Review of AECL and International Work on Sub-critical Blankets Driven by Accelerator-Based and Fusion Neutron Sources

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CNS 2013 Annual Conference, Toronto, ON

Monday, June 10, 2013

2:00 pm – 2:25 pm

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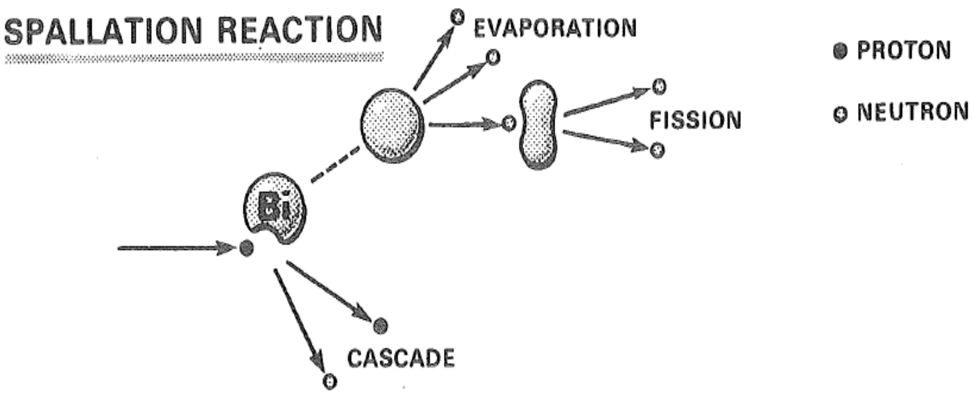
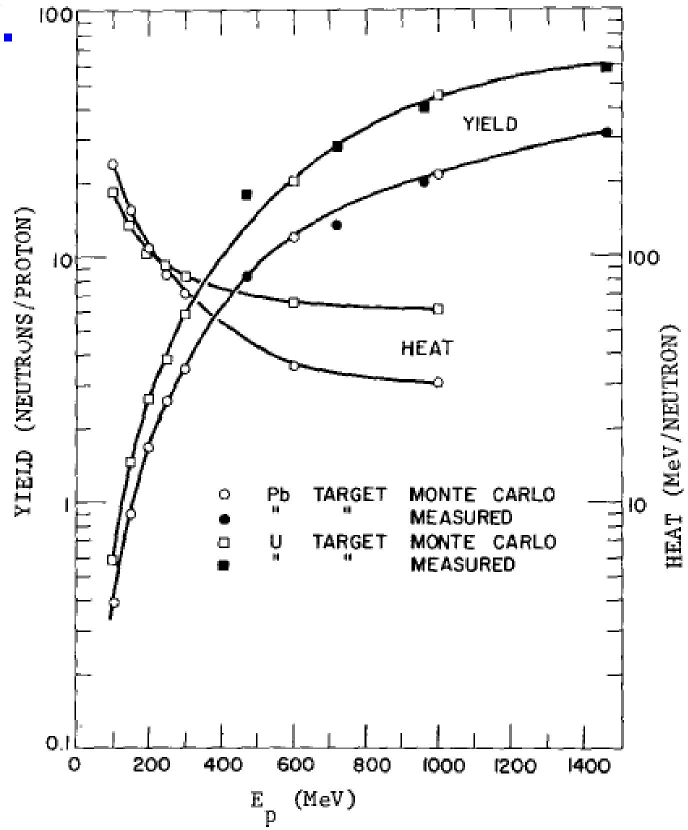
Introduction

- **Review – AECL & International Community.**
  - **Accelerator-driven sub-critical systems (ADS).**
  - **Hybrid Fusion Fission Reactors (HFFR).**
  - **1953-2012. Excludes CFFTP (1982-1997).**
- **What ADS and HFFRs have in common:**
  - **Electrically-driven neutron source.**
    - **Accelerator-based spallation neutron source.**
      - 1-GeV Protons or deuterons on Pb, Bi, U, Th, W, Hg, Be, Li targets.
    - **Fusion reactor.**
      - 14-MeV neutrons from D-T fusion; 2.45-MeV neutrons from D-D fusion.
  - **Sub-critical blanket surrounding neutron source.**
    - **k_{eff}< 1.000…k_{eff} ~0.9 to 0.99 typical.**
    - **Fertile, fissile, and fissionable materials.**
      - Th-232, U-238, U-233, U-235, Pu-239, Pu-241
    - **May also contain:**
      - Minor actinides (MA) (e.g., Am, Cm, etc.)
      - Long-lived fission products (LLFP) (e.g., Tc-99, Cs-135, I-129, Zr-93, etc.)
      - Lithium (for breeding tritium).

Spallation Neutrons

- Protons or deuterons at 0.5 to 1.5 GeV.
- Targets:
  - Pb, Bi, U, W, Hg, Be, Li, etc.
- 20 or more neutrons/proton.
- Neutron energies ≥ 1 MeV.





2 Measured and calculated neutron yields and calculated heat production vs. proton energy for 20 cm diameter lead and fully depleted uranium targets[31].

Fusion Neutrons

- **14.1-MeV neutrons from D-T fusion reaction (most probable).**
- **2.45-MeV neutrons from D-D fusion.**
- **Fusion fuel temperatures need to be at 10 keV to 200 keV.**

BASIC REACTION

FUSION

BURNING

$$D + T \rightarrow \alpha(3.5\ \text{MeV}) + n(14.1\ \text{MeV})$$

T-PRODUCTION

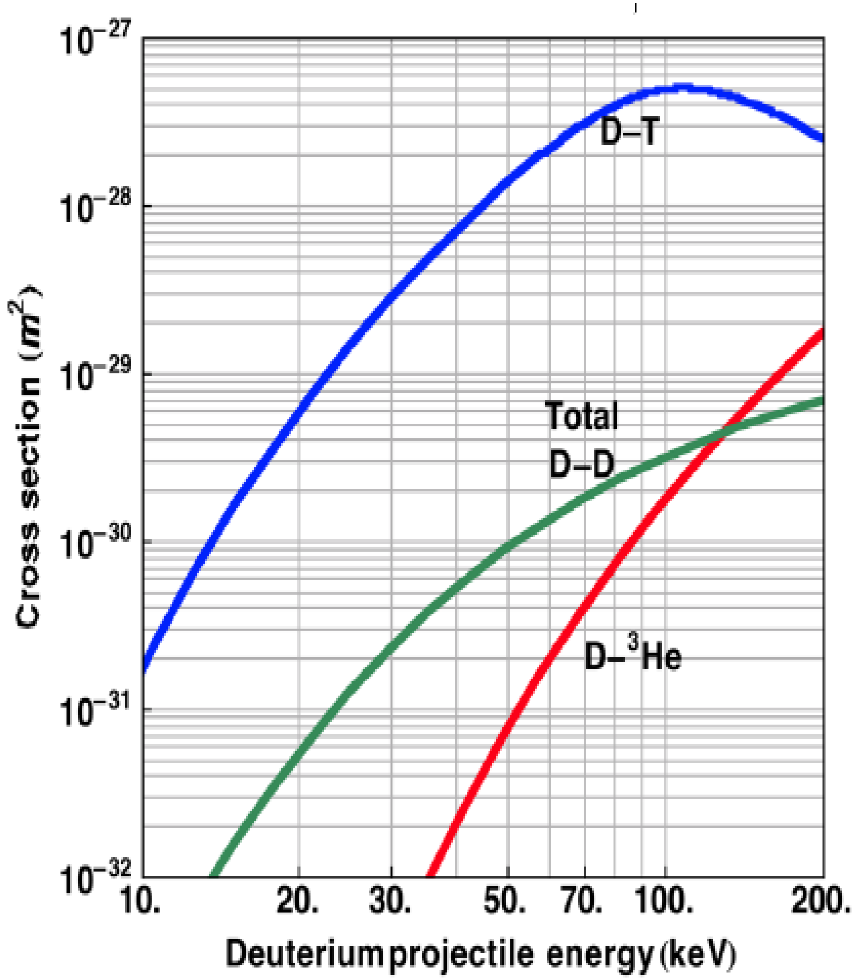
$$^{6}Li + n_{slow} \rightarrow \alpha + T + 4.8\ \text{MeV}$$

$$^{7}Li + n_{fast} \rightarrow \alpha + T + n - 2.5\ \text{MeV}$$

BREEDING + BURNING

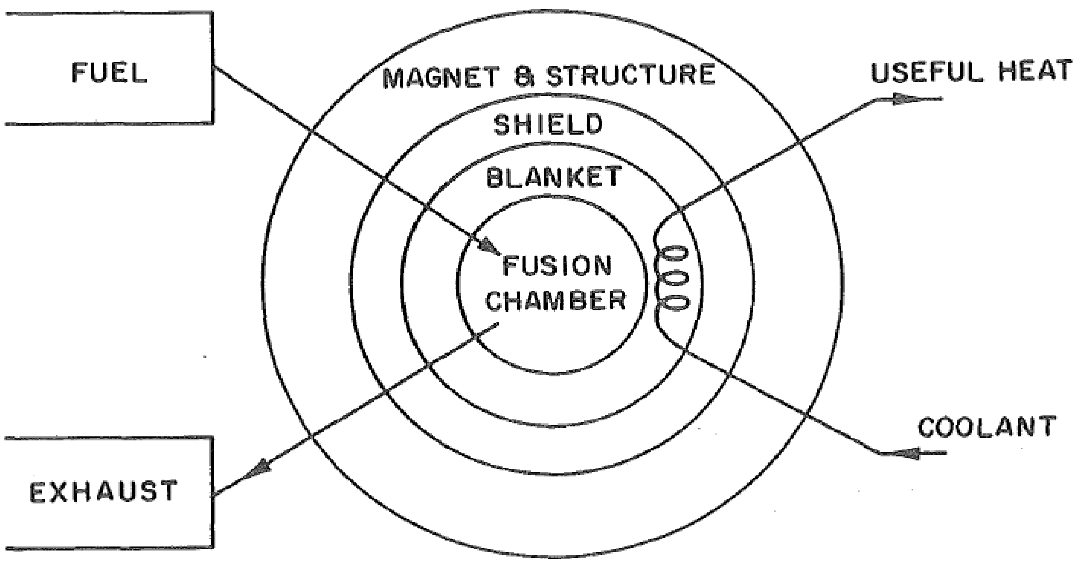
$$D + (1-a)\,^{6}Li + a\,^{7}Li \rightarrow 2\alpha + a\,n + (22.4 - 7.3a)\ \text{MeV}$$

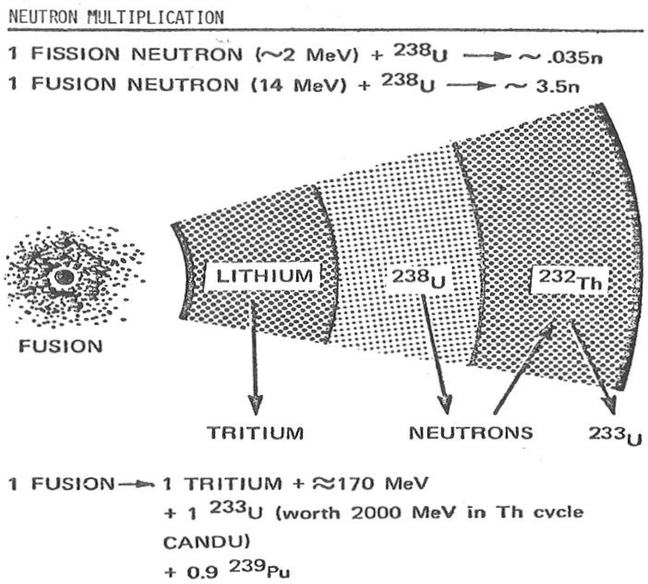
WHERE a IS NUMBER OF T PRODUCED BY $^{7}Li + n$ PER FUSION WITH T BALANCE, I.E. T PRODUCED = T BURNT.



Hybrid Fusion Fission Reactor (HFFR)

- **Q = Fusion Power / Electrical Power Input**
  - **Depends on design; better confinement → higher Q.**
  - **Q ~ 3 to 4 is breakeven point (electrical output ~ electrical input).**
  - **For a pure fusion reactor, Q ≥ 10 necessary for practicality, economics**
  - **For HFFR, Q ≥ 1 sufficient; typically Q ≤ 4.**
  - **Thermal power in HFFR 2 to 10 × fusion power.**
    - **Breed and burn of fissile fuel in blanket; fast-fission of U-238 and/or Th-232.**





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ADS/HFFR Applications

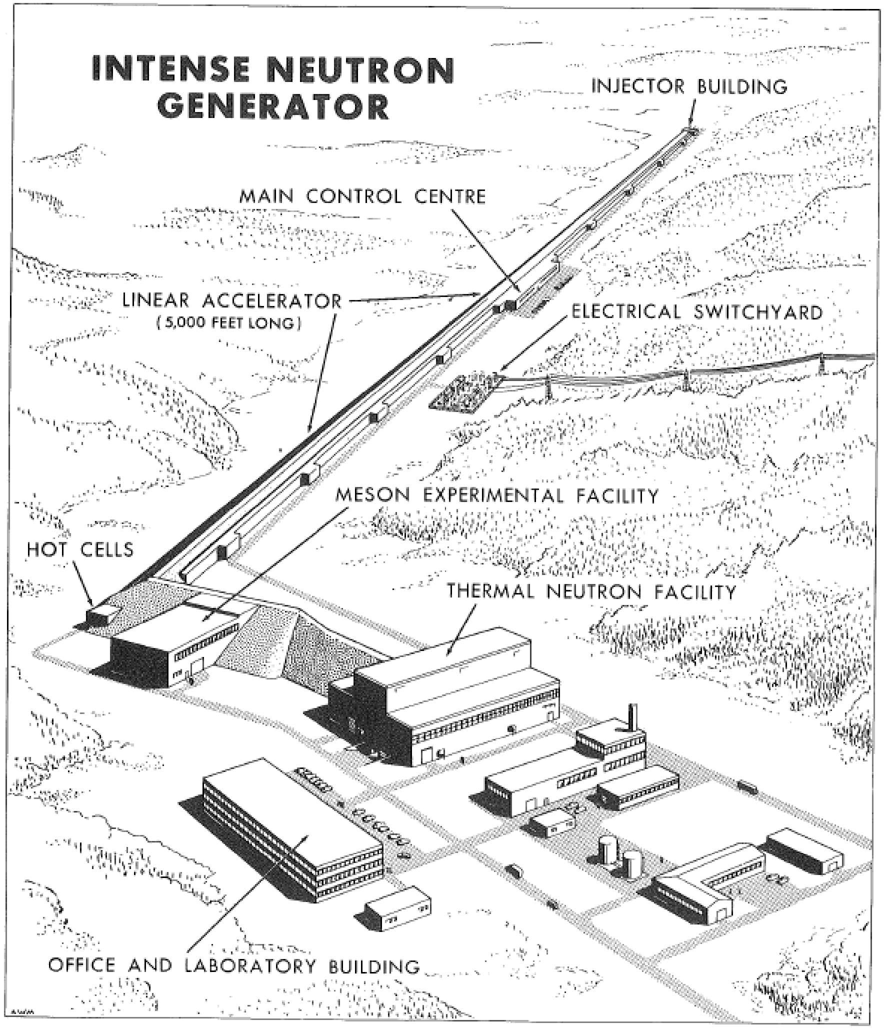
- **Power generation:**
  - A sub-critical driven reactor (keff ~ 0.99); enhanced safety.
  - Flexibility in power level; less constrained by Xe-135 build-up.
- **Breeding excess fissile fuel:**
  - U-233 (from Th-232), Pu-239 (from U-238).
    - Complements breeder reactors, with larger support ratio.
  - Use in conventional thermal reactors (LWR, HWR).
  - Use in high-conversion fast or thermal reactors.
    - PT-HWR (U/Th cycle).
    - Gen-IV fast reactors (SFR, LFR, GFR).
- **Consumption of minor actinides $\rightarrow$ (n,γ), (n,fission).**
  - Get rid of Am, Cm from spent uranium-based fuels; extract energy.
  - Reduce long-term radiological hazard and storage requirements.
- **Transmutation of long-lived fission products $\rightarrow$ (n,γ), (n,2n)**
  - Convert Cs-135, I-129, Zr-93, Tc-99 etc. into short-lived radioisotopes.
  - Reduce long-term radio-toxicity. Reduce storage costs.

AECL Work – Accelerator Breeders (AB)

- 1963-1982 main period of effort.
- Alternative to breeder reactors; energy security concerns.
- "Electro-nuclear breeding".
  - 1 AB could provide enough excess fissile fuel (U-233 or Pu-239) to support up to ~10,000 MWe of PT-HWRs (with full recycle).
- Extensive design studies.
- Comprehensive, staged development program proposed.
- Initiative eventually abandoned / postponed until very long-term.
  - High capital costs (accelerator), ~$1.5B (1981).
    - Fissile fuel produced would be ~ 3 to 4 × U-235 from enrichment facility.
  - Availability of cheap natural uranium in near-term.

AECL – CRL
Intense Neutron Generator (1967)

- **ING (Intense Neutron Generator).**
  - **Project ran 1963-1969.**
  - **Anticipated driver for breeder.**
  - **Facility ~ 1 km long.**
  - **1 GeV, 300 mA proton beam.**
  - **Pb/Bi target.**
  - **Utilize fast reactor technology.**
  - **Th and/or U blanket.**
    - **1.6 wt% to 3.2 wt% fissile.**
  - **Startup+topping fuel for PT-HWRs.**
    - **~700 to 1,200 kg/year of U-233 or Pu-239 $\rightarrow$ 10,000 MWe of PT-HWR.**
- **Follow-up system studies & plans.**
  - **1969-1982.**
  - **Smaller accelerators, other uses.**
  - **Staged, evolutionary development.**



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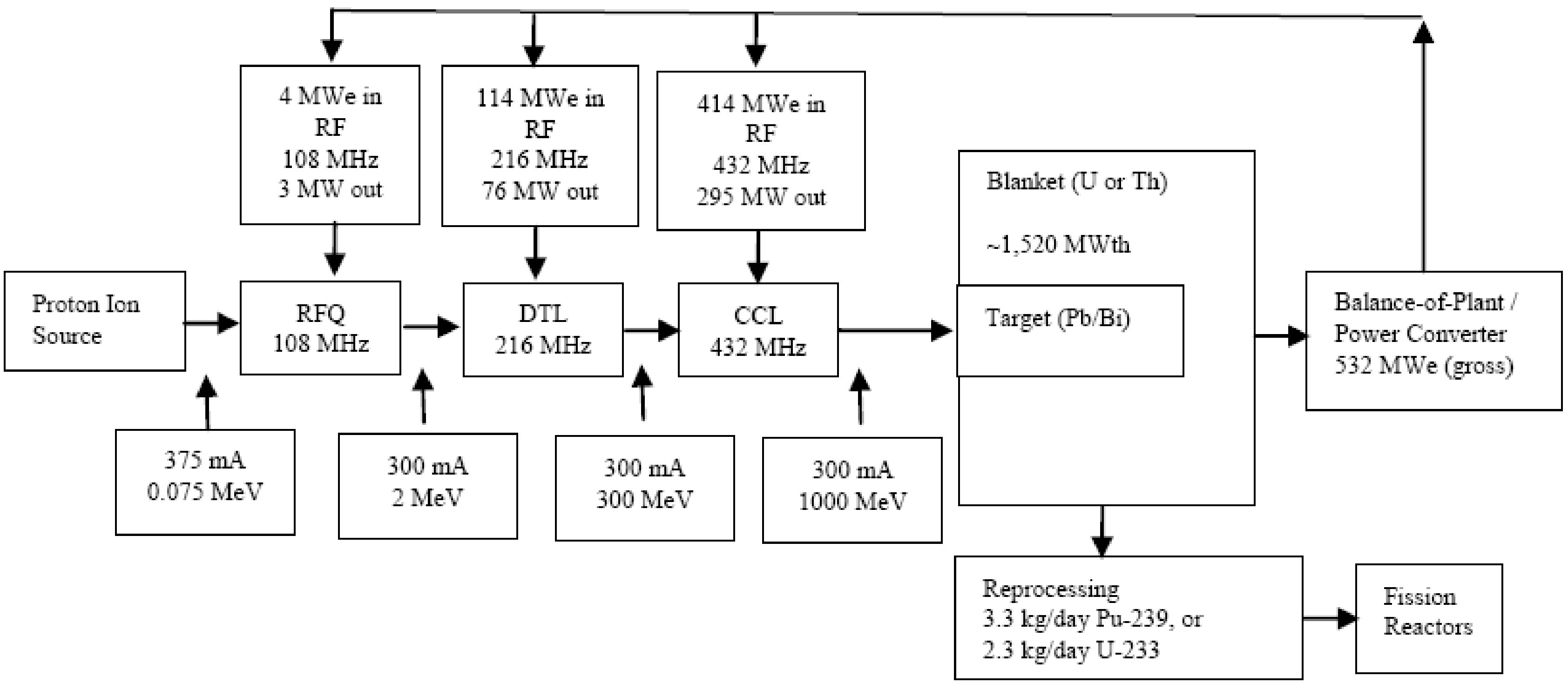
AECL – Accelerator Breeder

- 300 MW (1 GeV, 300 mA) proton beam on liquid Pb/Bi, ~4×10^{19} n/s
- 1,520 MWth blanket, 532 MWe system; self-sufficient in power.
- Fast-reactor technology for blanket, but other designs considered.



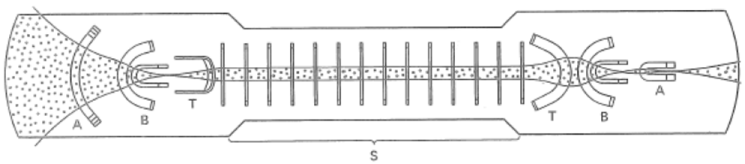
RFQ = Radio Frequency Quadrupole, DTL = Drift Tube Linac, CCL = Coupled Cavity Linac

AECL – Watching Brief on Fusion

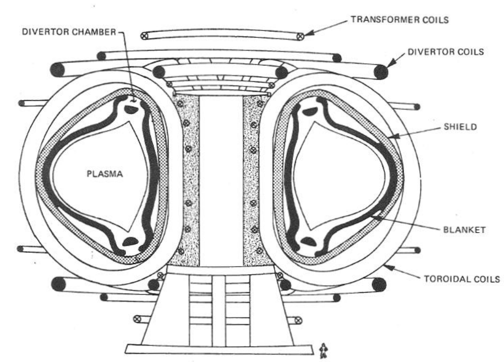
- **1972-1982:**
  - **AECL not engaged in active fusion reactor experimental research program, but maintained a "watching brief" on international developments for various fusion concepts and technologies.**
    - **Assessments by Physics Advance System Studies (PASS) group.**
    - **Assessments by Fusion Status Study (FUSS) group.**
  - **In parallel with accelerator breeder program, interest in adapting different fusion reactors as drivers for hybrid system.**
  - **System and economic studies.**
  - **Neutronic analyses, scoping studies of blanket performance.**
    - **Multi-region blankets (Li / U / Th / Graphite).**
    - **Generic results applicable to different fusion reactor drivers.**
    - **HFFRs have potential for lower capital costs than AB.**
    - **Early application for first-generation fusion reactors (Q~1).**

AECL Fusion Assessments (1972-1982)

- **Many fusion reactor concepts considered:**
  - **Tandem Magnetic Mirrors, Tokamaks**

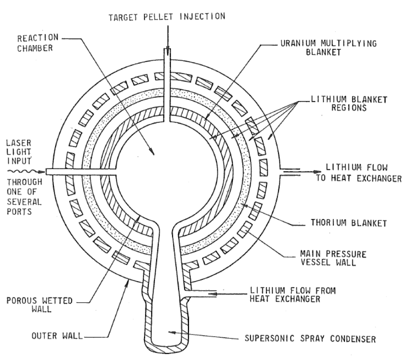


A= Auxiliary End Coil, B= Minimum-B Mirror Coil, T=Transition Coil, S=Central Solenoid



The Tokamak reactor model, cross-section view.

  - **Laser Inertial Confinement (L-ICF).**
  - **Various alternative concepts:**
    - **Particle-beam ICF (ion, electron).**
    - **Reversed Field Pinch,**
    - **Compact Toruses, Field Reversed Mirrors**
    - **Linear θ-Pinch, Long solenoid systems.**
    - **Dense Z-Pinch, Dense Plasma Focus.**
    - **LINUS (early variant of magnetized target fusion)**



SCHEMATIC VIEW OF THE REACTION VESSEL FOR THE FUEL BREEDING ASSEMBLY

- **Physics/engineering problems with all fusion concepts.**
  - **Difficult to achieve a pure fusion reactor that is practical.**
    - **Technical issues to overcome.**
    - **Hybrid reactors have potential to be viable in short-term.**

HFFR Issues / Opportunities

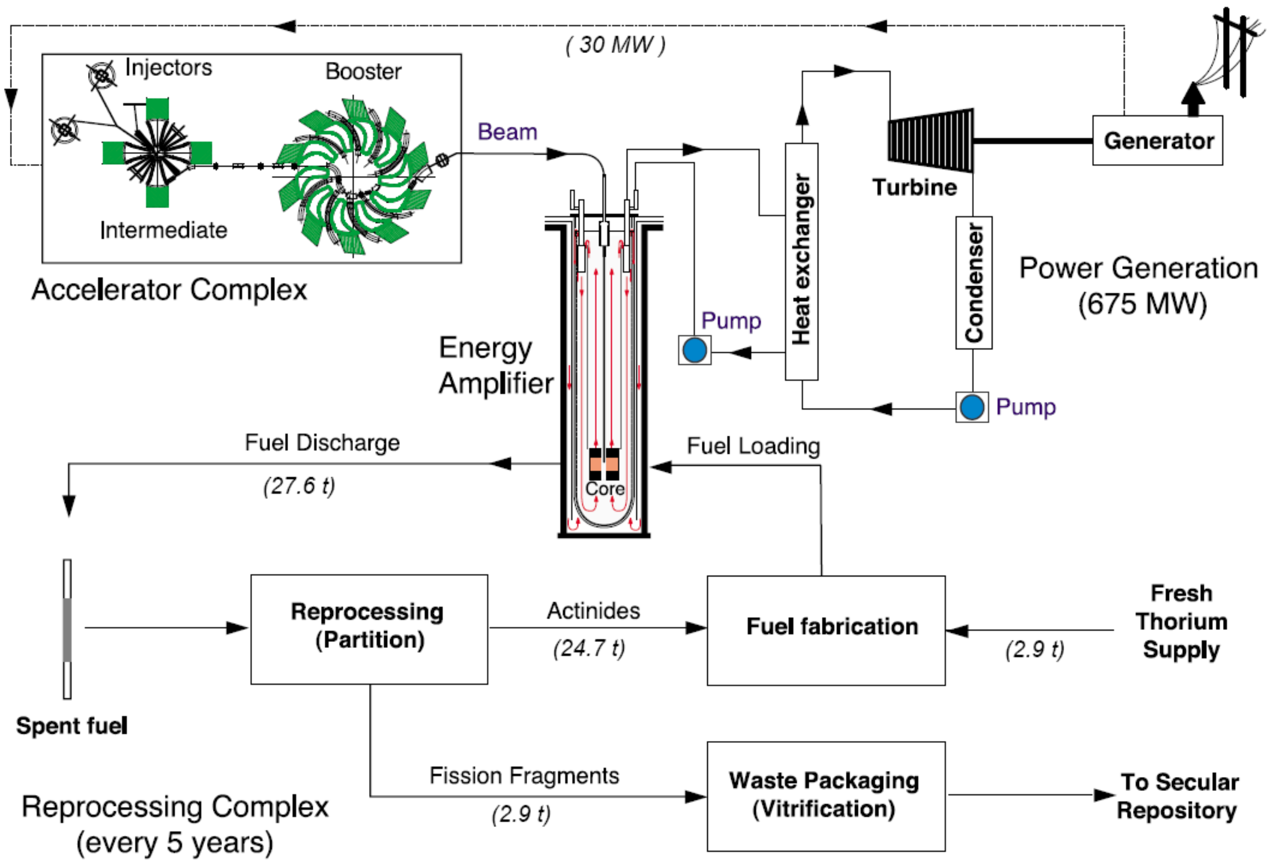
- L-ICF: modular system, but low laser efficiency, target control.
- Tokamaks and Tandem Mirrors expected to achieve Q>1 soon.
  - Higher Q for Tokamak, but Mirror steady-state, better geometry.
- HFFRs would need to serve dual-purpose (power and breeding).
  - One HFFR ($Q \sim 2$, $P_{fusion} \leq 300\ MW_{th}$, Total Power $\leq 1{,}400\ MW_{th}$)
  - Fissile fuel production ~800 to 1,000 kg/year.
    - Would support ~12 GWe of PT-HWR running on U-233/Th cycle.
- Most economical HFFR
  - Designed to produce U-233 from Th-232, with fission suppression.
  - If fusion reactor capital costs dominant, switch to U/Pu-239.
- HFFR should be able to produce fissile fuel at ~40% cost of AB, but:
  - Estimated capital costs (~$2.6B to $4.7B) exceed allowed values by a factor of 2.5 to 3.8.
  - Price of U-235 would need to increase by a factor of 3 (1981 prices).
  - High uncertainties in cost estimates until prototype built.

Highlights
International Work – ADS (1991-2000)

- Various concepts proposed:
  - Main goal is MA consumption / LLFP transmutation.
  - Protons, 4 to 250 mA, 1 to 3 GeV; RFQ/DTL/CCL accelerator stages.
  - Liquid Pb/Bi, or solid W targets.
  - 10 to 500 MW beam power, 900 to 1,500 MW blanket, self-sufficient.
  - Blankets: solid/clad, molten salts, liquid metals, particle suspensions, slurries, aqueous solutions, Pu/MOX cooled by Na or He.
  - Energy Amplifier (Carlos Rubbia – CERN – Nobel Laureate) ~ ING(AECL)
    - Multi-purpose ADS for breeding, transmutation and net power.
    - Multi-stage cyclotrons and super-conducting RF cavities.
    - 1.5-GeV, 20 mA protons on Pb; pool-type sub-critical (k_{eff}~0.97) fast reactor.
    - Th/TRU blanket fuel (oxide/metallic); 1,500 MWth / 675 MWe.
    - Liquid lead coolant – high thermal efficiencies.
    - ~400 to 600 kg/year of TRU (Pu+MAs) consumed.
- Use of ADS for transmutation to reduce hazards of MA/LFFP
  - To that of uranium ore in less than 100 years.
  - 1 ADS could consume MAs from 10 LWRs (1 GWe each).

Energy Amplifier – CERN (1995)

- Use of cyclotrons for proton acceleration.
- Emphasis on consumption of MAs (400 to 600 kg/year).



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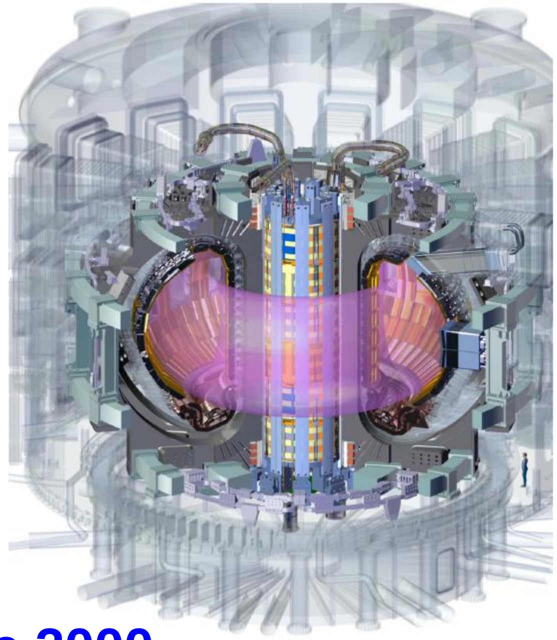
International ADS Experimental Facilities

- **Located mainly at national research labs and universities.**
  - **Very small scale facilities exist; minimal blanket power.**
  - **GUINEVERE project at SCK-CEN (Belgium).**
  - **KUCA, Kyoto University (Japan), YALINA facility (Belarus).**
  - **CIAE Institute (China)**
- **Spallation Neutron Source (SNS) – ORNL – operating since 2007**
  - **1 GeV, 1 mA protons on Hg target, 60 Hz repetition rate.**
- **MYRRHA - SCK-CEN Belgium – to startup by 2014.**
  - **Linac, 600-MeV, 3.2 mA protons hitting a Pb/Bi target. The blanket fuel is MOX. The core power will be 100 MW_{th}. Largest ADS in world.**
- **CLEAR-I/II/III – China – staged prototype development (2017-2032)**
  - **Accelerator coupled with sub-critical fast reactor.**
  - **CLEAR I to be 150 MeV, 10 mA, UO_2 Blanket (2017)**
  - **CLEAR III to be 1.5 GeV, 10 mA, Pb/Bi, TRU/Zr Blanket (2032)**
  - **1000 MW_{th}, ~400 kg/yr MAs consumed.**

Hybrid Fusion Fission Reactors International Work

- 1960s: small-scale addendum to fusion work.
- 1970-1982: stronger interest
  - LLNL, MIT, PNL, DOE, IAEA, and in Russia.
  - Concerns about technical feasibility of a pure fusion reactor.
    - Simple magnetic mirrors with limited confinement (Q~1.5).
    - New problems with Tokamaks and Laser ICF emerging.
  - HFFR's a "bridge" technology; first practical application of fusion.
  - Numerous design studies incorporating fertile/fissionable blankets into various fusion reactor concepts.
  - PNL suggested HFFRs could be competitive with fast breeders.
  - LLNL looked at tandem mirror and L-ICF hybrids.
    - A single 4000-MW_{th} HFFR could support 6 to 47 GWe of fission reactors.
    - Molten salt blanket with continuous reprocessing. Q~2 sufficient.
  - DOE: HFFR coupled with conventional reactors could be 25% cheaper than using fast breeder reactors, due to large support ratio.
    - Recycling costs could be reduced by direct use of fuel irradiated in HFFR into a thermal reactor – but need new clad instead of Zircaloy.

Hybrid Fusion Fission Reactors International Work

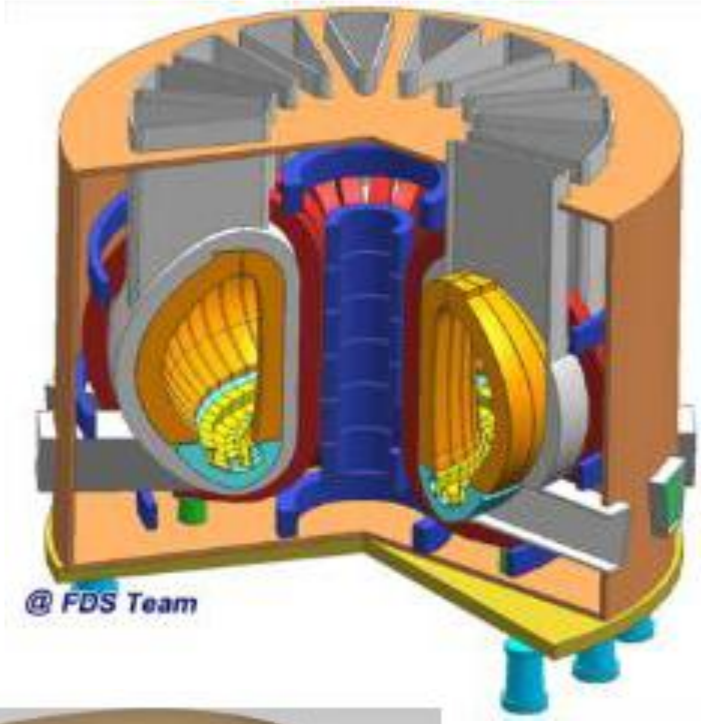


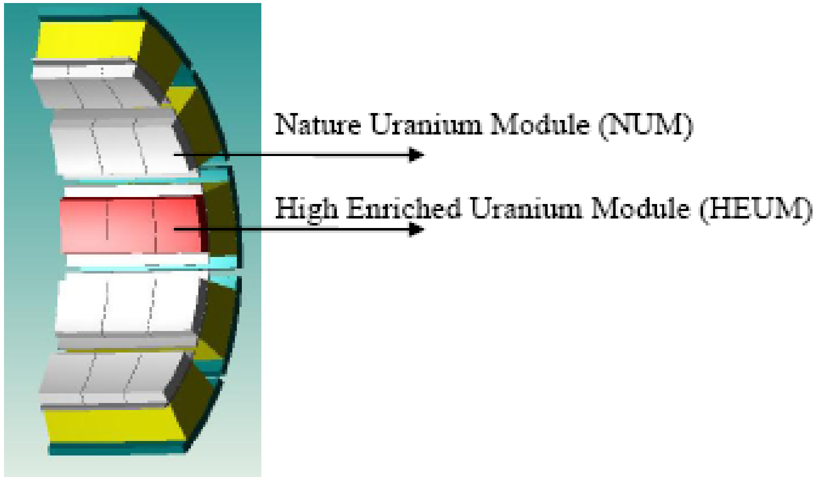
- **1980s / early 1990s: reduction in HFFR work**
  - **Re-focus on pure fusion systems.**
  - **Reductions in national fusion programs; consolidation of efforts.**
  - **MFTF-B Tandem Mirror project cancelled (1986).**
  - **Focus on Tokamak/ITER and L-ICF.**
  - **Some continuing efforts in Japan.**

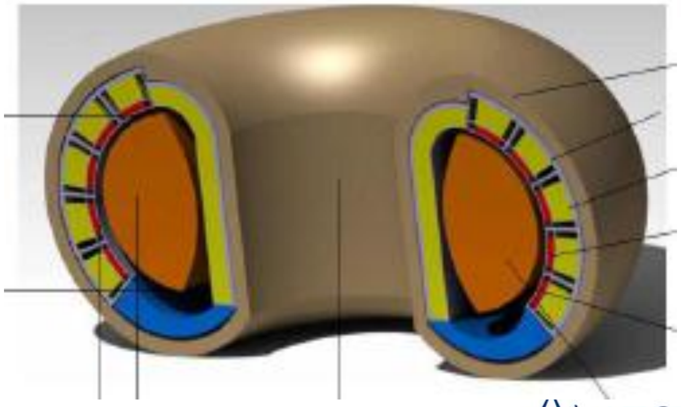
- **Late 1990s - 2012: changing again; growing since 2000.**
  - **Particularly in China, U.S.A., Russia, South Korea, Japan.**
  - **Updated conceptual design studies to adapt Tokamaks, L-ICF.**
    - **ITER site chosen in France, NIF (L-ICF) completed in 2009.**
  - **Manheimer (2009), U.S.A.**
    - **Hybrid using ITER design only economical approach for Tokamaks**
      - Molten Salt Blanket (UF_4/ThF_4/BeF_2/LiF)

China – Long Standing Effort to Develop Hybrid Tokamak

- Since late 1990s.
  - Parallel to ITER/DEMO development.
  - Several institutions/labs participating.
  - Dual blankets using U, Pu, MAs, LLFPs in particle and pebble beds cooled with Pb/Li and He.
- Goal for prototype HFFR by ~2032.
  - 50 to 200 MW (fusion power)
  - 500 to 3000 MWth (HFFR power)







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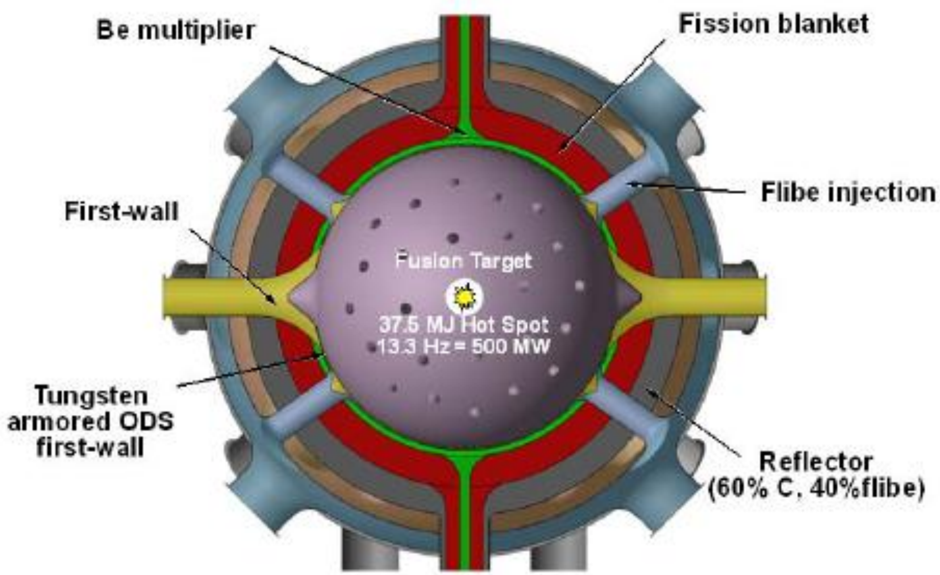
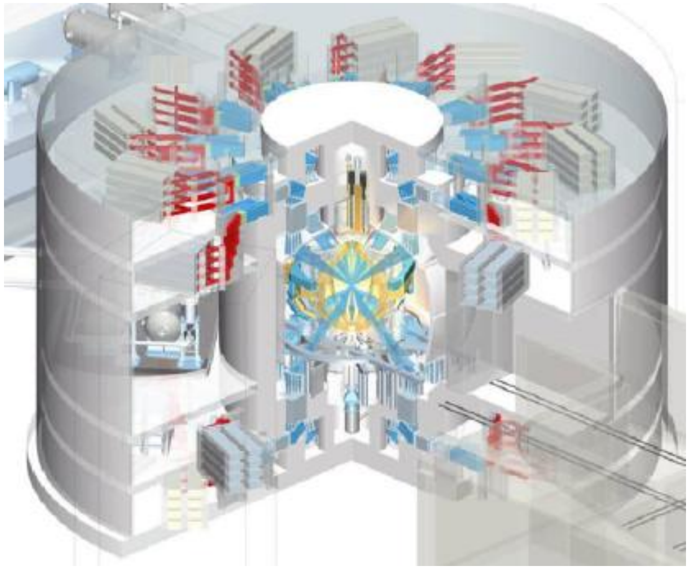
Update on Laser ICF Hybrid Fusion Fission Reactors

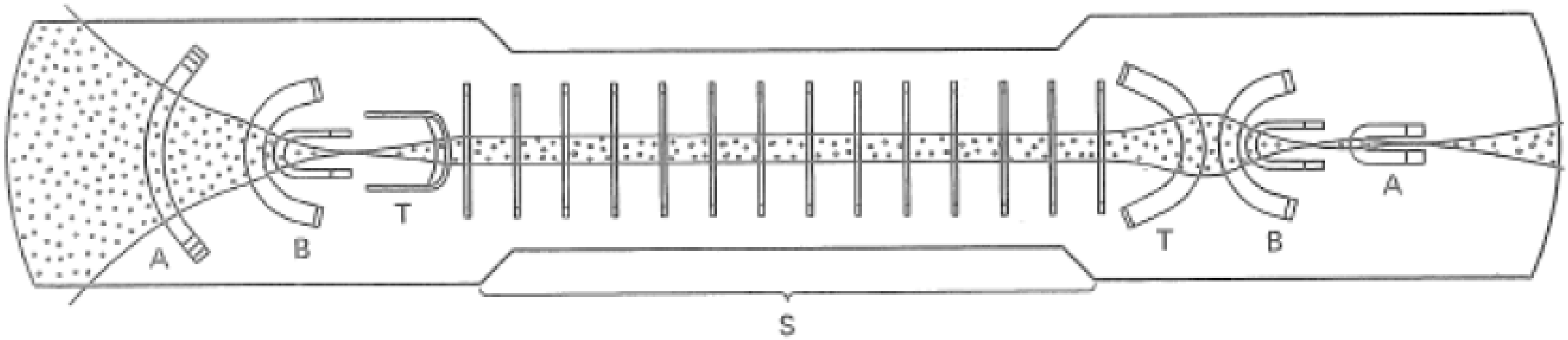
- **LLNL – Update of Hybrid Concept based on L-ICF.**
  - **LIFE (Laser Inertial Fusion Engine) adaptable for hybrid (2010-2012).**
  - **Two options: power option, breed option.**
    - **Power option was to burn weapons grade Pu, once-through closed cycle.**
    - **Breed option was to irradiate ThO_2 (pebble bed, cooled with molten salt)**
      - Use irradiated pebbles directly in HTGR to avoid chemical processing.
      - Tradeoff - support ratio lower (~2 reactors).





Revival of Tandem Magnetic Mirror HFFR

- Steady-state device, Cylindrical geometry, Open-ended system.
- Lower Q-values (Q ~ 1 to 10).
- MFTF-B Program in U.S. cancelled in 1986, but….
- A revival (2004) in tandem mirror HFFR, due to natural advantages.
  - Particularly in Russia and Japan.
  - Geometric symmetry, simplicity, engineering practicality.



A= Auxiliary End Coil, B= Minimum-B Mirror Coil, T=Transition Coil, S=Central Solenoid

UNRESTRICTED / ILLIMITÉ

Conclusions

- Evolution / staged development of ADS similar to that initially proposed by AECL / Canada.
  - Focus has changed to MA/LFFP consumption.

- ADS systems have high probability for technological success.
  - Smaller scale facilities operational in short term.
  - Benefit: reduction of MA's and LLFP inventories.
    - Power and fissile fuel production secondary
    - Unless price of U $\uparrow$ 3 $\times$
  - Could expect one major ADS transmutation facility in U.S.A., Europe, Russia, China, and Japan within next 40 years.
  - Issues: reduce capital + operational costs.
    - Innovation required.

Conclusions

- HFFR systems, while slightly more complex, could be more economical than pure fusion systems.
  - Lower Q requirements, low-Q fusion reactor easier.
  - Larger support ratio than fast breeders.
  - Burning MA/LLFPs option, but main attraction is power and breeding.
    - Would complement fleet of thermal and fast reactors.
    - 1 HFFR could support ~ 12 GWe of PT-HWRs
  - China appears on track for Tokamak-based HFFR by ~2030.
  - Issues: complexity of design – these remain for Tokamak / ICF.
  - A variant of the magnetic mirror, or *alternative concepts* may prove to be the best choice for HFFRs.
  - Solid-fuels without reprocessing may be best for first HFFRs.
    - Reduce complexity and allow more rapid implementation.
  - Gradually evolve to liquid blankets and continuous reprocessing.

Acknowledgements

- Fred Adams (AECL/CRL), Lakshman Rodrigo (retired)
- Bronwyn Hyland, Tracy Pearce (AECL/CRL).
- Library and Information Centre staff (AECL/CRL).
- Hugh Boniface, Bhaskar Sur, Darren Radford (AECL/CRL).
- Arnold Lumsdaine (ORNL).
- Susana Reyes (LLNL).
- Michael Todosow (BNL).

Upcoming Event

CWFEST-2013

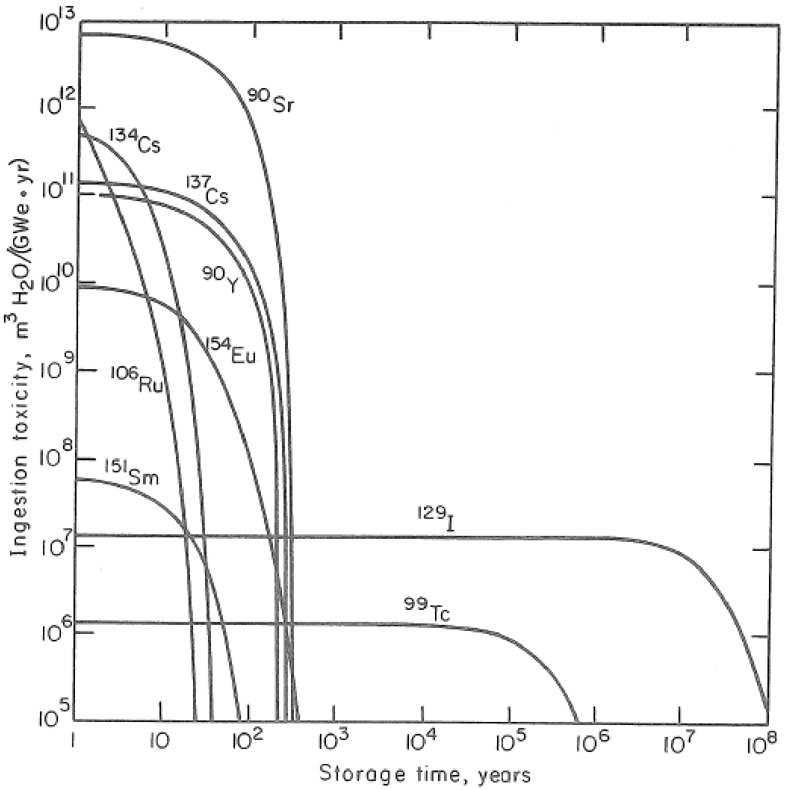
- Canadian Workshop on Fusion Energy Science and Technology.
- Friday, August 30, 2013, 8 am to 5 pm at UOIT – Oshawa, ON, Canada
- Sponsors: CNS, CNS-UOIT Branch, IEEE-Toronto, PES / NPSS Chapters
- Co-chairs: Professor Hossam Gaber (UOIT), Dr. Blair P. Bromley (AECL/CRL)
- Contacts: Hossam.Gaber@uoit.ca, bromleyb@aecl.ca
- Registration: $50 (discounts for various groups)
- To register: visit http://ewh.ieee.org/conf/sege/2013/CWFEST.html
- *CWFEST scheduled in conjunction with IEEE International Conference on Smart Energy Grid Engineering (SEGE'13), scheduled for Aug. 28-30, 2013 at UOIT.*
- *Information and updates, visit: http://ewh.ieee.org/conf/sege/2013/ and also http://cns-snc.ca/home*

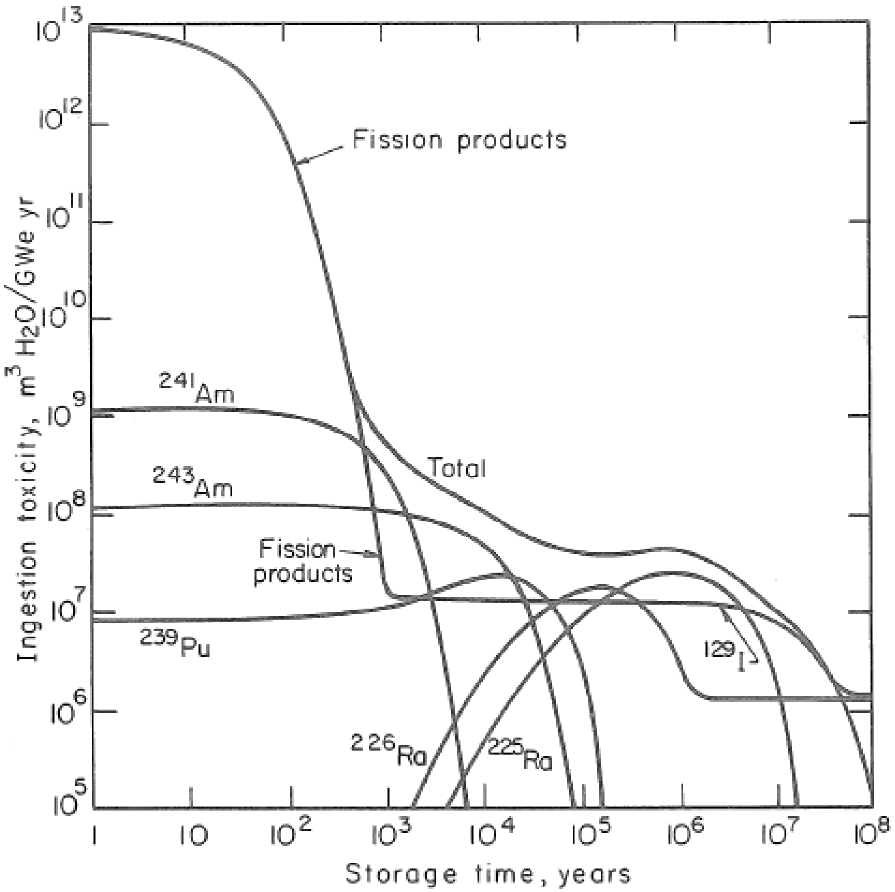
Extra Stuff

- See additional slides for misc. information

Minor Actinides and Long-Lived Fission Products

- **MA's and LLFP's problematic for > 10^4 years.**
- **Am decays to Np, Cm, Ra.**





High-Energy Nuclear Reactions

- At energies ≥ 2 MeV, direct fast fission of U-238 and Th-232 possible.
  - Also fast fission of isotopes of Pu, Am, Cm
- Neutron energy spectrum in ADS or HFFR harder than a fast reactor.

BASIC REACTIONS

FISSION

BURNING

$^{235}U + N \rightarrow \eta_{235}N + \sim 170\ MeV + PRODUCTS$

$^{239}Pu + N \rightarrow \eta_{239}N + \sim 140\ MeV + PRODUCTS$

$^{233}U + N \rightarrow \eta_{233}N + \sim 180\ MeV + PRODUCTS$

CONVERTING

$^{238}U + N \rightarrow {}^{239}Pu + \Delta E$

$^{232}Th + N \rightarrow {}^{233}U + \Delta E$

BREEDING

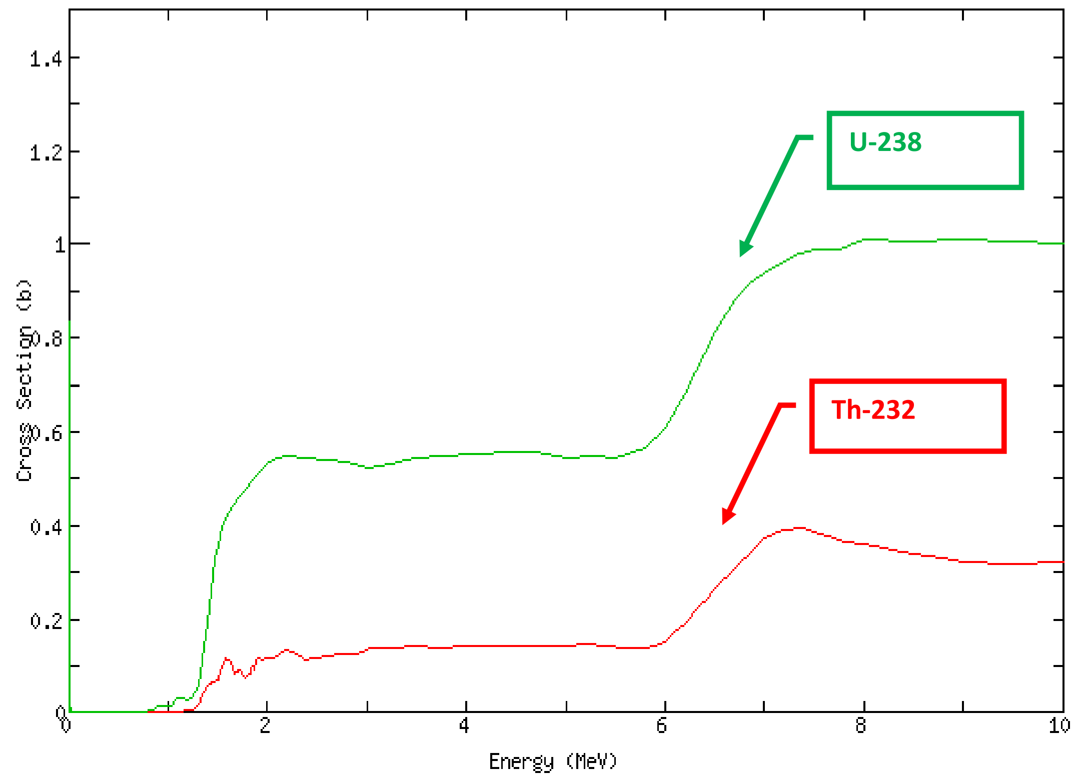
$^{238}U + 2N \rightarrow \eta_{239}N + \sim 140\ MeV + PRODUCTS$

$^{232}Th + 2N \rightarrow \eta_{233}N + \sim 180\ MeV + PRODUCTS$

FOR THERMAL REACTORS $\eta_{235} \simeq 2.05$

$\eta_{239} \simeq 1.90$

$\eta_{233} \simeq 2.25$



Stages in Accelerator Breeder Development - Planned

- Evolutionary.
  - ZEBRA, EMTF, PILOT
  - DEMO ~ ING
- Use smaller stages for other applications.
- AB could be designed to generate excess power.
  - In situ burning of U-233 or Pu-239.
- Costs:
  - ~$1.5B (1981) – DEMO
  - Fissile fuel 3 to 4 × cost of U-235 from enrichment facility.

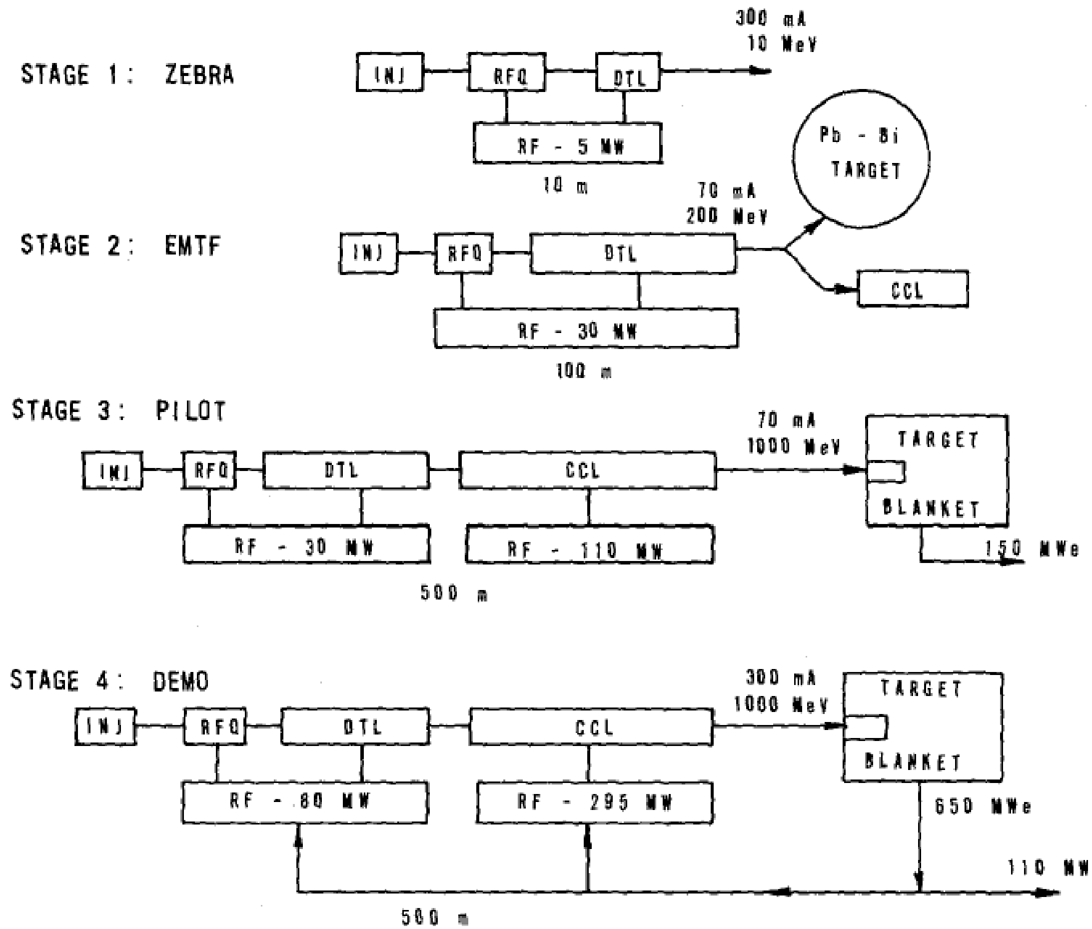


Figure 2 Stages in the development of an accelerator breeder facility.

- **Conceptual Designs**

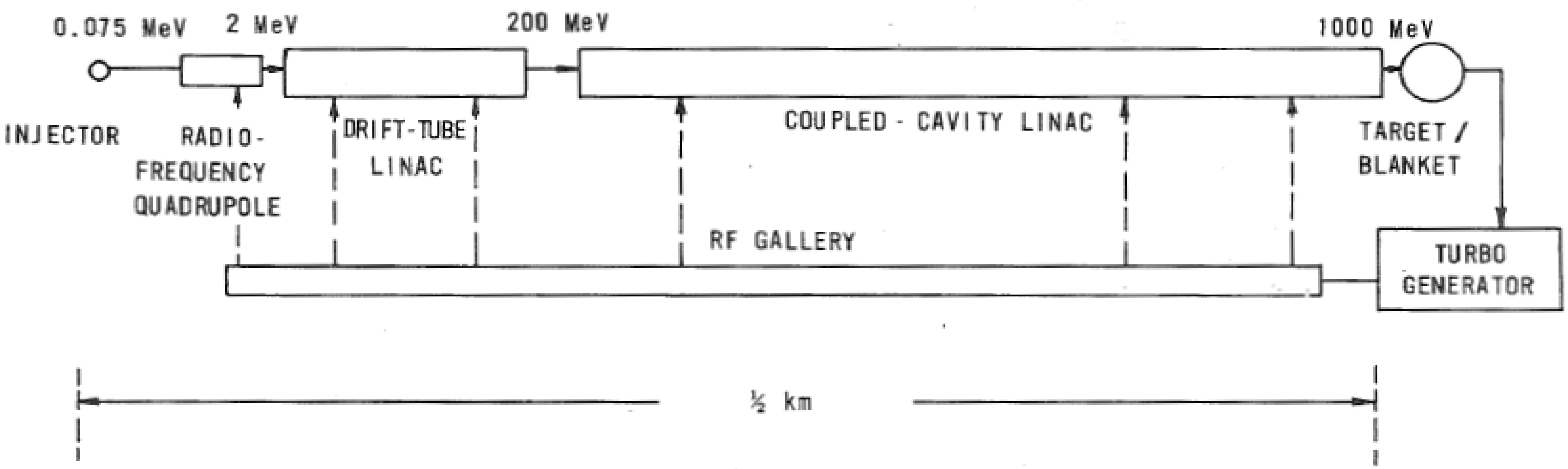


Fig. 1 Main components of an Accelerator Breeder.

AECL – Accelerator Breeder

- Schematic Diagram of a Windowless Target of Liquid Metal (Pb-Bi) surrounded by Blanket.
- Proton beam directly hits Pb/Bi, producing spallation neutrons.
- Initial design concept was simply a sub-critical fast reactor blanket cooled with sodium.

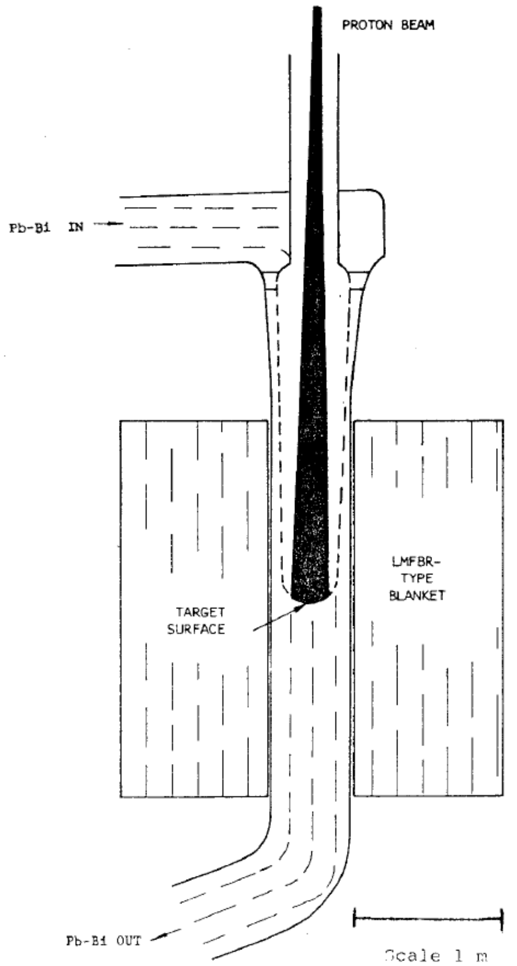


Figure 11 Schematic diagram of a windowless target of liquid metal surrounded by a liquid-metal blanket.

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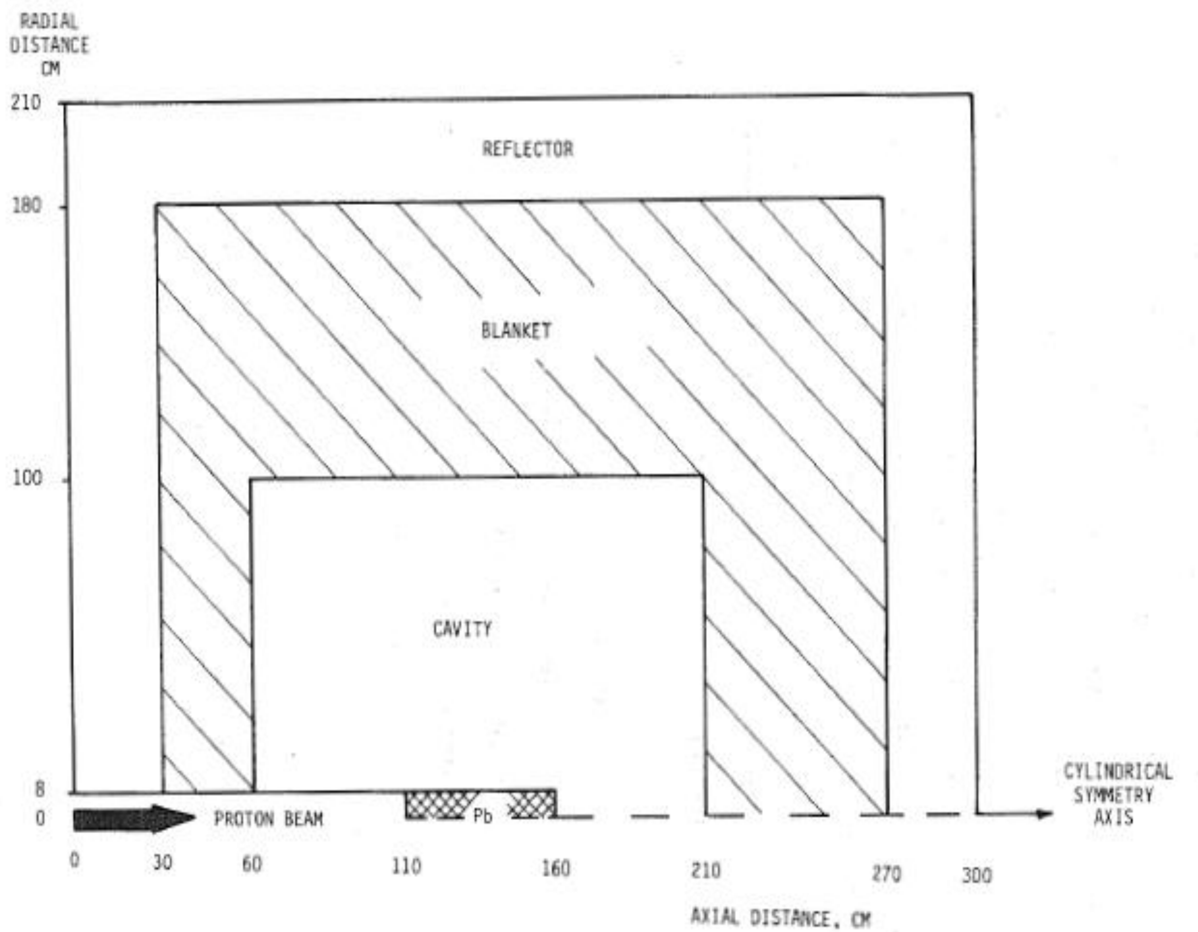
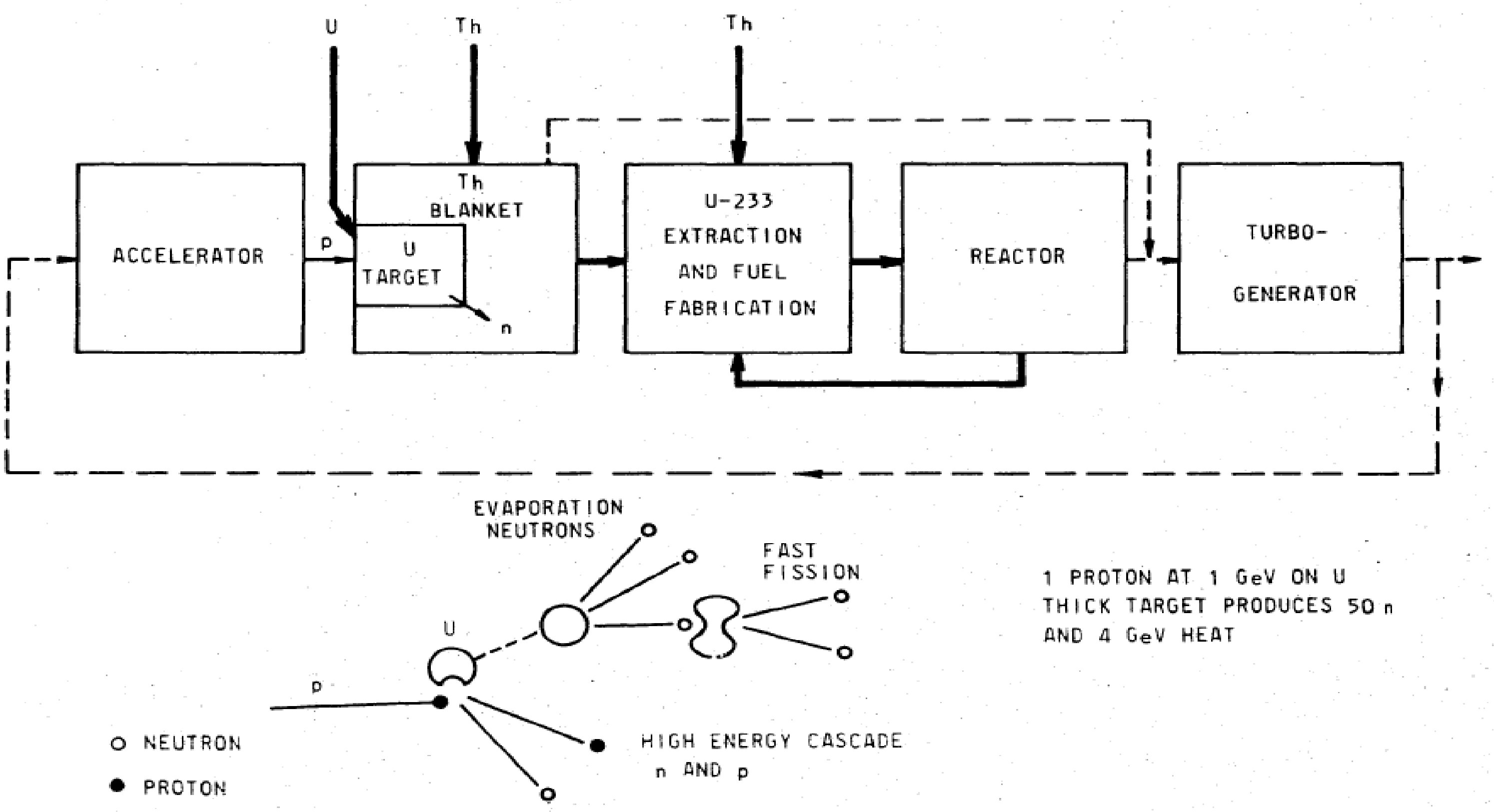
AECL – Accelerator Breeder Blanket Scoping Studies

- Blanket modelled as solid or hollow cylindrical cavity.
- U and/or Th.
- Metal, oxide, carbide fuels.
- Liquid metal (Na) or gas coolant (He).



Symbiosis – Accelerator Breeder & PT-HWR

- Fission reactor (PT-HWR) generates electrical power.
- U-233 is recycled and combined with extra accelerator-bred U-233.
- 1-GeV protons on U target (50 neutrons/proton), with Th blanket.



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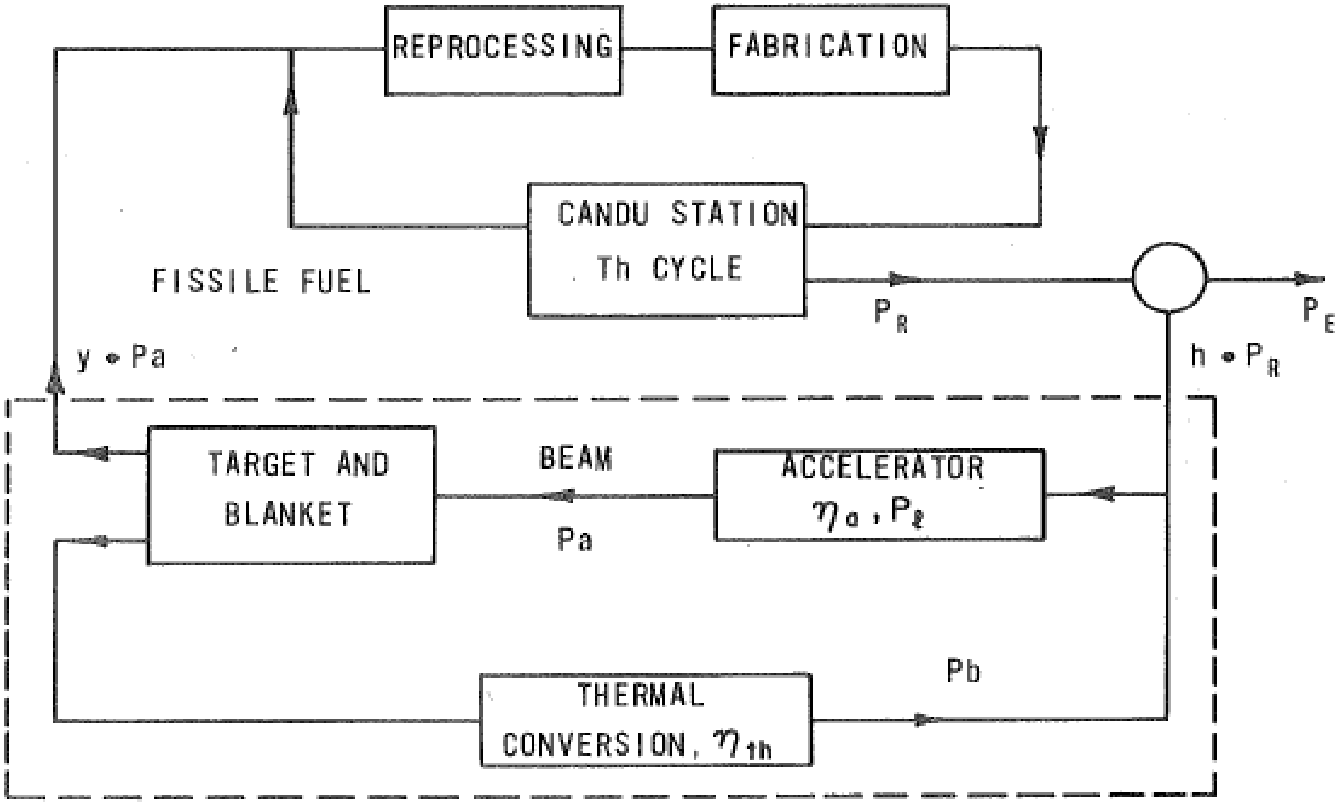
AECL – ADS Symbiosis with PT-HWR

- A 300-MW Beam Accelerator-Breeder could support 2 to 5 Pickering-size stations.
- PT-HWRs (U-233/Th with CR ~0.9, ~500 MWe).



Accelerator Breeder Performance Summary

- **Accelerator breeder self-sufficient in power.**
- **Pu-239 production costs lower than U-233.**
- **839 kg/year U-233; 1,241 kg/year Pu-239.**
- **Sufficient to support ~10,000 MWe (C.R.~0.9, with full recycle).**

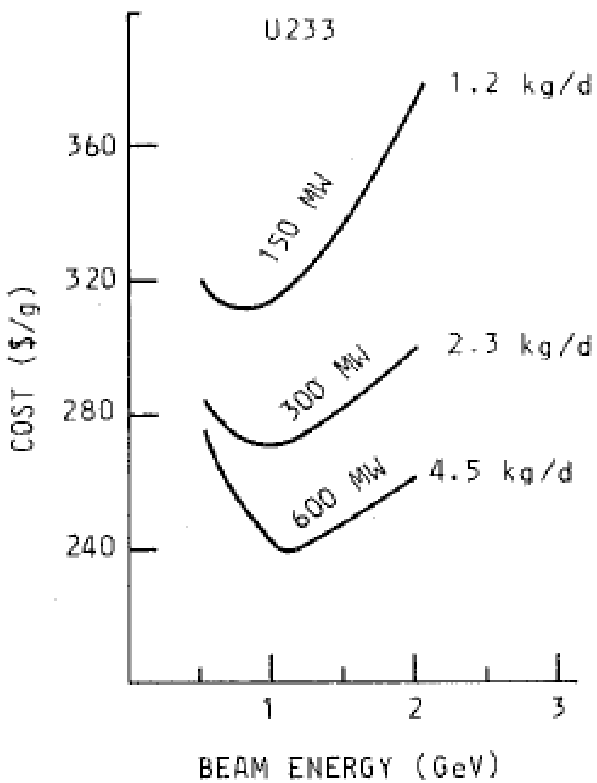
300 mA, 1 GeV AB summary

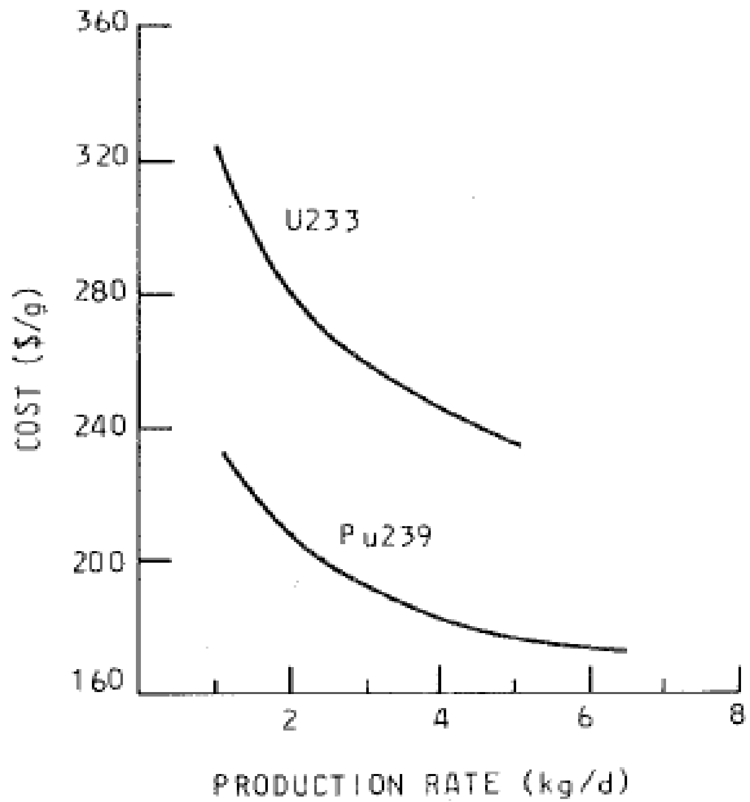
Target/Blanket Thermal Power	1520 MW_{th}
AC Power Generation	532 MW_e

	Blanket Enrichment (%)	Production Rate (kg/d)	Fuel Costs ($/g)
Pu239	1.6	3.4	183
U233	3.2	2.3	261

Cost of Fuel Bred by Accelerator (1981)

- Minimized by operating at ~ 1 GeV proton energy.
- Pu-239 production costs lower than U-233.
- Economies of scale favour larger facility.





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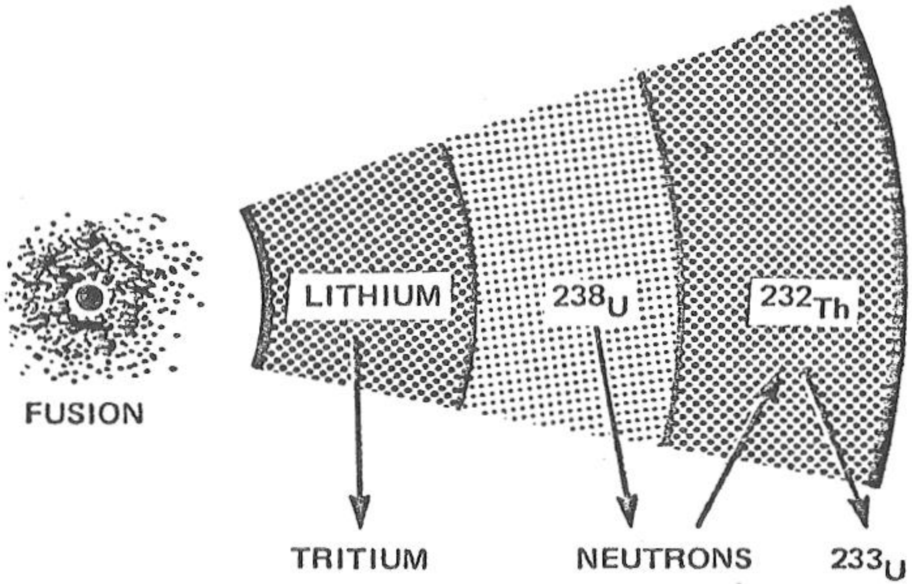
AECL – Hybrid Concepts

- **Must include lithium blanket region for tritium production.**
- **Uranium blanket enhances neutron multiplication due to fast fission of U-238 and *in situ* fission of Pu-239.**

NEUTRON MULTIPLICATION

1 FISSION NEUTRON (~2 MeV) + ^{238}U → ~ .035n

1 FUSION NEUTRON (14 MeV) + ^{238}U → ~ 3.5n



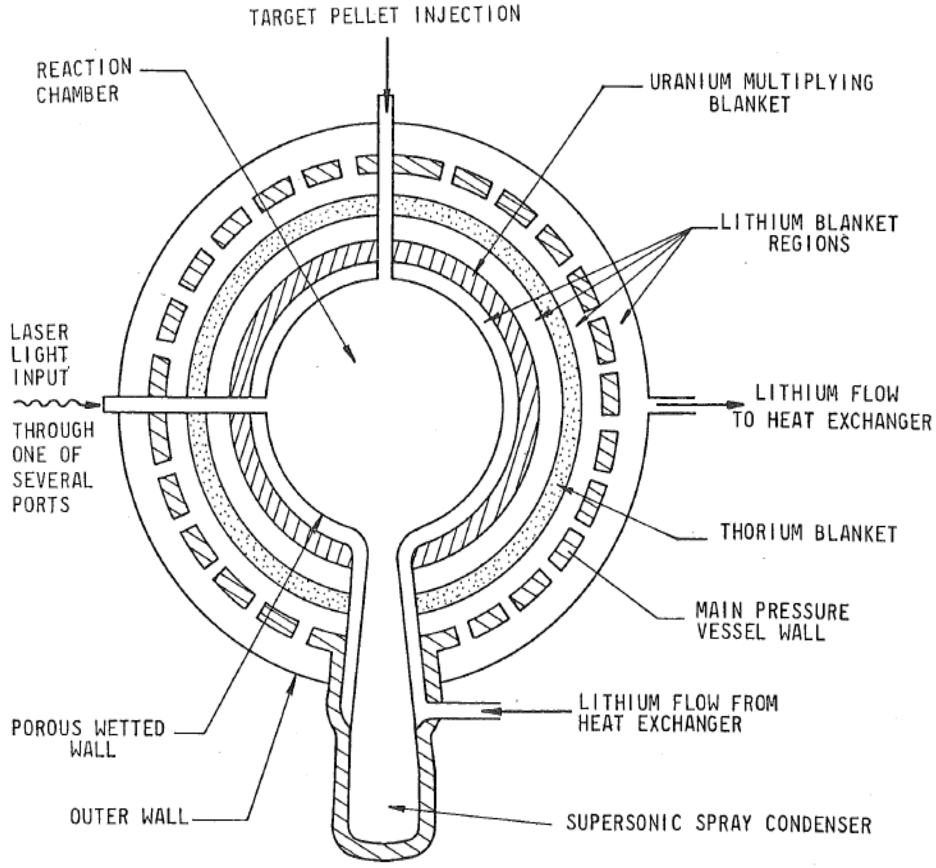
1 FUSION → 1 TRITIUM + ≈170 MeV

+ 1 ^{233}U (worth 2000 MeV in Th cycle CANDU)

+ 0.9 ^{239}Pu

AECL – Hybrid Fusion/Fission Blankets

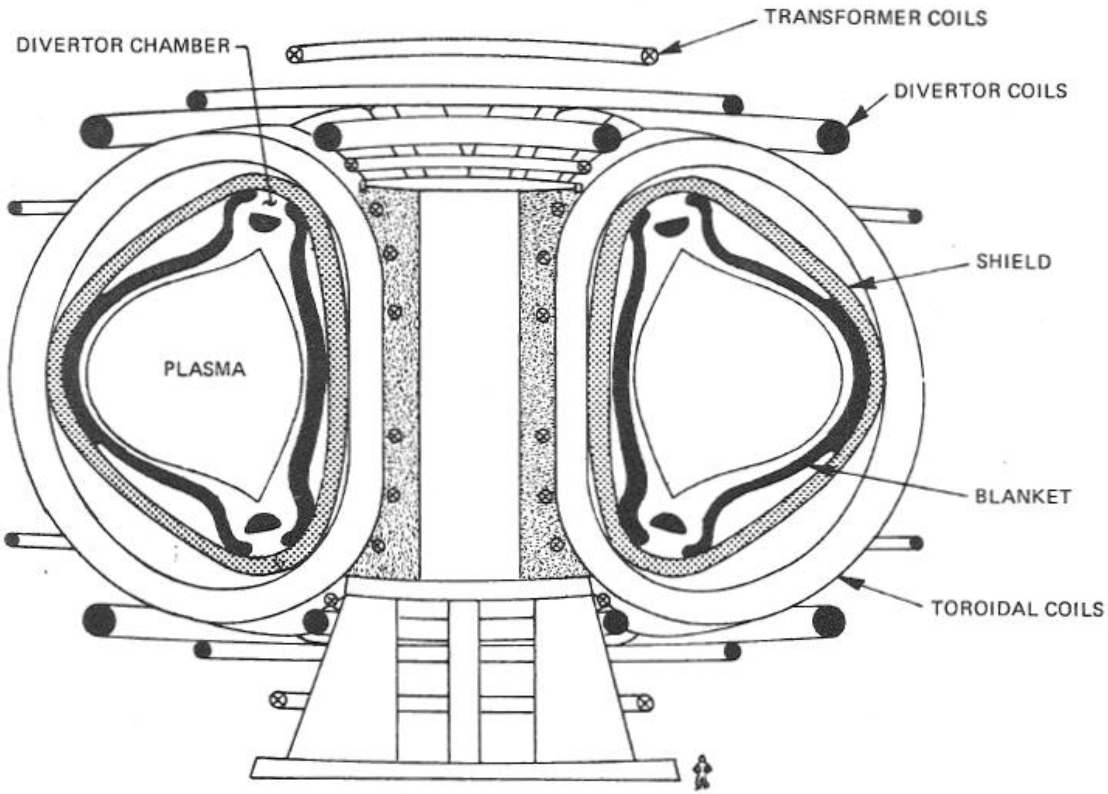
- **Laser-Driven Inertial Confinement Hybrid Fusion-Fission System.**
- **Alternating regions of thorium, uranium and lithium for breeding.**



SCHEMATIC VIEW OF THE REACTION VESSEL FOR THE FUEL BREEDING ASSEMBLY

Tokamak Fusion Reactor

- Mainstream concept.
- Source of fusion neutrons to drive fertile blankets.



The Tokamak reactor model, cross-section view.

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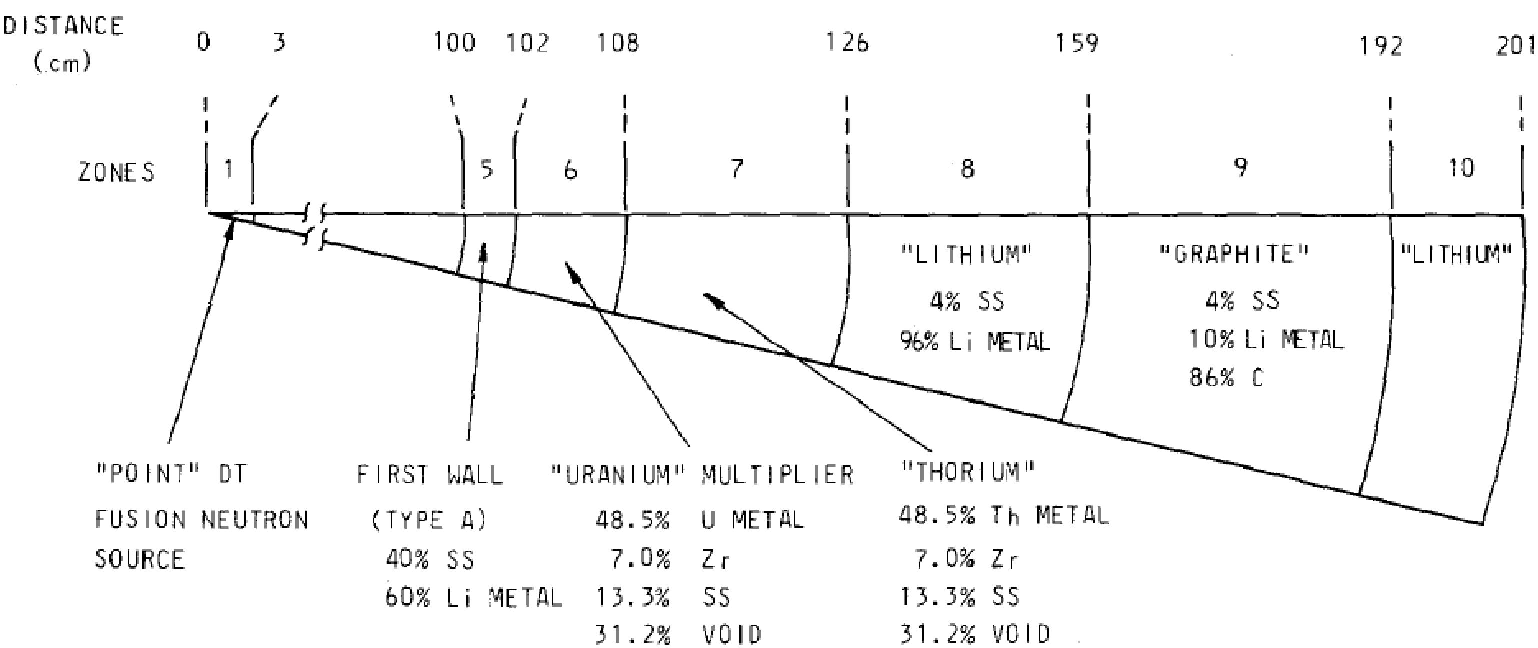
AECL – HFFR Blanket Studies

- **Multiple zones in blanket region**
  - **First wall / Uranium / Thorium / Lithium / Graphite / Lithium**

ZONE	5	6	7	8	9	10
ATOM DENSITIES (10^{24} cm^{-3})	0.4 x SS 0.00206 ^{6}Li 0.02577 ^{7}Li	0.133 x SS 0.00294 Zr 0.02313 ^{238}U 0.000046 ^{235}U	0.133 x SS 0.00294 Zr 0.01474 ^{232}Th	0.04 x SS 0.00330 ^{6}Li 0.04124 ^{7}Li	0.04 x SS 0.000344 ^{6}Li 0.004296 ^{7}Li 0.0656 C	0.04 x SS 0.00330 ^{6}Li 0.04124 ^{7}Li



AECL – Th-Blanket Performance

- Neutronic Performance of Th Blanket Drive by D-T Fusion Neutrons
- 0.68 U-233 atoms produced per D-T neutron.
- 0.08 Th-232 atoms fissioned per D-T neutron

Table 9.3. Neutronic performance of the Th blanket⁺ per DT fusion neutron. It is assumed that 32% of all neutrons reaching the blanket outer boundary are reflected.

Reaction		First Wall	"Thorium"	"Lithium"	"Graphite"	"Lithium"	Total
Neutron absorption		0.066	0.819	0.674	0.265	0.021	1.845
Excess (n,2n) and (n,3n) neutrons		0.041	0.517	0.016	0.001	0.0001	0.575
Fission neutrons		-	0.294	-	-	-	0.294
T_6: $^6Li(n,\alpha t)$		0.039	-	0.657	0.231	0.021	0.948
T_7: $^7Li(n,n'\alpha t)$		0.026	-	0.097	0.003	0.001	0.127
^{232}Th:	(n,γ)	-	0.680	-	-	-	0.680
	(n,f)	-	0.081	-	-	-	0.081
	$(n,2n)$	-	0.259	-	-	-	0.259
	$(n,3n)$	-	0.090	-	-	-	0.090

System balance: Sources = 1 + 0.575 + 0.294 = 1.869

Losses = Leakage + Absorption = 0.024 + 1.845 = 1.869

^{233}U breeding ratio = $^{232}Th(n,\gamma)$ = 0.68

Blanket energy multiplication = 2.5

⁺The blanket arrangement is similar to the U-Th case with, specifically, a 180 mm thick "thorium" zone following the first wall, then 300 mm of "lithium", 420 mm of "graphite" and finally 90 mm of "lithium". The first-wall radius is 3 m.

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AECL – U/Th-Blanket Performance

- Neutronic Performance of U/Th Blanket Driven by D-T Fusion Neutrons
- 0.76 U-233 atoms produced per D-T neutron.
- 0.38 Pu-239 atoms produced per D-T neutron.

Table 9.2. Neutronic performance of the U-Th blanket, depicted in Fig. 9.1, per DT fusion neutron. It is assumed that 32% of all neutrons reaching the blanket outer boundary are reflected. The uranium is depleted uranium.

Interaction / Zone	First wall (5)	Uranium Multiplier (6)	"Thorium" (7)	"Lithium" (8)	"Graphite" (9)	"Lithium" (10)	Total
Neutron absorption	0.077	0.636	0.850	0.730	0.206	0.047	2.546
Excess (n,2n) and (n,3n) neutrons	0.037	0.261	0.272	0.009	0.0003	0.0001	0.579
Fission neutron sources	-	0.851	0.166	-	-	-	1.017
T_6: ^{6}Li(n,αt)	0.049	-	-	0.713	0.181	0.046	0.989
T_7: ^{7}Li(n,n'αt)	0.024	-	-	0.060	0.001	0.001	0.086
^{232}Th: (n,γ)	-	-	0.757	-	-	-	0.757
^{232}Th: (n,f)	-	-	0.048	-	-	-	0.048
^{232}Th: (n,2n)	-	-	0.137	-	-	-	0.137
^{232}Th: (n,3n)	-	-	0.047	-	-	-	0.047
^{238}U: (n,γ)	-	0.383	-	-	-	-	0.383
^{238}U: (n,f)	-	0.217	-	-	-	-	0.217
^{238}U: (n,2n)	-	0.109	-	-	-	-	0.109
^{238}U: (n,3n)	-	0.058	-	-	-	-	0.058
^{235}U: (n,f)	-	0.006	-	-	-	-	0.006

System balance: Sources = 1 + 0.579 + 1.017 = 2.596

Losses = Leakage + Absorption = 0.051 + 2.546 = 2.597

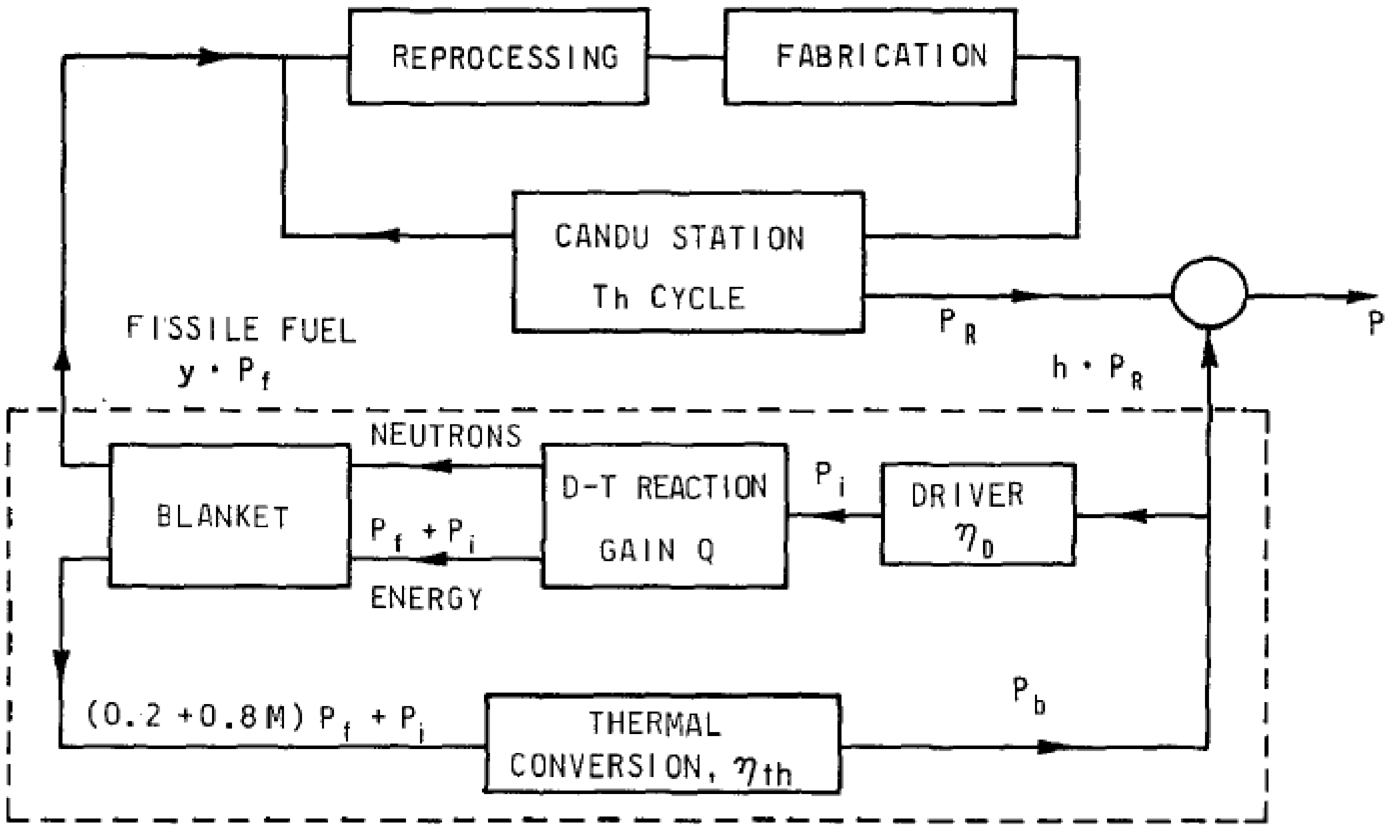
^{233}U breeding ratio = ^{232}Th(n,γ) = 0.76

^{239}Pu breeding ratio = ^{238}U(n,γ) = 0.38

Blanket energy multiplication = 5.5

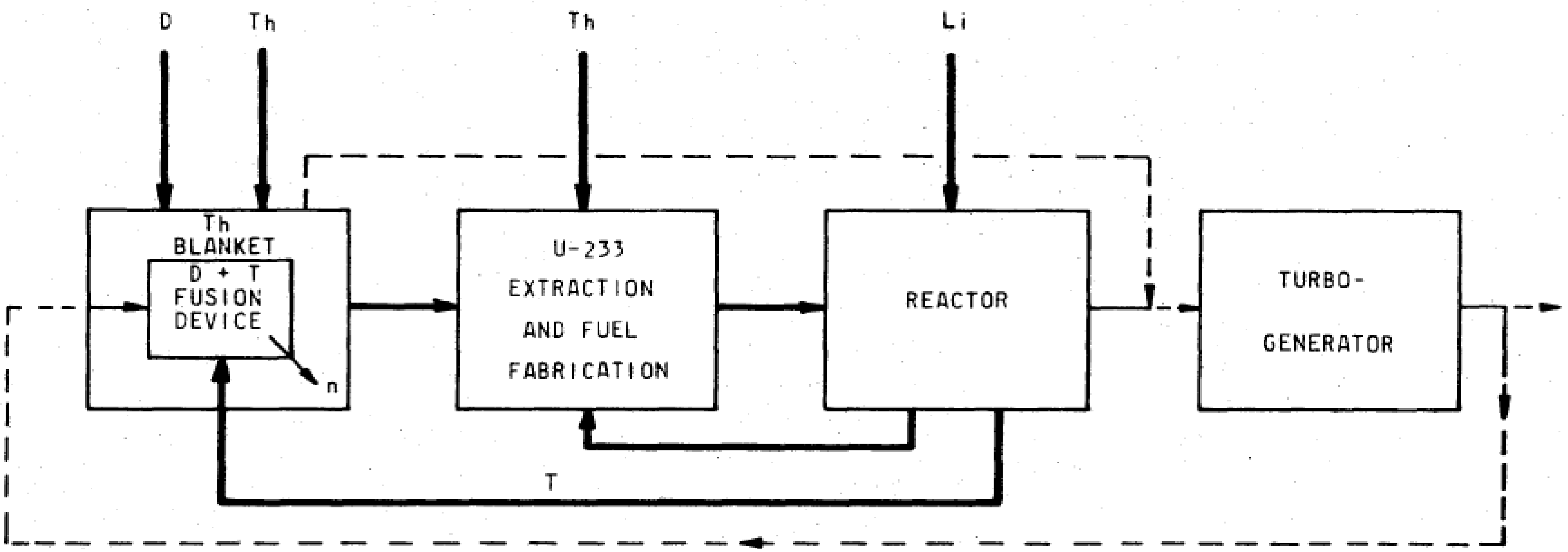
AECL – HFFR Symbiosis with PT-HWR

- **A low Q (~1.3), low-power (133 MW fusion) hybrid fusion reactor could make sufficient fuel (U-233) to support ≥ 2,000 MWe of PT-HWRs (U-233/Th with CR ~0.9, ~500 MWe).**



Symbiosis - Fusion Reactor & PT-HWR

- Fission reactor (PT-HWR) generates electrical power.
- U-233 is recycled and combined with fusion-bred U-233 and Th-232.
- Tritium is bred from lithium in blankets in both fusion and fission



FUSION REACTIONS

$$D + T \rightarrow {}^{4}He + n + 17.6\ MeV$$

$$^{6}Li + n(SLOW) \rightarrow T + {}^{4}He + 4.8\ MeV$$

$$^{7}Li + n(FAST) \rightarrow T + {}^{4}He + n - 2.5\ MeV$$

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Early Expectations (1981) for Tokamaks and Tandem Mirrors

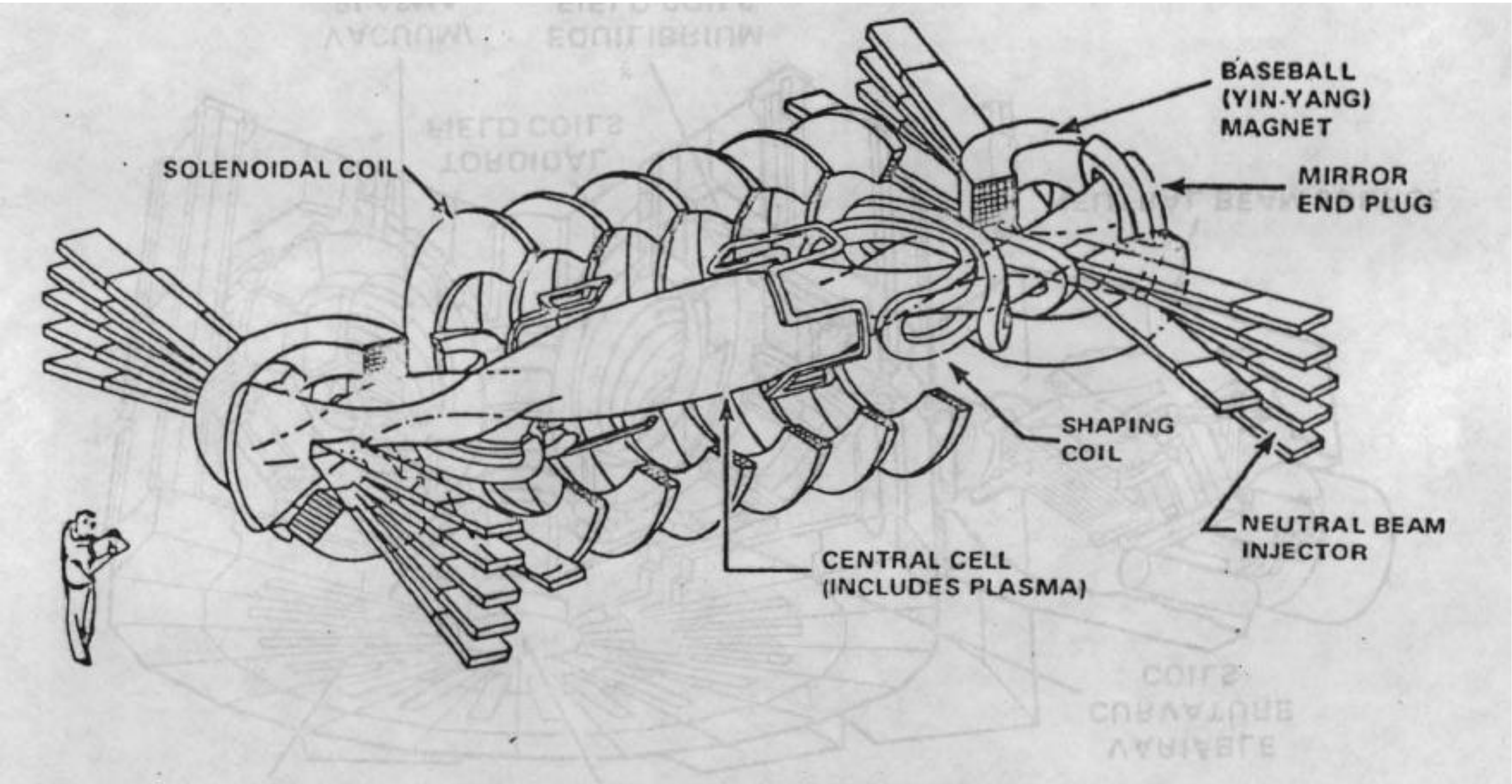
- Q~1 for TFTR, ~10 to 20 for larger (ITER?)
- Q~0.5 was expected for MFTF-B, ~10-50 for a large-scale tandem mirror with various confinement enhancements, such as field reversed configuration.
- Q ≥ 1 needed for economical hybrid system.

TABLE 4.4. Comparison of Attained and Expected Parameters for Tokamaks and Tandem Mirrors

Parameter	Tokamak			Tandem Mirror		
	Attained[a]	TFTR[c]	Reactor[d]	Attained[e]	MFTF-B[g]	Reactor
$n\tau\,(cm^{-3}\cdot s)$	3.3×10^{13}	$\approx10^{13}$	3×10^{14}	7×10^{10}	5×10^{13}	2.5×10^{13}[j]
T_i (keV)	7.1	≥5	7-10	.25	15	10[k]
β	0.3	.007	.06-1.0	.2	.24[h]	.4 to .75[j]
Q	.02[b]	1.0	10-20	—[f]	.5	10-50[ℓ]

Tandem Magnetic Mirror – MFTF-B

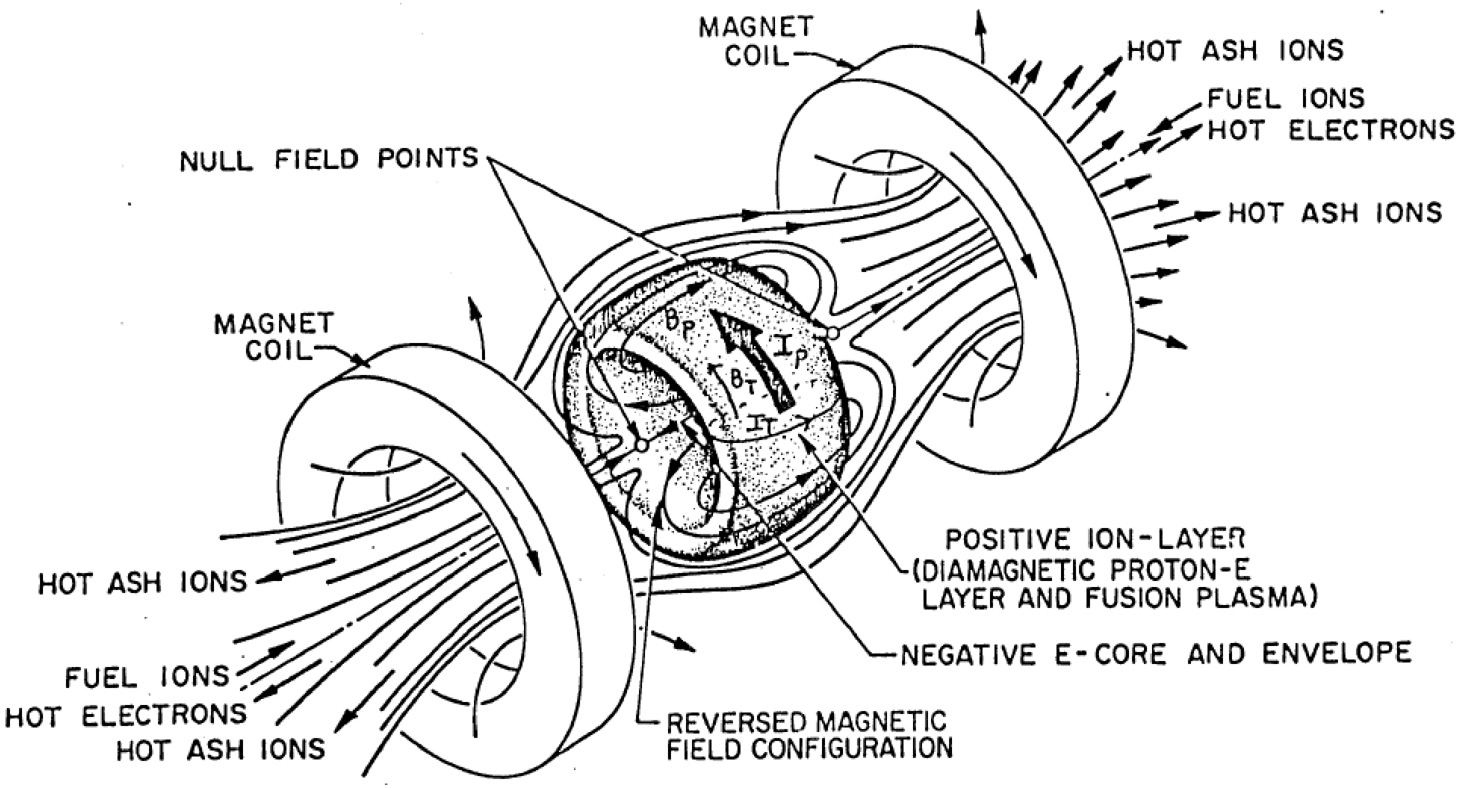
- Central solenoid + Baseball Field Coils at ends provides confinement.



Schematic Diagram of the Tandem Mirror Experiment

Enhanced Confinement for Magnetic Mirrors – Field Reversed Configuration

- High angular plasma current creates opposing magnetic field.
- Compact torus created inside mirror for enhanced confinement.



POSSIBLE ION-LAYER, ELECTRON-CORE REACTING PLASMA CONFIGURATION

Approximate Parameters for a 4,000 MWth Magnetic Mirror HFFR

- Q~2; 3000 kg/year of U-233 produced.
- Sufficient to support ~ 3 GWe (no recycle).
- Sufficient to support ~22 GWe (CR~0.9, full recycle)

TABLE 4.2 Approximate parameters for a 4000 MW(th) hybrid fusion-fission reactor system[11]

Central Cell	plasma Q	2.0
	length	35 m
	radius	2.0 m
	B	2 T
	electron density	$\sim 5 \times 10^{13} cm^{-3}$
	β	≤ 1
	ion temperature	~10 keV
Neutral beam energy		~200 keV
Injected neutral beam power		400 MW
Fusion power		800 MW
Power generated in blanket		3400 MW(th)
Efficiency of producing neutral beams		~60%
Total fissile material (^{233}U) production		~3 Mg/a
Total cost		$\sim 2 \times 10^9$ \$ (U.S. 1980)

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HFFR Sizes for PT-HWR Thorium Burning Reactors

- **One HFFR (~420 MW fusion), Th blanket → 1000 kg/year of U-233.**
  - **Will support ≥7,300 MWe PT-HWRs (with recycling).**
- **Larger support ratio with HFFR with U-blanket.**

TABLE 13a. Fusion-fission hybrid reactor sizes for CANDU thorium burning reactors. The RCU (Reference CANDU Unit) is taken to be 1 GW(e) in size, operating at 0.88 conversion, 29.2% thermal efficiency (Ref. 34).

		Fusion-Fission Blanket Option		
Item	Item description	A(Th)	B(Th-U)	C(U)
1a	Equivalent ^{233}U breeding ratio B	0.68	1.08	1.37
2a	Fusion Power/RCU; i.e. (x/y) ••• MW(f)/GW(e)	57.5	36.2	28.5
3a	Fusion power for 7.3 RCU's [i.e. production of 1 Mg ^{233}U/a, 80% capacity] ••• MW(f)	420	264	208
4a	Fusion power for 25 RCU's [i.e. production of 3.4 Mg ^{233}U/a, 80% capacity] ••• MW(f)	1430	900	710
5a	Blanket energy multiplication factor	2.5	5.5	9.0
6a	Fusion-hybrid thermal power/RCU ••• $MW_H(t)/GW(e)$	126	166	211
7a	Fusion-hybrid thermal power for 7.3 RCU's [i.e. production of 1 Mg ^{233}U/a, 80% capacity] ••• $MW_H(t)$	920	1210	1540

Allowed Capital Costs for HFFRs

- Estimated costs (1981) are at least 2.5 times allowed costs.
- Larger fusion reactor favoured – economies of scale.
- Price of uranium ore would need to go up, or capital costs of fusion reactor need to go down.

Table 10.3. Capital cost data from American studies of hybrid fusion-fission breeders which generate fissile material and net energy (h>0). An allowed capital cost is calculated for each breeder assuming that it supplies make-up fuel to a CANDU system sized to use all of the breeder fissile output.

Device[1,2]		P_f Fusion Power MW	P_b Breeder Gross Power, MW(e)	h %	$h \cdot P_R$ Net Breeder Power, MW(e)	Fissile Yield Mg/year		Capital Cost[3], 1981 CAN $ Estimated (E) 10^9 $	Allowed (A) 10^9 $	Ratio E/A
Tandem Mirror	(B6)	813	1800	2.0	892	2.92	U	4.25	1.61	2.6
Tandem Mirror	(B7)	875	1533	1.8	650	2.32	Pu	3.55	1.22	2.9
Tandem Mirror	(B7)	580	1500	2.9	620	1.85	Pu	3.49	0.94	3.7
Standard Mirror	(B8)	400	1715	2.6	603	2.0	Pu	2.59	0.95	2.7
Tokamak	(B9)	1180	2250	5.6	1600	2.41	Pu	4.70	1.88	2.5
Tokamak	(B10)	218	740	3.2	480	1.27	Pu	2.63	0.68	3.8
Laser	(B11)	200	535	2.6	400	1.3	Pu	4.15	0.62	6.7
ICF	(B12)	690	1245	3.8	817	1.81	Pu	2.83	1.09	2.6

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Highlights
International Work – ADS (2001-2012)

- **Most ADS energy self-sufficient, or generate surplus power.**
  - **500 MW_{th} to 3,000 MW_{th}**
  - **Consume 200 to 1,200 kg/yr MAs, 400 kg/yr LLFPs**
    - **Consume MA/LLFPs from 5 to 10 LWRs (~1 GWe each) – same as earlier.**
  - **Produce 100 to 600 kg/year of fissile fuel.**
- **Collaborations at BNL / INL / Texas A&M University**
  - **ADS to consume SNF and MAs; multi-beam isochronous cyclotron**
  - **0.8-GeV protons, >12 mA, 400 MW_{th}, molten salt (UCl_3/$ThCl_3$/NaCl).**
  - **Burn spent nuclear fuel without reprocessing. Reduce MAs by 10,000.**
- **ANL Studies**
  - **Four large ADS units could get rid of entire U.S. inventory of SNF (~70,000 tonnes) within 33 years.**
- **Lingering issues**
  - **Confidence due to smaller scale accelerators in operation.**
  - **Engineering issues (accelerator, target, blanket) to perfect a large-scale ADS that is reliable, practical and economical.**

International Work - ADS

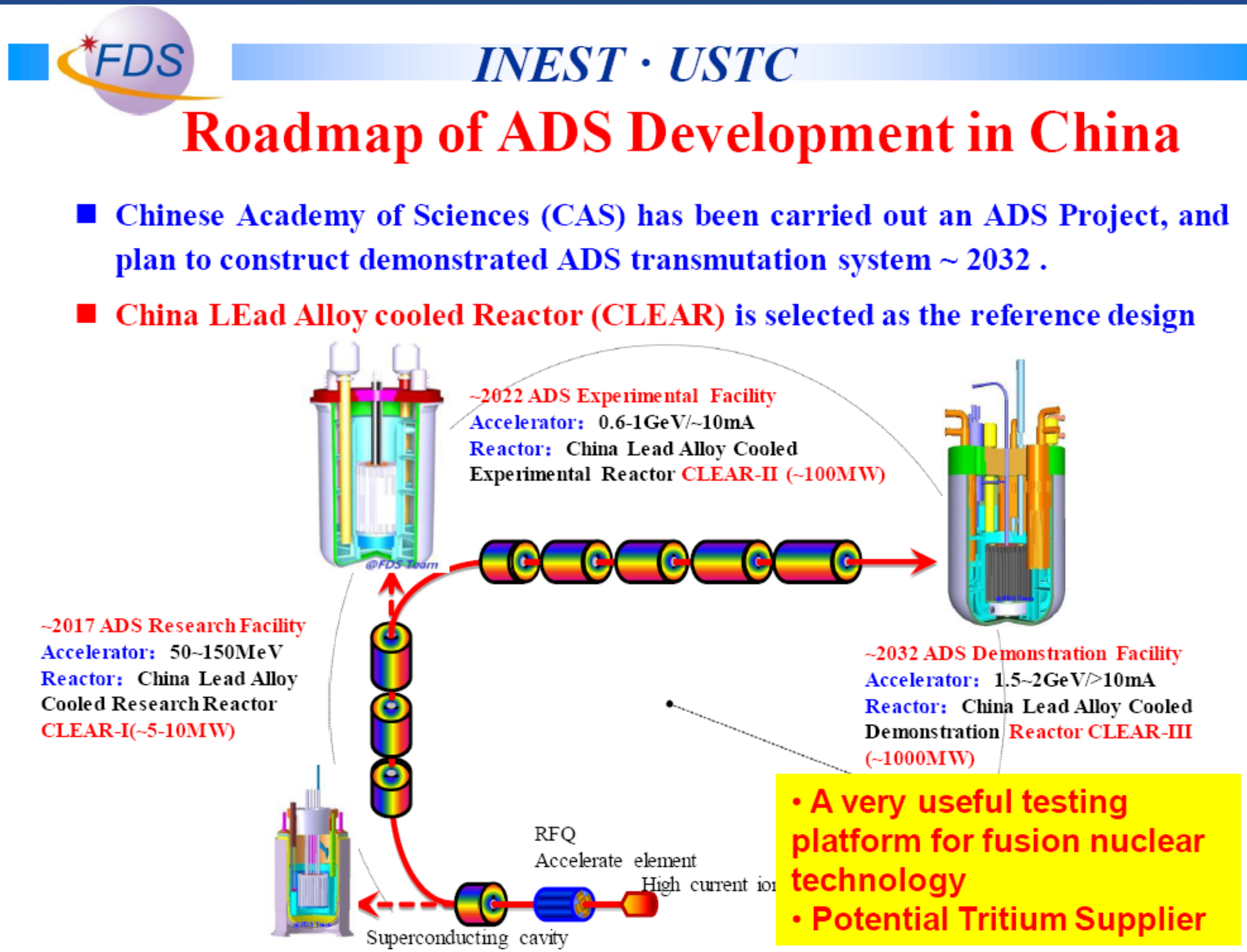
- **1950s - World uranium supplies less assured.**
  - **Electro-nuclear breeders (ADS and HFFR) proposed in addition to fast breeder reactors.**
  - **Material Testing Accelerator (MTA) project at LBNL ran from 1949-1954**
    - **Linear accelerator – D on Be target (350 MeV, 500 mA), uranium blanket.**
  - **Simple magnetic-mirror-type fusion devices proposed to provide 14-MeV neutrons to bombard depleted uranium blankets.**
- **1970-1990 – Renewed interest in ADS for breeding, transmutation.**
  - **During 1970s, BNL, LLNL, ORNL proposed ADS systems very similar to AECL's ING, for breeding.**
  - **1980s: looking for alternative to reactors, for enhanced safety, emphasis on destruction of minor actinides and long-lived isotopes.**
  - **Numerous studies in several nations:**
    - **Computational, experimental, scoping, benchmarking, conceptual designs.**
    - **U.S. (LANL / BNL / ORNL), Europe, Japan, Russia, China.**
    - **Accelerator and target design (1-GeV protons on Pb/Bi target main idea).**
    - **Parallels earlier staged program proposed by AECL.**

Highlights
International Work – ADS (2001-2012)

- Various groups continuing studies.
  - Large similarities – only so many ways to design such systems.
  - Large, multi-stage linear accelerators (~ 1 km long).
  - 1-GeV to 2-GeV protons, 1 to 300 mA, Pb/Bi targets.
- Blanket variations
  - Th, NU, MOX, SNF, partitioned MAs and LLFPs.
  - Solid oxide, metals, pebble-bed, coated particles in suspensions, molten salts (fluoride or chloride), aqueous solutions.
  - Liquid metal, molten salt, gas coolants.
- Tradeoffs
  - Molten salts advantageous for continuous processing.
  - Solid fuel with Pb coolant has commonality with fast reactor technology.
  - Fast spectrum maximizes transmutation; minimizes U-233 fission.
    - Metallic alloys preferred to oxides to harden spectrum.

ADS in China – 2032 Goal

- **Full scale ADS system by ~2032 (20 years from now).**
- **Slightly subcritical.**
- **20 MW beam power.**



- **A very useful testing platform for fusion nuclear technology**
- **Potential Tritium Supplier**

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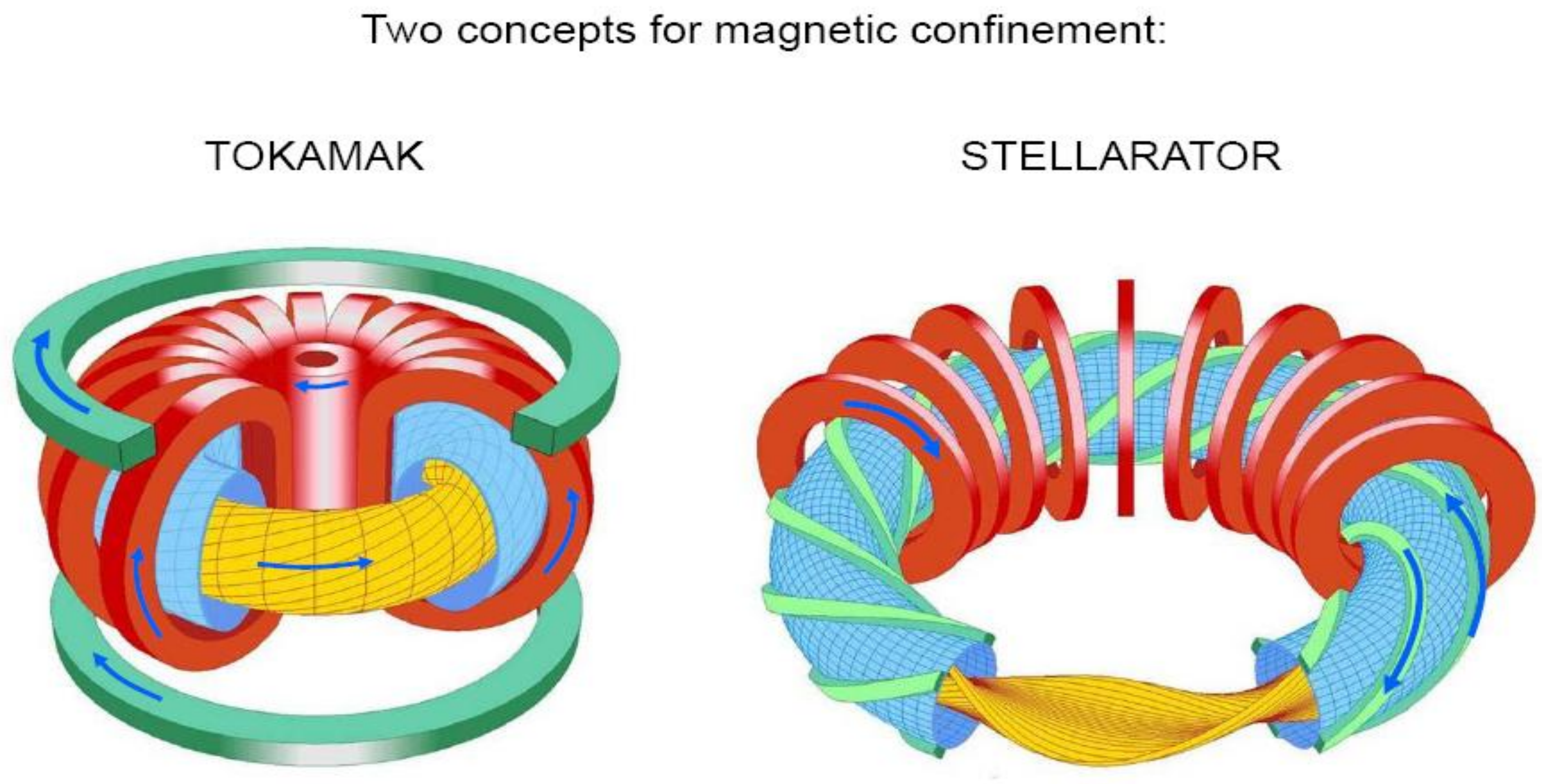
Mainstream Magnetic Confinement Concepts

- **Tokamak – high toroidal current in plasma – slow pulse.**
- **Stellarator – helical field coils – steady state device.**



HFFR in China – 2032 Goal.

- **Prototype HFFR in China by ~2032.**
- **Use Tokamak technology.**
- **Effort parallel with ITER.**