Physics Design of 600 MWth HTR
&
5 MWth Nuclear Power Pack

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Indian High Temperature Reactors Programme

Compact High Temperature Reactor (CHTR)

A technology demonstration facility

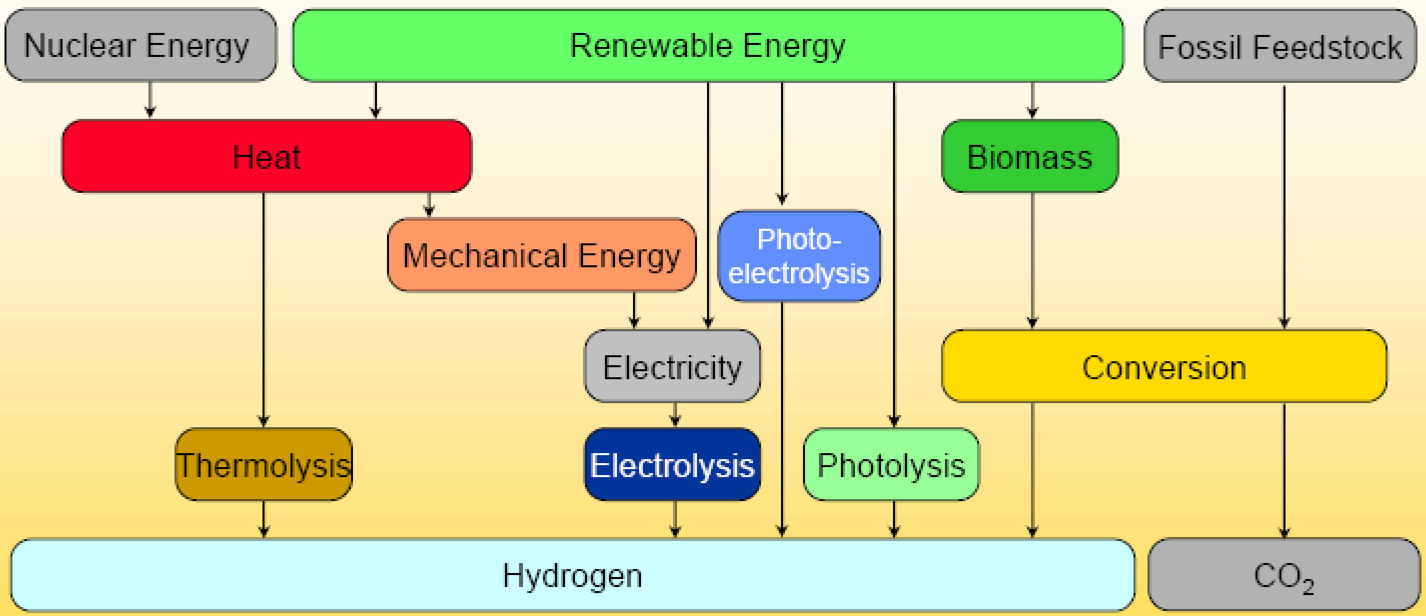
High Temperature Reactor (HTR)

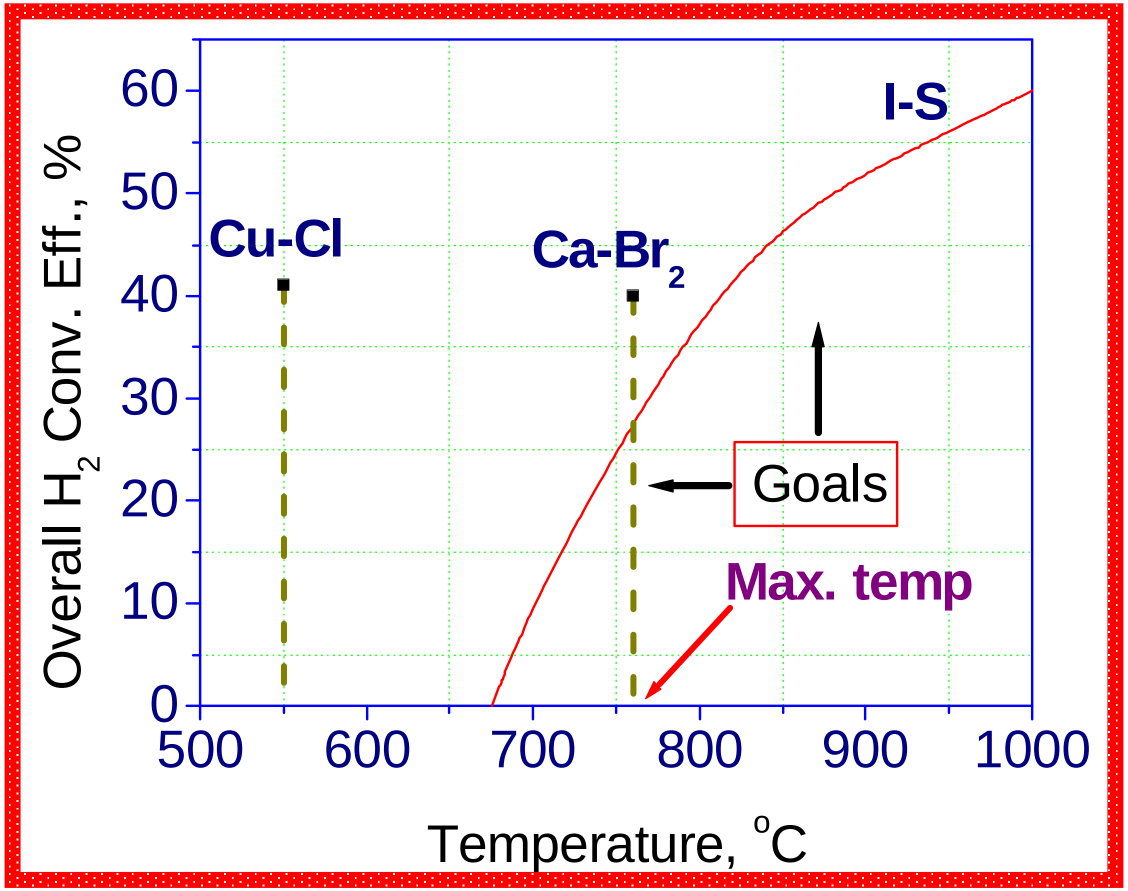
For hydrogen generation

Nuclear Power Pack (NPP)

To supply electricity in remote areas not connected to grid

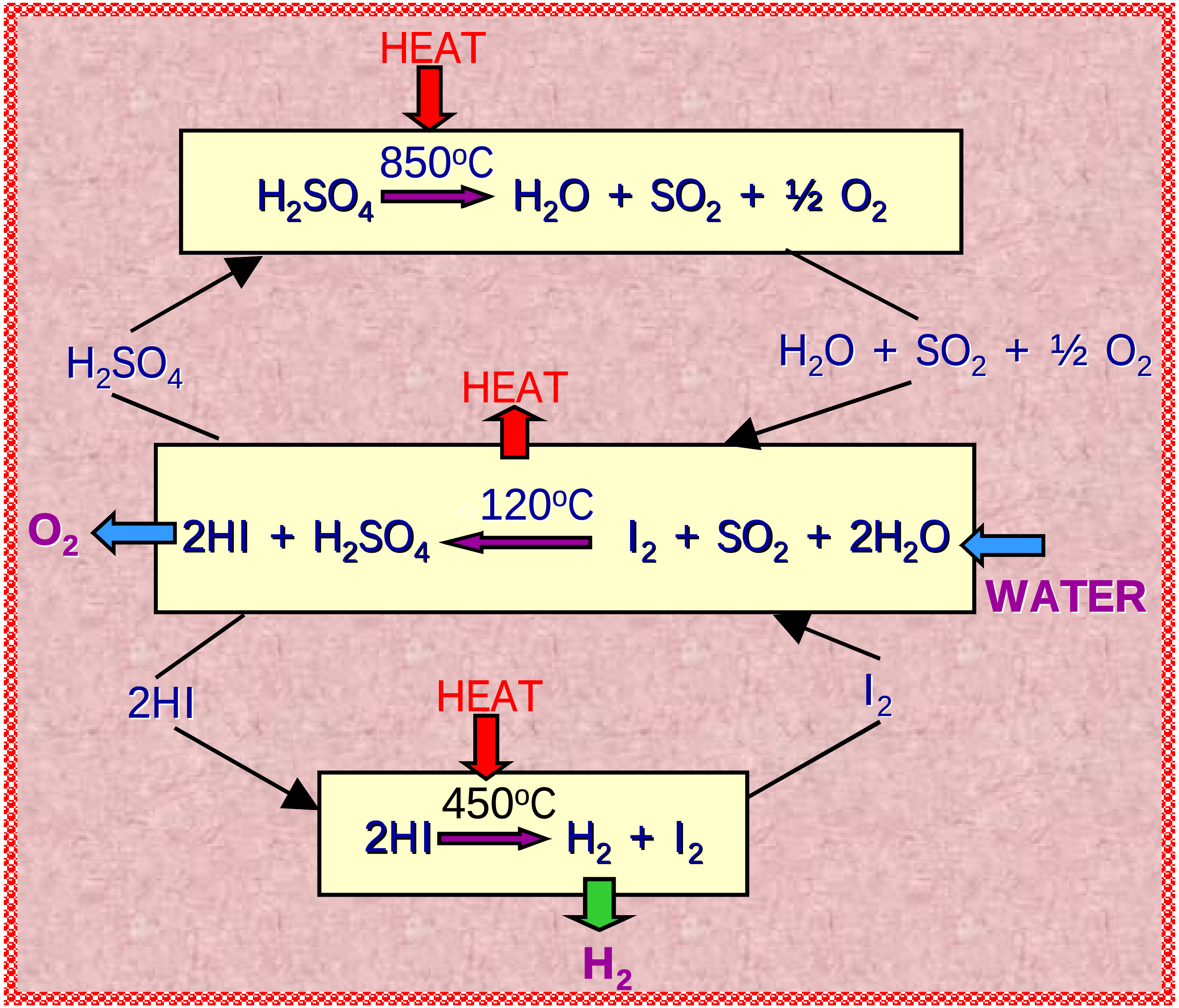
Hydrogen production pathways





Ref: High Efficiency Generation of Hydrogen Fuels Using Nuclear Power, G.E. Besenbruch, L.C. Brown, J.F. Funk, S.K. Showalter, Report GA-A23510 and ANL reports

I-S Process Reaction Scheme



600 MW(Th) HTR

Objective

To provide high temperature heat required for thermo-chemical processes for hydrogen production

Pebble bed reactor

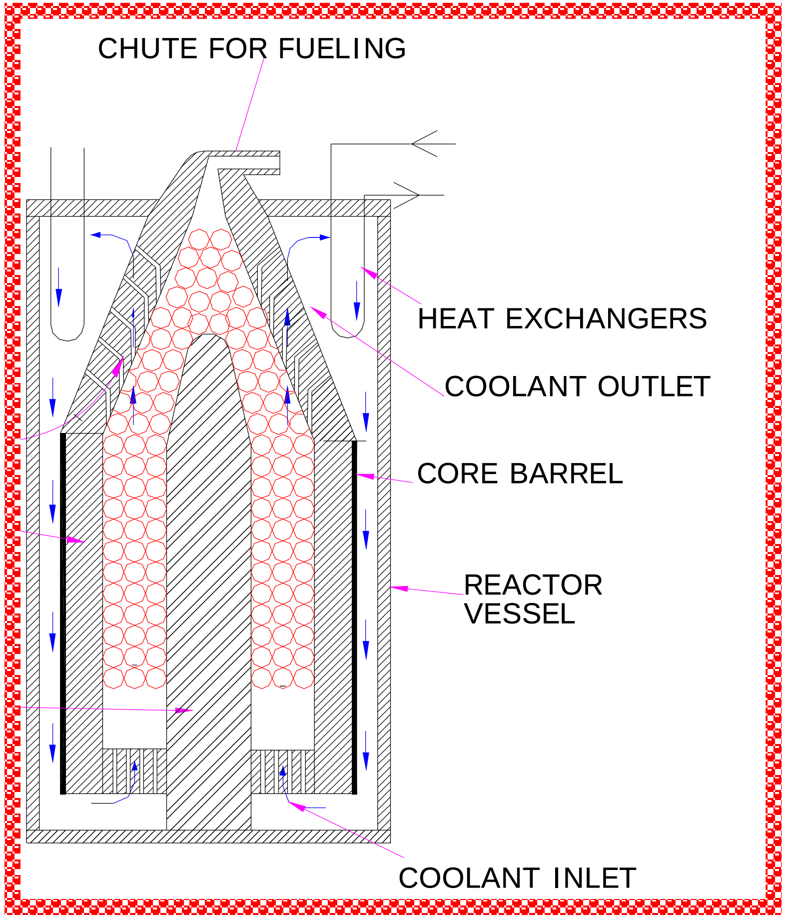
It is a Pebble Bed Reactor moderated and reflected by graphite & loaded with randomly packed spherical fuel elements called Pebble and cooled by molten Pb/Bi.

Key features

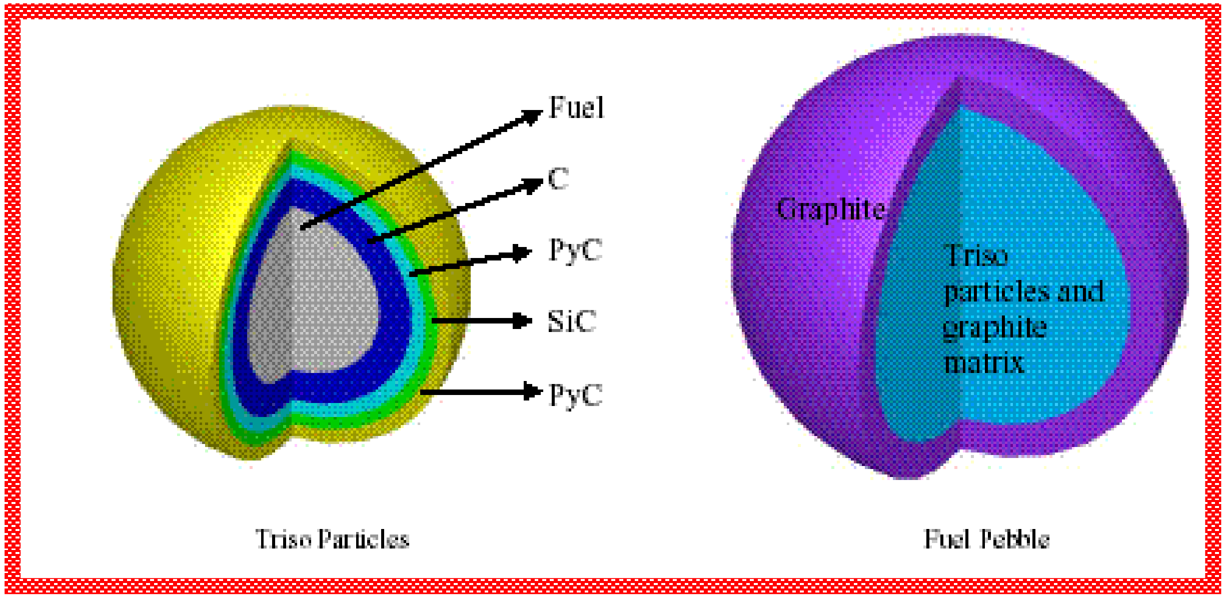
Use of triso particles

Its an advanced design with a higher level of safety and efficiency

Core configuration for pebble bed design



Cross-sectional view of triso particle and pebble



Triso Particle

Advantages of Pebbles

- On line refueling
- Homogeneous core (less power peaking)
- Simple fuel management
- One way of control by replacing dummy pebbles

Proposed Broad Specifications

Reactor power	600 MWth for following deliverables (Optimized for hydrogen Production) 1. Hydrogen: 80,000 m^3/hr 2. Electricity: 18 MWe • Drinking water: 375 m^3/hr
Coolant outlet/inlet temperature	1000°C / 600°C
Moderator	Graphite
Coolant	Molten lead
Reflector	Graphite
Mode of cooling	Natural circulation of coolant
Fuel	$^{233}UO_2$ & ThO_2 based high burn-up TRISO coated particle fuel
Energy transfer systems	Intermediate heat exchangers for heat transfer for hydrogen production + High efficiency turbo-machinery based electricity generating system + Water desalination system for potable water
Hydrogen production	High efficiency thermo-chemical processes

Pebble Configuration

- Pebble diameter (fuelled portion): 90 mm
- Outer pebble diameter: 100 mm
- Number of pebbles: 150000
- Packing density (Volume %) ≈ 59%

Challenges in the design

- To design optimum pebble and core configuration to get maximum energy per gm inventory of fissile isotopes.

- Control initial excess reactivity

Computational Technique

- Multi-group Integral Transport theory code "ITRAN" & Diffusion theory code " Tri-htr" used for simulations.

- Triso particles homogenized

Comparison of fuel inventory

Packing Percentage	Enrichment Percentage	Amount of U^{233} in gm per pebble	Burn up (FPDs)	Initial k-eff	Remarks
8.6	7.3	3.4	450	1.2701	
5.0	8.0	2.2	190	1.2415	
5.0	10.0	2.7	330	1.3372	
4.5	7.0	1.7	80	1.1559	
4.5	8.0	2.0	150	1.2169	
4.5	10.0	2.4	270	1.1559	
4.0	8.0	1.7	100	1.1879	
4.0	10.0	2.2	210	1.2902	
4.0	12.0	2.6	320	1.3686	
4.0	14.5	3.2	450	1.4456	
3.5	8.0	1.5	60	1.1507	
3.5	10.0	1.9	160	1.2576	
3.5	12.0	2.3	250	1.3402	
3.5	16.3	3.1	450	1.468	

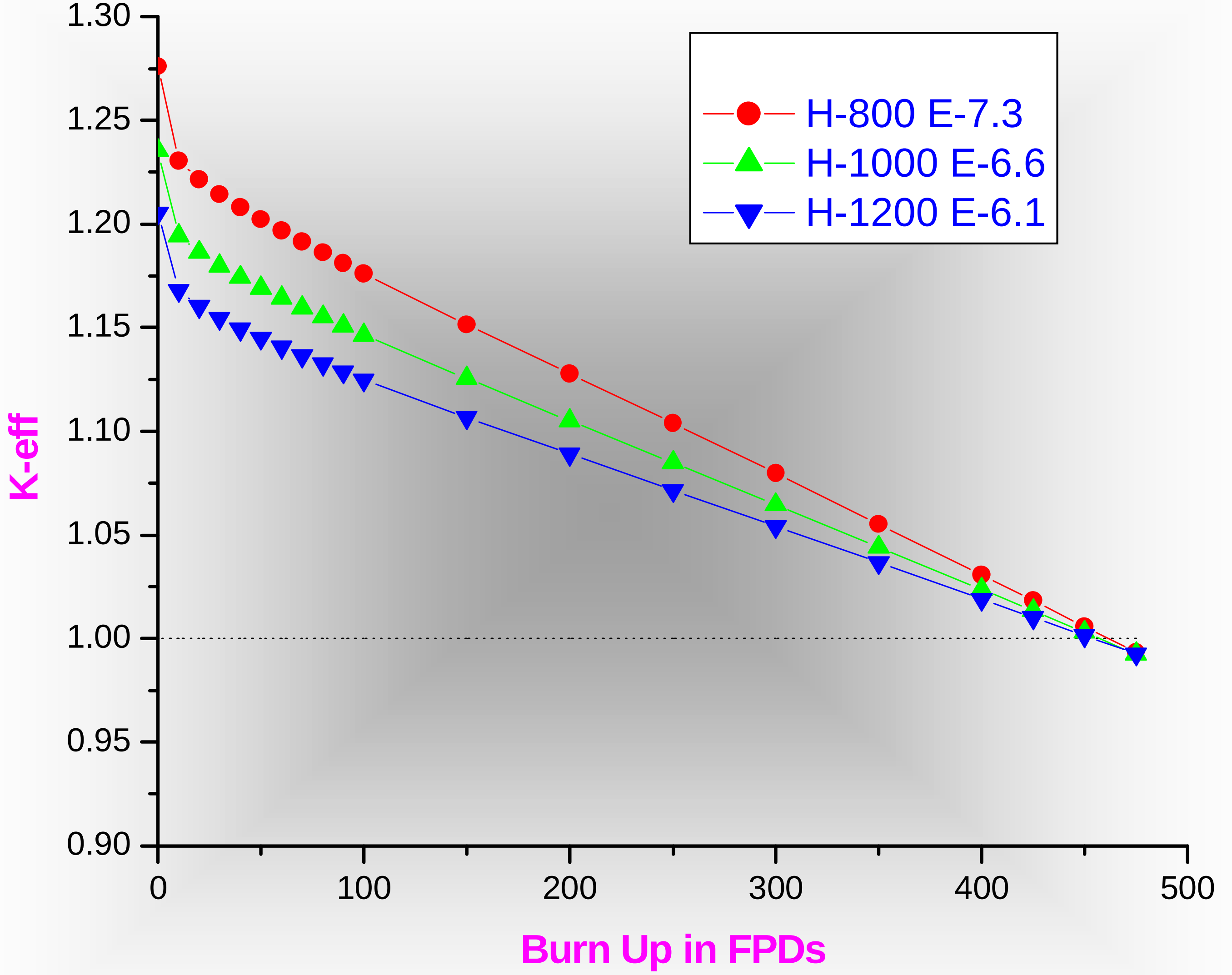
Optimized Pebble Configuration

Packing fraction 8.6%

Enrichment 7.3% (H=800 cm, 900FPDs)

Comparison between different height

Parameters	H=8 m	H=10 m	H=12 m
Enrichment (%)	7.3	6.6	6.1
Initial K-eff	1.2701	1.23556	1.20545
Amount of heavy metal Per pebble (gm)	U^{233} =3.4 Th^{232} = 43.2	U^{233} =3.1 Th^{232} = 43.5	U^{233} =2.8 Th^{232} = 43.7
No. of Pebbles	150,000	187,000	225,000
Amount of fuel In the core (Kg)	U^{233} =510 Th^{232} = 6480	U^{233} =581 Th^{232} = 8156	U^{233} =630 Th^{232} = 9832
$U^{233}+U^{235}$) out (Kg)	219.3	284.8	353.53
MWD/gm fissile elements	1.85	1.90	1.95
Burn up (FPDs)	900	900	900



Variation of K-eff with Burn Up for different height

Estimation of Fuel Temperature Coefficient
(H=1200, P=8.6%, E=6.1%)

Fuel temperature (^0C)	Value of K-eff	Fuel Temperature Coefficient (per ^0C)
1000	1.20545	Reference
1100	1.20361	-1.268x10-5
1200	1.20193	-1.214x 10-5
900	1.20745	-1.374 x 10-5
800	1.20965	-1.440x 10-5

Major Problem

- **Initial K-eff is too high**

1.276 for 8m height 7.3% Enrichment

1.205 for 12m height 6.1Enrichment

Study to reduce initial k-eff

OPTIONS

- Reduce number of fuel balls & keep (fuel balls + dummy balls = constant)

Initial power will be reduced

- Reduce enrichment

Available burn up will be less

Comparison of different cases

H (M)	P (%)	E (%)	FUEL BALL	DUMMY BALL	INITIAL K-EFF	REMARK
12	8.6	6.1	1/2	1/2	1.1588008	Little improvement
8	8.6	7.3	1/2	1/2	1.2356665	Not much improvement
8	8.6	6	1/2	1/2	1.1440712	Beneficial
8	8.6	6	All fuel	-	1.1899716	Beneficial
12	8.6	5	2/3	1/3	1.1086059	Initial K-eff reduces sufficiently

CONCLUSIONS

- For the same burn up fuel inventory is less for lower packing fraction. But as packing fraction decreases initial K-eff increases.
- Energy production in terms of MWD/gm of fissile inventory is more for 12m core height compared to 8m core height.
- Initial reactivity can be controlled by reducing enrichment as well using control rods. But burn up reduces.
- Further study to control initial reactivity by using ThO2 ball is in progress.
- Fuel temperature coefficient is satisfactory
- System can be controlled using control rods & burnable absorber.

Physics Design of
5 MW_{th}
Nuclear Power Pack

Salient Features

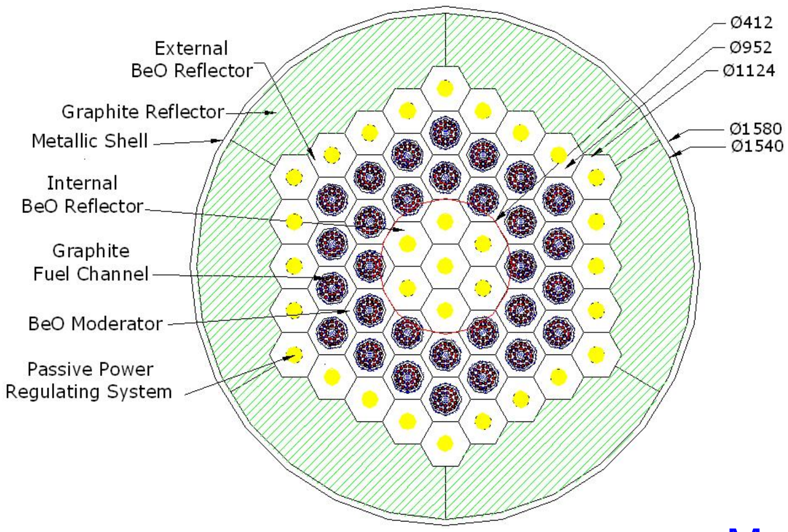
- It will be compact and can run for around 10 years without any refueling.
- The reactor should be able to control and regulate its operation in a perfectly passive manner.
- The overall reactivity change during core life should be less.

Basic Design Parameters

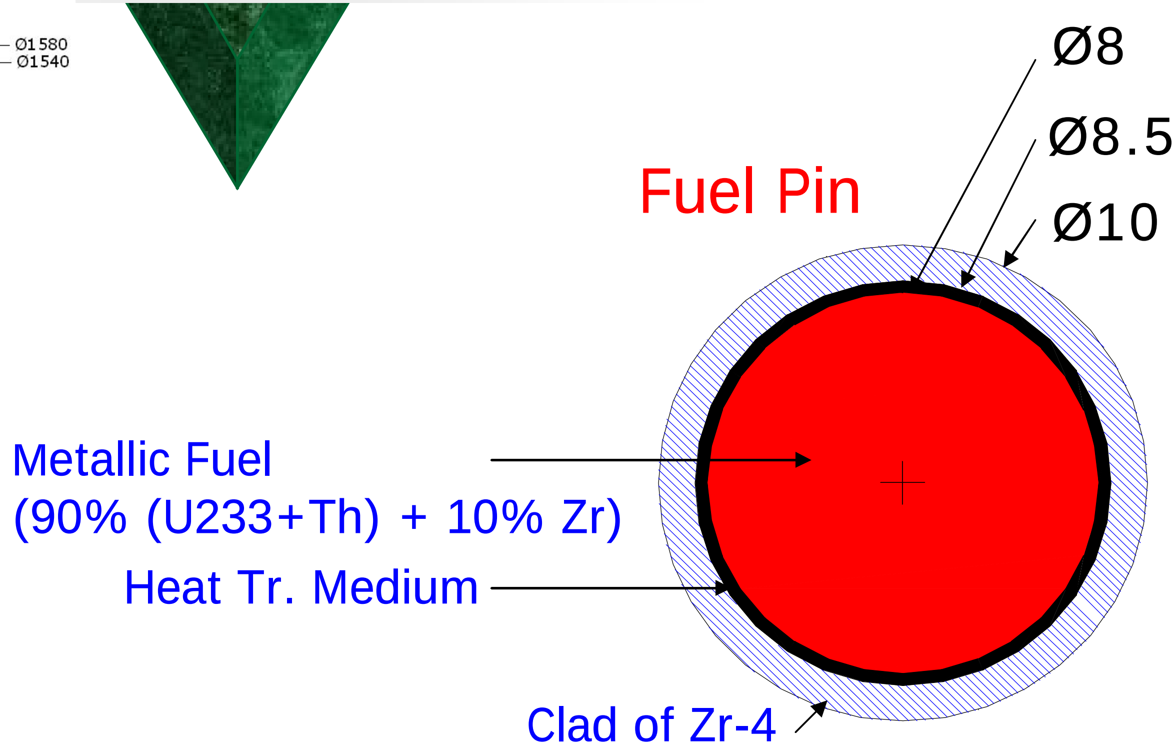
Reactor Power	:	5 Mw_{th}
Core Life	:	Around 10 years
Fuel	:	Metallic U^{233} + Th^{232}
Moderator	:	BeO
Reflector Material	:	BeO and Graphite
Coolant	:	Pb-Bi
Core Height	:	1000 mm
Core Inlet Temperature	:	450^0C
Core Outlet Temperature	:	600^0C
No. Of Fuel Assemblies	:	30
No. Of Control Locations	:	31

Nuclear Power Pack

30 Fuel beds
24 (Ex) + 7 (In)
control locations

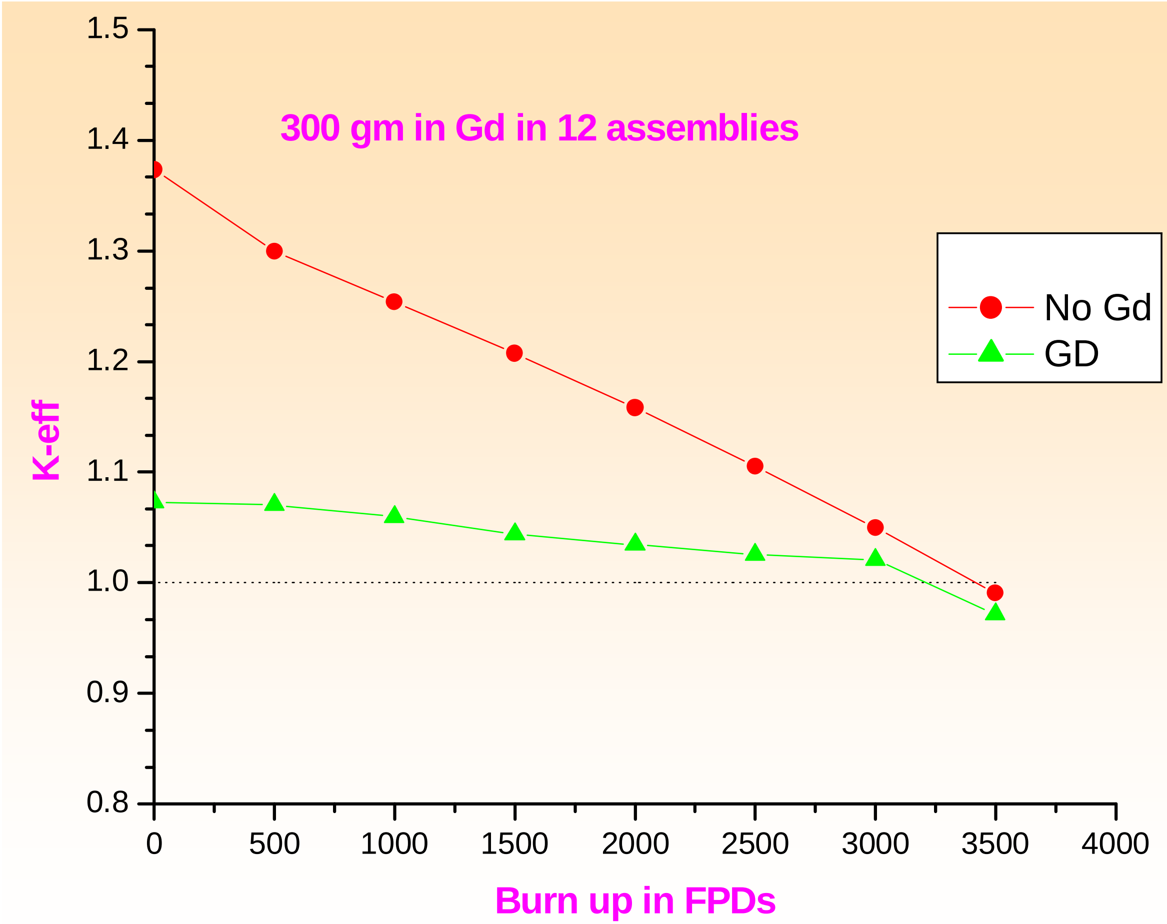


Fuel Pin



Important Parameters

❄ **Enrichment**	**14%**
❄ **Core life**	**3000 FPDs**
❄ **Amount of Gd**	**300gm in each of 12**



Variation of K-eff with Burn up

Total fuel for entire core

- U^{233} 28.88 Kgs
- Th^{232} 156.78 Kgs

Estimation of Control Rods Worth at Hot Condition

(14% enrichment)

Position Of Control Rods	Value of K-eff
All Control Rods out	1.07280
All Control Rods in	0.79748
All Control Rods in except one having Maximum worth	0.80661
Worth of all Control Rods = 321.8 mk	
Max. Worth of a Single Control Rod = 14.19 mk	

Height of Control Rods at Criticality

(14% enrichment)

- At criticality control rods will be 39.5 cm in the core plus 15 cm in the bottom reflector.
- In this condition the worth of one control rod having maximum worth is 2.9 mk.

Estimation of Fuel Temperature Coefficient

- Fuel temperature coefficient is at 775 ^{0}C it is -1.6953 x 10^{-5} per ^{0}C

CONCLUSION

- Initial K-eff is very large necessitating the introduction of burnable poison in the core.
- 14.0 cm pitch is considered adequate.
- This can be used as a Nuclear battery which will run around 10 years without any refueling.

ACKNOLEDGEMENT

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THANK
YOU

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