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

Blair P. Bromley
Computational Reactor Physics Branch
AECL – Chalk River Laboratories
CNS 2013 Annual Conference, Toronto, ON
Monday, June 10, 2013
2:00 pm – 2:25 pm
Introduction

- **Review – AECL & International Community.**
  - Accelerator-driven sub-critical systems (ADS).
  - Hybrid Fusion Fission Reactors (HFFR).

- **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.
    - $k_{\text{eff}} < 1.000 \ldots k_{\text{eff}} \sim 0.9$ 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 $\geq 1$ MeV.

2 Measured and calculated neutron yields and calculated heat production vs. proton energy for 20 cm diameter lead and fully depleted uranium targets$^{11}$. UNRESTRICTED / ILLIMITÉ
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**
\[
D + T \rightarrow \alpha(3.5 \text{ MeV}) + n(14.1 \text{ MeV})
\]

**T-PRODUCTION**
\[
^6\text{Li} + n_{\text{slow}} \rightarrow \alpha + T + 4.8 \text{ MeV} \\
^7\text{Li} + n_{\text{fast}} \rightarrow \alpha + T + n - 2.5 \text{ MeV}
\]

**BREEDING + BURNING**
\[
D + (1-a)^6\text{Li} + a^7\text{Li} \rightarrow 2\alpha + a\, n + (22.4 - 7.3a) \text{ MeV}
\]

Where \(a\) is number of T produced by \(^7\text{Li} + n\) 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 $\rightarrow$ higher Q.
  - $Q \sim 3$ to 4 is breakeven point (electrical output $\sim$ electrical input).
  - For a pure fusion reactor, $Q \geq 10$ necessary for practicality, economics
  - For HFFR, $Q \geq 1$ sufficient; typically $Q \leq 4$.
  - Thermal power in HFFR $2$ to $10 \times$ fusion power.
    - Breed and burn of fissile fuel in blanket; fast-fission of U-238 and/or Th-232.
**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 → (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 → (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).
  – 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 → 10,000 MWe of PT-HWR.

• Follow-up system studies & plans.
  – Smaller accelerators, other uses.
  – Staged, evolutionary development.
• 300 MW (1 GeV, 300 mA) proton beam on liquid Pb/Bi, \( \sim 4 \times 10^{19} \) 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
  - Laser Inertial Confinement (L-ICF).
  - Various alternative concepts:
    - Particle-beam ICF (ion, electron).
    - Reversed Field Pinch,
    - Compact Toruses, Field Reversed Mirrors
    - Linear $\theta$-Pinch, Long solenoid systems.
    - Dense Z-Pinch, Dense Plasma Focus.
    - LINUS (early variant of magnetized target fusion)

- 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 ($Q \sim 2$, $P_{\text{fusion}} \leq 300 \text{ MW}_{\text{th}}$, Total Power $\leq 1,400 \text{ MW}_{\text{th}}$)
  - Fissile fuel production $\sim 800$ to $1,000$ kg/year.
    - Would support $\sim 12$ 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 $\sim 40\%$ cost of AB, but:**
  - Estimated capital costs ($\sim$ $2.6B$ 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

- 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/metalllic); 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).

- Use of cyclotrons for proton acceleration.
- Emphasis on consumption of MAs (400 to 600 kg/year).
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<sub>th</sub>. 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<sub>2</sub> Blanket (2017)
  - CLEAR III to be 1.5 GeV, 10 mA, Pb/Bi, TRU/Zr Blanket (2032)
  - 1000 MW<sub>th</sub>, ~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\text{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.
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)
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....
  - 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
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-VOIT 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 $\geq 2$ 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**

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

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

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

**Converting**

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

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

**Breeding**

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

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

FOR THERMAL REACTORS $n_{235} \sim 2.05$

$n_{239} \sim 1.90$

$n_{233} \sim 2.25$
**Stages in Accelerator Breeder Development - Planned**

- **Evolutionary.**
  - ZEBRA, EMTF, PILOT
  - DEMO ~ ING

- **Use smaller stages for other applications.**
  - In situ burning of U-233 or Pu-239.

- **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.
• 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.
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.
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

<table>
<thead>
<tr>
<th>Target/Blanket Thermal Power</th>
<th>1520 MW&lt;sub&gt;th&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Power Generation</td>
<td>532 MW&lt;sub&gt;e&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Blanket Enrichment (%)</th>
<th>Production Rate (kg/d)</th>
<th>Fuel Costs ($/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pu239</td>
<td>1.6</td>
<td>3.4</td>
<td>183</td>
</tr>
<tr>
<td>U233</td>
<td>3.2</td>
<td>2.3</td>
<td>261</td>
</tr>
</tbody>
</table>
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.
- Must include lithium blanket region for tritium production.
- Uranium blanket enhances neutron multiplication due to fast fission of U-238 and \textit{in situ} fission of Pu-239.
- Laser-Driven Inertial Confinement Hybrid Fusion-Fission System.
- Alternating regions of thorium, uranium and lithium for breeding.
Tokamak Fusion Reactor

- Mainstream concept.
- Source of fusion neutrons to drive fertile blankets.
**AECL – HFFR Blanket Studies**

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

### Table

<table>
<thead>
<tr>
<th>ZONE</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATOM</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
<td>SS</td>
</tr>
<tr>
<td>DENSITIES</td>
<td>0.00266 6^{Li}</td>
<td>0.00264 Zr</td>
<td>0.00204 Zr</td>
<td>0.00330 6^{Li}</td>
<td>0.000344 6^{Li}</td>
<td>0.00339 6^{Li}</td>
</tr>
<tr>
<td>(10^{24} cm^{-3})</td>
<td>0.02577 7^{Li}</td>
<td>0.02313 239^{U}</td>
<td>0.01474 232^{Th}</td>
<td>0.04124 7^{Li}</td>
<td>0.004236 7^{Li}</td>
<td>0.04124 7^{Li}</td>
</tr>
</tbody>
</table>

### Diagram

- **DISTANCE (cm):** 0, 3, 100, 102, 108, 126, 159, 192, 201
- **ZONES:** 1, 5, 6, 7, 8, 9, 10
- **"LITHIUM":** 4% SS, 96% Li metal
- **"GRAPHITE":** 4% SS, 10% Li metal, 86% C
- **"LITHIUM":**
- **"POINT" DT FUSION NEUTRON SOURCE (TYPE A):**
  - 40% SS, 70% Zr, 31.2% VOID
  - 60% Li metal, 13.3% SS, 31.2% VOID

"FIRST WALL" "URANIUM" MULTIPLIER "THORIUM"
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.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>First Wall</th>
<th>&quot;Thorium&quot;</th>
<th>&quot;Lithium&quot;</th>
<th>&quot;Graphite&quot;</th>
<th>&quot;Lithium&quot;</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron absorption</td>
<td>0.066</td>
<td>0.819</td>
<td>0.674</td>
<td>0.263</td>
<td>0.021</td>
<td>1.845</td>
</tr>
<tr>
<td>Excess ( (n,2n) ) and ( (n,3n) ) neutrons</td>
<td>0.041</td>
<td>0.517</td>
<td>0.015</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.575</td>
</tr>
<tr>
<td>Fission neutrons</td>
<td></td>
<td>0.294</td>
<td></td>
<td>0.015</td>
<td>0.001</td>
<td>0.294</td>
</tr>
<tr>
<td>( ^6\text{Li}(n,\alpha) )</td>
<td>0.039</td>
<td></td>
<td>0.657</td>
<td>0.231</td>
<td>0.021</td>
<td>0.948</td>
</tr>
<tr>
<td>( ^7\text{Li}(n,\alpha') )</td>
<td>0.026</td>
<td>0.097</td>
<td>0.003</td>
<td>0.001</td>
<td>0.127</td>
<td>0.680</td>
</tr>
<tr>
<td>( (n,\gamma) )</td>
<td></td>
<td>0.680</td>
<td></td>
<td></td>
<td>0.680</td>
<td>0.680</td>
</tr>
<tr>
<td>( (n,f) )</td>
<td></td>
<td>0.081</td>
<td></td>
<td></td>
<td>0.081</td>
<td>0.081</td>
</tr>
<tr>
<td>( (n,2n) )</td>
<td></td>
<td>0.259</td>
<td></td>
<td></td>
<td>0.259</td>
<td>0.259</td>
</tr>
<tr>
<td>( (n,3n) )</td>
<td></td>
<td>0.090</td>
<td></td>
<td></td>
<td>0.090</td>
<td>0.090</td>
</tr>
</tbody>
</table>

System balance: Sources = 1 + 0.575 + 0.294 = 1.869
Losses = Leakage + Absorption = 0.024 + 1.845 = 1.869

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

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.
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>
<thead>
<tr>
<th>Interaction</th>
<th>Zone</th>
<th>First wall (5)</th>
<th>Uranium Multiplier (6)</th>
<th>&quot;Thorium&quot; (7)</th>
<th>&quot;Lithium&quot; (8)</th>
<th>&quot;Graphite&quot; (9)</th>
<th>&quot;Lithium&quot; (10)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron absorption</td>
<td>0.077</td>
<td>0.636</td>
<td>0.850</td>
<td>0.730</td>
<td>0.206</td>
<td>0.047</td>
<td>2.546</td>
<td></td>
</tr>
<tr>
<td>Excess (n,2n) and (n,3n) neutrons</td>
<td>0.037</td>
<td>0.261</td>
<td>0.272</td>
<td>0.009</td>
<td>0.0003</td>
<td>0.0001</td>
<td>0.579</td>
<td></td>
</tr>
<tr>
<td>Fission neutron sources</td>
<td>-</td>
<td>0.851</td>
<td>0.166</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.017</td>
<td></td>
</tr>
<tr>
<td>T6: 6Li(n,ut)</td>
<td>0.049</td>
<td>-</td>
<td>-</td>
<td>0.713</td>
<td>0.181</td>
<td>0.046</td>
<td>0.989</td>
<td></td>
</tr>
<tr>
<td>T7: 7Li(n,n'ut)</td>
<td>0.024</td>
<td>-</td>
<td>-</td>
<td>0.060</td>
<td>0.001</td>
<td>0.001</td>
<td>0.086</td>
<td></td>
</tr>
<tr>
<td>232Th (n,γ)</td>
<td>-</td>
<td>-</td>
<td>0.757</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.757</td>
<td></td>
</tr>
<tr>
<td>232Th (n,f)</td>
<td>-</td>
<td>-</td>
<td>0.048</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.048</td>
<td></td>
</tr>
<tr>
<td>232Th (n,2n)</td>
<td>-</td>
<td>-</td>
<td>0.137</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.137</td>
<td></td>
</tr>
<tr>
<td>232Th (n,3n)</td>
<td>-</td>
<td>-</td>
<td>0.047</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.047</td>
<td></td>
</tr>
<tr>
<td>238U (n,γ)</td>
<td>-</td>
<td>0.383</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.383</td>
<td></td>
</tr>
<tr>
<td>238U (n,f)</td>
<td>-</td>
<td>0.217</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.217</td>
<td></td>
</tr>
<tr>
<td>238U (n,2n)</td>
<td>-</td>
<td>0.109</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.109</td>
<td></td>
</tr>
<tr>
<td>238U (n,3n)</td>
<td>-</td>
<td>0.058</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.058</td>
<td></td>
</tr>
<tr>
<td>235U (n,f)</td>
<td>-</td>
<td>0.006</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.006</td>
<td></td>
</tr>
</tbody>
</table>

System balance: Sources = 1 + 0.579 + 1.017 = 2.596
Losses = Leakage + Absorption = 0.051 + 2.546 = 2.597

233U breeding ratio = 232Th(n,γ) = 0.76
239Pu breeding ratio = 238U(n,γ) = 0.38
Blanket energy multiplication = 5.5
A low Q (~1.3), low-power (133 MW fusion) hybrid fusion reactor could make sufficient fuel (U-233) to support \( \geq 2,000 \text{ MWe} \) of PT-HWRs (U-233/Th with CR \( \sim 0.9 \), \( \sim 500 \text{ MWe} \)).
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.
Early Expectations (1981) for Tokamaks and Tandem Mirrors

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tokamak</th>
<th>Tandem Mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_T ) (cm(^{-3})·s)</td>
<td>( 3.3 \times 10^{13} )</td>
<td>( 7 \times 10^{10} )</td>
</tr>
<tr>
<td>( T_1 ) (keV)</td>
<td>7.1</td>
<td>.25</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.3</td>
<td>.2</td>
</tr>
<tr>
<td>( Q )</td>
<td>.02</td>
<td>(-)</td>
</tr>
</tbody>
</table>

\( a \), \( c \), \( d \), \( e \), \( g \), \( h \), \( i \), \( k \), \( f \), \( j \), \( l \)
Tandem Magnetic Mirror – MFTF-B

- Central solenoid + Baseball Field Coils at ends provides confinement.
Enhanced Confinement for Magnetic Mirrors – Field Reversed Configuration

- High angular plasma current creates opposing magnetic field.
- Compact torus created inside mirror for enhanced confinement.
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 |
|---------------------------------|-------------|
| plasma Q                       | 2.0         |
| length                         | 35 m        |
| radius                         | 2.0 m       |
| Central Cell                   |             |
| B                              | 2 T         |
| electron density               | ~5 x 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                     | ~2 x 10^{9} $ (U.S. 1980) |
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).

<table>
<thead>
<tr>
<th>Item</th>
<th>Item description</th>
<th>Fusion-Fission Blanket Option</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A(Th)</td>
</tr>
<tr>
<td>1a</td>
<td>Equivalent $^{233}$U breeding ratio B</td>
<td>0.68</td>
</tr>
<tr>
<td>2a</td>
<td>Fusion Power/RCU; i.e. (x/y) $\cdot$ MW(f)/GW(e)</td>
<td>57.5</td>
</tr>
<tr>
<td>3a</td>
<td>Fusion power for 7,3 RCU's i.e. production of 1 Mg $^{233}$U/a, 80% capacity $\cdot$ MW(f)</td>
<td>420</td>
</tr>
<tr>
<td>4a</td>
<td>Fusion power for 25 RCU's i.e. production of 3.4 Mg $^{233}$U/a, 80% capacity $\cdot$ MW(f)</td>
<td>1430</td>
</tr>
<tr>
<td>5a</td>
<td>Blanket energy multiplication factor</td>
<td>2.5</td>
</tr>
<tr>
<td>6a</td>
<td>Fusion-hybrid thermal power/RCU $\cdot$ MW$_H$(t)/GW(e)</td>
<td>126</td>
</tr>
<tr>
<td>7a</td>
<td>Fusion-hybrid thermal power for 7,3 RCU's i.e. production of 1 Mg $^{233}$U/a, 80% capacity $\cdot$ MW$_H$(t)</td>
<td>920</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Device</th>
<th>$P^*_f$</th>
<th>$P^*_b$</th>
<th>h</th>
<th>$h \cdot P^*_R$</th>
<th>Fissile Yield</th>
<th>Capital Cost $^3$, 1981 CAN $^9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tandem Mirror</td>
<td>813</td>
<td>1800</td>
<td>2.0</td>
<td>892</td>
<td>2.92 U</td>
<td>Estimated (E) 4.25 Allowed (A) 1.61 Ratio E/A 2.6</td>
</tr>
<tr>
<td>Tandem Mirror</td>
<td>873</td>
<td>1533</td>
<td>1.8</td>
<td>650</td>
<td>2.32 Pu</td>
<td>3.55 1.22 2.9</td>
</tr>
<tr>
<td>Tandem Mirror</td>
<td>580</td>
<td>1500</td>
<td>2.9</td>
<td>620</td>
<td>1.85 Pu</td>
<td>3.49 0.94 3.7</td>
</tr>
<tr>
<td>Standard Mirror</td>
<td>400</td>
<td>1715</td>
<td>2.6</td>
<td>603</td>
<td>2.0 Pu</td>
<td>2.59 0.95 2.7</td>
</tr>
<tr>
<td>Tokamak</td>
<td>1180</td>
<td>2250</td>
<td>5.6</td>
<td>1600</td>
<td>2.41 Pu</td>
<td>4.70 1.88 2.5</td>
</tr>
<tr>
<td>Tokamak</td>
<td>218</td>
<td>740</td>
<td>3.2</td>
<td>480</td>
<td>1.27 Pu</td>
<td>2.63 0.68 3.8</td>
</tr>
<tr>
<td>Laser</td>
<td>200</td>
<td>535</td>
<td>2.6</td>
<td>400</td>
<td>1.3 Pu</td>
<td>4.15 0.62 6.7</td>
</tr>
<tr>
<td>ICF</td>
<td>690</td>
<td>1245</td>
<td>3.8</td>
<td>817</td>
<td>1.81 Pu</td>
<td>2.83 1.09 2.6</td>
</tr>
</tbody>
</table>
• **Most ADS energy self-sufficient, or generate surplus power.**
  – 500 MW\textsubscript{th} to 3,000 MW\textsubscript{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\textsubscript{th}, molten salt (UCl\textsubscript{3}/ThCl\textsubscript{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.
• 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.

Roadmap of ADS Development in China

- Chinese Academy of Sciences (CAS) has been carried out an ADS Project, and plan to construct demonstrated ADS transmutation system ~ 2032.
- China LEad Alloy cooled Reactor (CLEAR) is selected as the reference design.

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

-2017 ADS Research Facility
  Accelerator: 50–150MeV
  Reactor: China Lead Alloy Cooled Research Reactor CLEAR-I (~5-10MW)

-2022 ADS Experimental Facility
  Accelerator: 0.6-1GeV/10mA
  Reactor: China Lead Alloy Cooled Experimental Reactor CLEAR-II (~100MW)

-2032 ADS Demonstration Facility
  Accelerator: 1.5-2GeV/10mA
  Reactor: China Lead Alloy Cooled Demonstration Reactor CLEAR-III (~1000MW)
Mainstream Magnetic Confinement Concepts

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

Two concepts for magnetic confinement:

**TOKAMAK**

**STELLARATOR**
HFFR in China – 2032 Goal.

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

Proposed Roadmap of Fusion-driven Hybrid Reactor Application

- Concepts and Design, Material and Technology R&D
- Hybrid Concept, R&D: Now~2015
- MFX (hybrid Test Reactor): ~2025
- SFB (hybrid DEMO): ~2030
- Power Plant: ~2050

• Waste Transmutation
• Fuel Breeder
• Energy Production

10~15 yr earlier