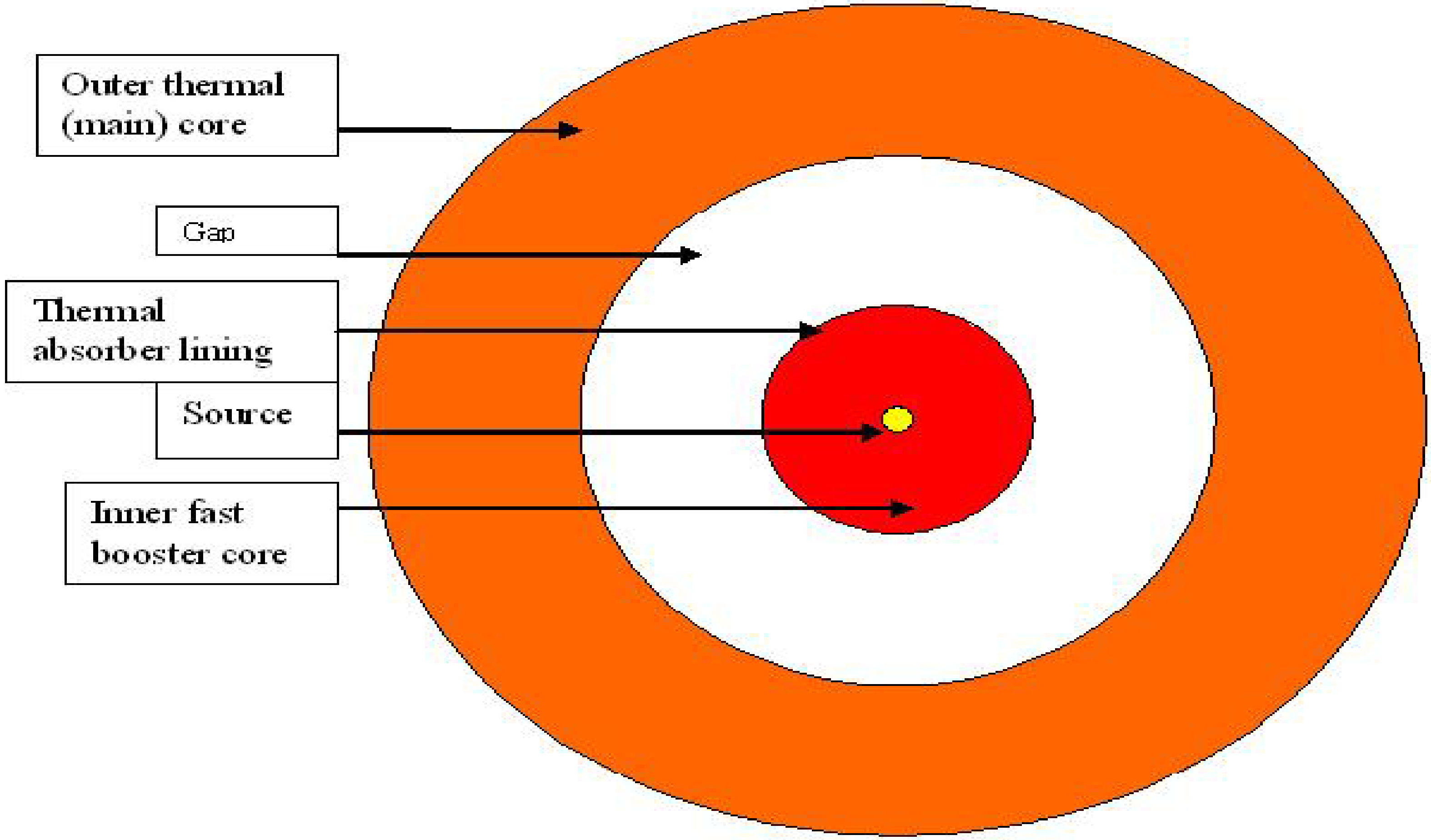
In the control rod free concept, the operating keff is limited to the range 0.95-0.98

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 multiplication 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 keff is limited to the desired value**
- **Consequently, accelerator power requirement for 750 MW(t) is ~ 1-2 MW**

ADS One-way coupled concept



Fast booster zone may consume Transuranics , and thermal region has Th+ ^{233}U as fuel.

Technologies for ADS

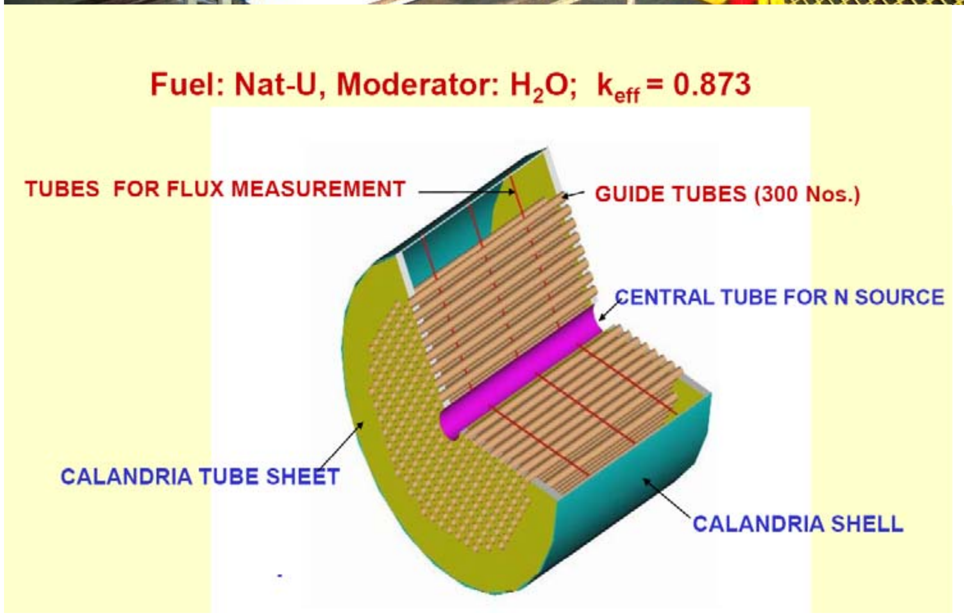
- **High power proton accelerator: 1 GeV, cw or high duty factor & (average) current**
- **High beam current front-end : low random beam losses for minimal radio-activation of hardware**
- **Superconducting RF cavities: high electrical efficiency & large aperture for beam**
- **RF power systems: high reliability against random beam trips- redundant & standby hardware.**
- **Spallation target & associated process system.**
- **Molten heavy metal for intense volumetric beam power density**
- **Materials: resistance to neutron irradiation & liquid metal corrosion at high-temperature.**
- **Sub-critical reactor**
- **Optimized asTRU transmuter or for thorium fuel-cycle.**
- **Configuration: technology issues- fast & thermal neutrons.**
- **Transients & safety studies- beam trips, reactivity swings.**

Ongoing Indian activities in ADS program

- **Design studies of a 1 GeV, 30 mA proton linac.**
- **Development of 20 MeV high current proton linac for front-end accelerator of ADS.**
- **Construction of LBE experimental loop for design validation and materials tests for spallation target module.**
- **Development of computational tools and data for neutronics of spallation target and coupled sub-critical reactor.**
- **Experimental validation of reactor physics codes and data with 14-MeV neutrons in sub-critical core at PURNIMA labs.**
- **Design studies for ADS reactor applications.**

14 MeV Neutron Generator - Experimental facility

- Experiments on physics of ADS and validation of simulations.
- use of 14-MeV neutrons produced by DC accelerator & D+T reaction. Also, a 400-keV RFQ is being built *for higher beam current.*
- Simple sub-critical assembly (k_{eff}=0.87) of natural uranium and light water is chosen
- Plans for : measurements of flux distribution, flux spectra, total fission power, source multiplication, and degree of sub-criticality will be carried out.



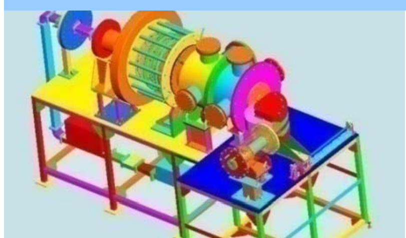
Scheme of Proton Linac Development

Normal Conducting

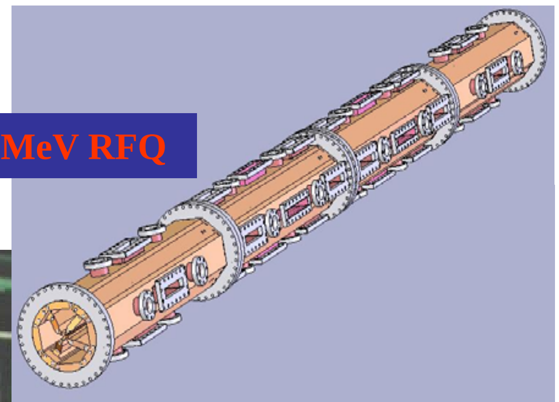
LEHIPA-High current injector 20 MeV, 30 mA

Proton IS 50 keV → **RFQ 3 MeV** → **DTL 20 MeV** → **DTL/ CCDTL** / **Low-β SC linac: SC-1, SC-2** → **100 MeV** → **High-β SC Linac** → **1 GeV**

Design completed and fabrication is in progress

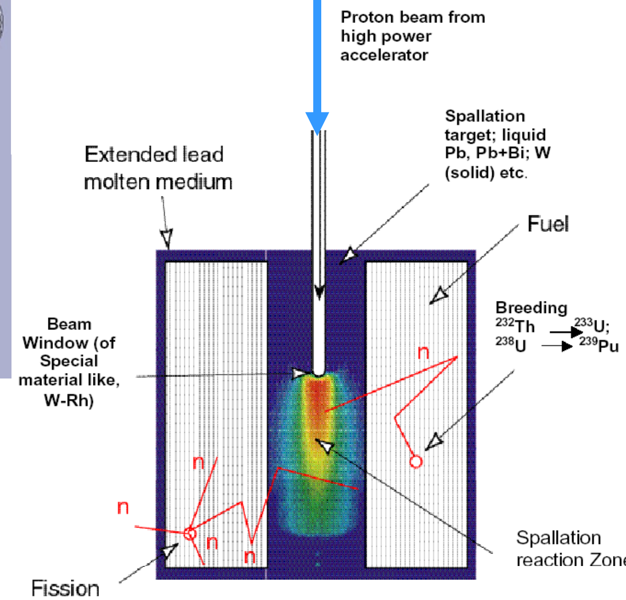


ECR Ion Source



3-MeV RFQ

Proton beam dump



Summary

- **Maximize the Energy Potential of Nuclear Fuel Material through use of Closed Fuel Cycle & Thorium**
- **Development of FBR is a key component in realizing high level of electricity generation in India, needed for meeting its large demands**
- **Development of Th based Nuclear Energy systems is a high priority in India**
- **India would pursue R&D to implement ADS for sustainable nuclear power program.**
-

India would like to invite and participate in international R&D activities- on accelerator, nuclear data , spallation target and fuel cycle options.

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