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

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Abstract

A review of work done by AECL and the international community on the topics of accelerator-driven sub-critical systems (ADS) and hybrid fusion-fission reactors (HFFR) is given, spanning the period of 1953 to 2012. ADS/HFFRs have applications in power production, fissile fuel breeding, consumption of minor actinides (MAs), transmutation of long-lived fission products (LLFPs), and production of tritium. AECL carried out pioneering studies in ADS for breeding from 1963 to 1982, while maintaining a "watching brief" on fusion technology, anticipating HFFRs as an early application. International work has focused on ADS for waste transmutation and HFFRs for fuel production, with excess power as a by-product.

1. Introduction

A review is given of work that has been done on the related topics of accelerator-driven sub-critical systems (ADS) and hybrid fusion-fission reactors (HFFR) in Canada by Atomic Energy of Canada Limited (AECL) and also within the international community over the time period of 1953 to 2012. This does not include the work done by AECL through the Canadian Fusion Fuels Technology Project (CFFTP) over the period of 1982 to 1997 [1]. Understanding past and recent work provides guidance on what options Canada may want to pursue in ADS/HFFRs for ensuring long-term energy security, while addressing environmental concerns about high-level radioactive waste. The development of HFFRs is an opportunity for an earlier and economic deployment of fusion technology.

ADS and HFFRs are similar in that both involve a neutron source that is used to bombard a surrounding sub-critical (k_{eff}<1.000) blanket. In an ADS, an accelerator is used to create a high-energy (e.g. ~1 GeV) beam of protons (H) or deuterons (D) which bombard a target (e.g., Pb, Bi, U, W, Hg, Be, Li, Tritium, etc.) to create high-energy neutrons (> 1 MeV) by the process of spallation [2] or by fusion reactions (such as $D+T \rightarrow {}^{4}He + n$). In the spallation process, typically 20 or more neutrons are released per incident proton or deuteron. Alternatively, in a HFFR, a fusion reactor may be used as a source of high-energy neutrons (e.g., 14.1-MeV neutrons from D-T fusion, or 2.45-MeV neutrons from D-D fusion ($D + D \rightarrow {}^{3}He + n$)). Such a fusion reactor would have a low Q value ($Q \leq 4.0$, Q = ratio of output fusion power / input electrical power), making it unfeasible or impractical for generating electricity on the basis of fusion energy alone, but would be quite satisfactory for a HFFR. Typically, a fusion reactor must have $Q \geq 4$ to become a net power producer, and $Q \geq 10$ (or much higher) to meet minimum criteria for being practical and economical.

Depending on what materials are used in the sub-critical blanket, the ADS/HFFR may be used for one or more of the following applications:

i) Power production through fission of fissile and fissionable isotopes, including fast fission of fertile isotopes (e.g. ${}^{232}Th$, ${}^{238}U$).

ii) Breeding of fissile isotopes (e.g., ${}^{233}U$, ${}^{239}Pu$) from fertile fuels.

iii) Destruction of MAs (e.g., isotopes of Am, Cm, etc.) by neutron capture and fission.

iv) Transmutation by neutron capture of LLFPs, which have a half-life > 1,000 years (e.g., ^{135}Cs, ^{129}I, ^{99}Tc, ^{93}Zr, etc.).

v) Production of tritium by neutron capture in ^{6}Li (and ^{7}Li with fast neutrons).

Depending on the design of the blanket and the balance of plant, the ADS/HFFR may be a net producer, or consumer of electricity. In the ADS/HFFR, electrical power is re-circulated to operate the accelerator (or fusion reactor); excess power (if any) is fed to the grid. As a fuel breeder, an ADS/HFFR would serve the same role as a breeder reactor and would complement and provide fissile fuel for existing and advanced converter power reactors. As a transmutation system, an ADS/HFFR would help eliminate the inventory of MAs and LLFPs from spent fuel that must go into long-term storage. Radiological hazards for shorter-lived radio-isotopes (such as ^{90}Sr and ^{137}Cs) last at least 300 years, whereas the hazards for LLFPs and MAs last more than 100,000 years.

2. AECL Work

A brief history of the work done by AECL- Chalk River Laboratory (CRL) from 1963 to 1982 on the topic of accelerators and fusion reactors is shown in Reference [3]. The term "electronuclear breeding" is used in many of AECL's early reports, and refers mainly to ADS for breeding fissile fuel, but also includes HFFRs. The electronuclear breeder was considered by AECL to be an attractive alternative to using a reactor-based breeder system to ensure long-term fissile fuel supplies and energy security. Concerns about capital costs and the availability of cheap uranium eventually made the electronuclear breeder unattractive to government and industry in the short-term and was discontinued.

2.1 Accelerator Breeders

The main AECL project was the Intense Neutron Generator (ING) (1963-1969) [4], which was to serve as a driver for an accelerator breeder system. The ING project was cancelled in 1969, but there were several smaller-scale follow-on technical and economic studies carried out until the mid-1980s [5], anticipating that the accelerator breeder initiative would be revived, along with other applications for accelerator-based neutron sources [6]. It was envisioned that an accelerator breeder would provide start-up and topping fissile fuel for high-conversion pressure-tube heavy water reactors (PT-HWR) operating on the $^{233}U/^{232}Th$ cycle, in a symbiotic relationship.

The ING would have used a multi-stage linear accelerator, ~0.5 to 1 km long, to produce a 1-GeV, 300-mA (300 MW) proton beam hitting a flowing liquid Pb/Bi target to produce spallation neutrons (~4×10^{19} n/s). The spallation neutrons would hit a surrounding sub-critical blanket containing ^{238}U and/or ^{232}Th with some initial enrichment of fissile fuel (~1.6 wt% to 3.2 wt%). The blanket would utilize technology developed for sodium-cooled fast breeder reactors, although other design permutations involving PT-HWR-type lattices or molten salts were also considered. The fissile production rate would be ~700 to 1,200 kg per year of ^{239}Pu (or ^{233}U), which would be sufficient to support ~1 GW_e of increased capacity, or topping enrichment for ~5 to 10 GW_e of reactors with a conversion ratio > 0.90 (e.g., a PT-HWR), with full recycling of spent fuel. This ADS (see Figure 1) would be electrically self-sustaining (532 MW_e / 1,520 MW_{th}); increased power could be feasible by using higher initial enrichment in the blanket along with *in situ* burning of bred fuel.

A progressive four-stage / four-device ADS development program was proposed [5]. Each stage of development was intended to provide a spallation neutron source for various applications (potentially including fusion reactor components irradiation testing and tritium production), and would be a building block for the subsequent stage. Stage 1 was to be ZEBRA (Zero Energy BReeder Accelerator), a 10-MeV, 300-mA proton accelerator, to be used for target testing and proving various accelerator component technologies. Stage 2 was EMTF (Electro-nuclear Materials Testing Facility) a 200-MeV, 70-mA proton accelerator with a Pb/Bi target, which would provide up to 20% of the desired full-scale beam power, and would be used for testing target and blanket materials and components. Stage 3 was the Pilot facility (1-GeV, 70-mA, Pb/Bi target), which would include a fissile/fertile blanket (~430 MW_{th}), and a power conversion system to generate ~150 MW_e. The Pilot would be used to acquire the engineering and technical data needed to design a full-power target/blanket. Stage 4 was the DEMO (300 mA, 1 GeV) prototype commercial plant, and would generate 1,500 to 1,900 MW_{th} in the blanket, with a gross power of ~500 to 650 MW_e. Up to 110 MW_e of excess power would be sent to the grid for additional revenue to offset the operational costs of the facility. Preliminary cost analyses indicated that the DEMO facility would cost ~$1.5 Billion (1981), and the fissile fuel produced would be ~3 to 4 times the 1981 cost of ^{235}U (~$48/gram) from an enrichment facility.

2.2 Fusion Watching Brief and HFFR Blanket Studies

AECL devoted less effort to fusion reactors, and kept a "watching brief" on international developments during the late 1960s through to the early 1980s. AECL carried out reviews of various fusion reactor technologies to assess their potential as pure stand-alone fusion reactors, including both magnetic and laser inertial confinement fusion systems [7]. Numerous assessment reports on fusion were prepared and issued by the Physics Advanced Systems Study (PASS) group at CRL. AECL was engaged as a partner in the Canadian Fusion Fuels Technology Project (CFFTP) during the late 1980s and the 1990s [1], focusing on the production and handling of tritium.

As a parallel, but smaller scale initiative to the ADS program, AECL spent some effort performing a number of analytical and economic studies of HFFRs for breeding fissile fuel for PT-HWRs, focusing on neutronic analyses of fertile blankets [8], [9]. Many of these analyses were generic, and applicable to HFFRs using either inertial or magnetic confinement systems (See Figure 2). The attraction of the HFFR was its potential to produce high-energy fusion neutrons and to breed fissile fuel with lower capital costs, provided that the fusion fuel confinement time, density and temperature could be increased simultaneously in a system such that $Q \geq 1$.

After an extensive period of investigation by AECL's Fusion Status Study Group, a comprehensive analysis and assessment report [9] was issued on the technological and economic outlook for HFFRs as breeders. The following were key observations and lessons:

i) Fusion reactors considered for neutron sources included Tokamaks (see Figure 4 a)), Tandem Magnetic Mirrors (see Figure 3), Laser-based Inertial Confinement Fusion (L-ICF) (see Figure 4 c)), and various alternative concepts (e.g., particle-beam ICF systems, Reverse Field Pinch, Compact Toruses, Field-Reversed Mirror, Linear Theta-Pinch, Long-Linear Solenoid Systems, LINUS, Dense Z-Pinch, Plasma Focus, etc.)
ii) All fusion concepts face physics/engineering problems that may make them fail to achieve the required performance, or would render them impractical to maintain and operate. Thus, HFFRs may be viable even if pure fusion systems are not.

iii) The advantage of the L-ICF is that the driver system (the laser bank) can be isolated from the reactor system, facilitating easier maintenance. However, L-ICF suffers from low laser efficiency, and engineering difficulties associated with target focussing and high repetition rates.

iv) In 1981, both Tokamaks and Tandem Mirrors were expected to be able to achieve breakeven (Q>1), although the Tandem Mirror was noted to be a potentially more practical fusion reactor for an HFFR, given its simpler, cylindrical geometry and steady-state operation (see Figure 3).

v) HFFRs were expected to serve a dual purpose, producing fuel and power simultaneously.

vi) An HFFR plant would be expected to provide sufficient fissile fuel to support ~12 GW_e of power from PT-HWRs with a conversion ratio >0.9, operating on the $^{233}U/^{232}Th$ cycle with full recycling of spent fuel. HFFR fissile fuel production would be ~800 to 1,000 kg/year. Total HFFR power (fusion + fission) would be ~900 to 1,400 MW_{th}. Fusion power would be ~200 to 300 MW_{th}. The Q value would be ~2, although higher values would improve economics.

vii) The most economic HFFR would be one designed to produce ^{233}U from ^{232}Th, with fission suppression; however, if the capital costs were dominated by the fusion reactor component, then a $^{239}Pu/^{238}U$ blanket was preferred, because the higher fast fission rate of ^{238}U and ^{239}Pu production rate (relative to ^{232}Th fast fission and ^{233}U production). The associated fuel production and electricity revenue would offset capital costs of the fusion reactor component.

viii) The HFFR was expected to be able to produce fissile fuel at ~40% of the cost of the ADS, due to the higher neutron and power production relative to electrical input.

ix) In 1981, estimated capital costs of HFFRs (~$2.6B to $4.7B, depending on design) exceeded the allowed capital costs (~$0.6B to $1.9B) by a factor of ~2.5 to 3.8, suggesting that the HFFR was not yet economically competitive.

x) If the cost of ^{235}U were to increase by a factor of 3 to ~$140/gram (1981), then the hybrid breeder would be economical. However, it was recognized that estimates for capital costs will have high uncertainties until an actual prototype is built.

3. International Work

In the late 1940s, when the world supply of natural uranium was less assured, it was conjectured in the U.S.A. that a combination of fast breeder reactors and electro-nuclear breeders (using ADS and/or HFFRs) would be needed to create reliable supplies of ^{239}Pu and ^{233}U. Early efforts at the Lawrence Livermore National Laboratory (LLNL) investigated ADS with the MTA (Material Testing Accelerator) program which existed from 1949-1954 [12], and nearby groups looked at a simple mirror-type HFFR [13]. These efforts were discontinued by the mid-1950s after new discoveries of uranium ore deposits were found, and given projections that breeder reactors would be more economical. The situation would change again with emerging issues, starting in the early 1970s.

3.1 Accelerator Driven Systems for Breeding and Waste Transmutation

Researchers at BNL, LLNL, and ORNL investigated ADS for breeding in the 1970s [14], corroborating the early work by AECL, with very similar designs. By the late 1980s, the ADS was given serious consideration for MA/LLFP transmutation, radio-isotope production, and high-energy/high-flux irradiations, as an alternative to reactors. Since the 1990s, there have been numerous computational, experimental, scoping, benchmarking, and design studies [15], [16]. Experimental facilities (large and small scale) have been built at national research laboratories, and at a number of universities, with significant work being carried out in the U.S.[17], Europe [18], Japan [19], [20], Russia [21], and China [22]. Much of the international development work, particularly with regards to the accelerator and target design, parallels the staged development program proposed earlier by AECL [5].

Highlights from 1991 to 2000 include:

i) Use of ADS could reduce the hazards of MA/LFFPs to that of uranium ore after a decay period of less than 100 years.
ii) Proposed ADS systems use 4 to 250 mA of 1 to 3 GeV proton beams on liquid Pb/Bi or solid W targets, using RFQ, DTL, and CCL accelerator components. Beam powers ~10 MW to 500 MW; sub-critical reactor power ~900 MW_{th} to 1,500 MW_{th}. Blanket fuels in the form of solid (oxide or metal alloy) with clad, molten salts, liquid metals, particle suspensions, slurries, and aqueous solutions were considered. Fast assemblies of Pu or MOX cooled by He gas or liquid Na were also analyzed.
iii) ADS designs were expected to be able to transmute MAs from up to 10 LWRs (~1 GW_e each).
iv) Nobel Laureate Carlo Rubbia (CERN) proposed the Energy Amplifier (EA) [16], a multi-purpose ADS for transmutation, breeding, and power generation. EA-1500 design features included: multi-stage cyclotrons and super-conducting RF cavities, 1.5-GeV protons on a Pb target, pool-type sub-critical fast reactor (k_{eff}~0.97), Th/TRU blanket fuel (oxide and/or metallic), up to 120 GWd/t burnup, molten Pb coolant, 1,500 MW_{th} / 675 MW_e, ~400 kg/year of TRU incinerated.

Highlights from 2001 to 2012 (since the beginning of the "Nuclear Renaissance") include:

i) The majority of accelerator-driven system concepts involve using a large linear accelerator (nearly 1 km long) to create 1-GeV to 2-GeV protons (with beam currents ranging from ~1 mA to 300 mA) to hit a liquid Pb/Bi target to create spallation neutrons, which then bombard a surrounding blanket. The neutron yield is expected to be ~20 neutrons per proton.

ii) Numerous ADS blanket designs were considered, using ^{232}Th, NU, MOX, SNF (spent nuclear fuel), and partitioned MAs and LLFPs as materials for neutron bombardment. Numerous fuel forms (solid oxide or metal alloy with clad, pebble-bed, coated particle in suspension, molten salts (fluoride or chloride salts), aqueous solutions) and coolants (e.g., liquid metal, molten salt, gas) were investigated.

iii) For continuous reprocessing of the irradiated blanket, the use of molten salts may be advantageous; however, commonality with fast reactor technology lead to a preference in using a Pb-based liquid metal coolant with either cladded solid fuel pins, or coated particles suspended in the lead coolant. Use of pebble bed fuels in a gas-cooled blanket is another potential, lower priority option.

iv) A fast spectrum is preferred for maximizing transmutation and minimizing fissions in ^{233}U. Thus, metallic-alloys are preferred over oxide fuels to reduce thermalization of neutrons.

v) Most ADS concepts are intended to be energy self-sufficient and to generate surplus power to send to the grid. A large-scale ADS (500 MW_{th} to 3,000 MW_{th}) would be expected to be able to transmute 200 kg/year to 1,200 kg/year of MAs, up to 400 kg/year of LLFPs, or produce 100 kg/year to 600 kg/year of fissile fuel. Depending on the exact design features, an ADS would be able to consume the annual MA/LLFP production from 5 to 10 LWRs (~1 GW_e each), corroborating results from earlier studies in the 1990s [15], [16].

vi) There are only a few larger-scale experimental ADS devices in the world, located at national research laboratories and universities. The largest, most significant ones are the Spallation Neutron

Source (SNS) (1 GeV, 1 mA protons on an Hg target) operating at ORNL since 2007 [23], and the MYRRHA (600-MeV, 3.2-mA proton beam, Pb/Bi target, MOX blanket, 100 MW_{th}) to start in 2014 at SCK-CEN in Belgium [24]. China is actively pursuing ADS development, coupled with fast reactor technology with its proposed CLEAR projects (CLEAR III is to be 1.5 GeV, 10 mA, Pb/Bi target, TRU-Zr)-Zr blanket, 1000 MW_{th}, ~400 kg/yr of MA's transmuted) [25].

v) Researchers at BNL, INL, and Texas A&M University [17], are developing an accelerator-driven sub-critical molten salt (ADSMS) fission reactor concept for power generation and MA destruction in SNF. The proton driver is a multi-beam isochronous cyclotron stack that can deliver multiple beams (~2.5 MW each) of 800 MeV protons with total power >10 MW to drive fission in a sub-critical core (at 400 MW_{th} or higher). The core consists of a 600-800ºC molten salt eutectic of either UCl_3/NaCl or $ThCl_3$/NaCl, allowing a faster spectrum. Pairing the ADSMS with conventional fission reactors could extract 10 times more energy from SNF. Continuous removal of poisons (such as Cl-35) allows it to operate to > 50% burnup without intervention. An ADSMS core with U-based fuel could burn spent nuclear fuel without re-processing, and a Th-based ADSMS core could reduce minor actinides by a factor of 10,000.

vi) Researchers at ANL examined the use of ADS transmutation for the disposal of the U.S. SNF inventory [26]. It was found that that four large-scale ADS units operating for ~33 full power years could dispose of the U.S. SNF inventory (~70,000 tonnes) expected by 2015.

vii) While there is high confidence in ADS, given that there has been extensive development in large accelerators for research applications and smaller-scale accelerators for medical and industrial applications, it is expected that much engineering R&D is still required to make a large-scale ADS (including the accelerator, target, and blanket components) more energy efficient, practical, reliable and economical [27], [28].

3.2 International Work on Hybrid Fusion-Fission Reactors

Small-scale studies on HFFR's during the 1960s were more of an addendum to mainstream fusion reactor research. Greater interest in HFFRs arose during the 1970s, particularly at LLNL and MIT. This was motivated by concerns about the status of fusion technology development, with difficulties in achieving sufficient confinement time at the required fusion fuel densities and temperatures for a pure fusion reactor. The HFFR was a "bridge technology" that would allow net power generation and a first-generation deployment of practical fusion reactors. Although HFFRs would share a number of the problems and difficulties of both fusion and fission reactors, they would also have some unique advantages relative to both, and could be used as an alternative to the ADS. There are two main time periods for HFFR work: 1971-1982, and 1983-2012. The latter period is when there was a consolidation of fusion research programs worldwide, with R&D efforts focusing mainly on Tokamak and L-ICF technologies, and also when the ITER project emerged.

From 1971 to 1982, various studies on hybrid reactors using magnetic mirrors, Tokamak devices, L-ICF systems and other devices were carried out, mainly in the U.S.A. and Russia. Studies also included economic analyses, comparing HFFRs, ADS and fast breeder reactors. Highlights include:

i) Performance data from experimental magnetic mirror devices demonstrated $Q \geq 1.5$ should be feasible (sufficient for HFFRs), although $Q \geq 10$ would be challenging without enhancements.

ii) PNL studies [29] suggested that HFFRs could be economically competitive with fast breeders.

iii) LLNL/UCRL carried out several conceptual design studies for both tandem-mirror [30] and L-ICF hybrid systems [31]. The performance requirements for an L-ICF in an HFFR were reduced by an order-of-magnitude. The tandem magnetic mirror (see Figure 3) was considered an excellent driver for an HFFR because of its cylindrical geometry and steady state operation with excellent prospects for development. A single HFFR (~4000 MW_{th}) could support from 6 GW_e to 47 GW_e of fission reactors. The highest support ratio is obtained using a molten-salt thorium blanket with continuous reprocessing, and a fleet of high-conversion reactors operating on the $^{233}U/^{232}Th$ cycle. These results were reaffirmed by Dolan [10] who suggested that HFFRs could be economical with Q~2.
iv) An IAEA survey [32] considered mirror and Tokamak-based HFFR designs, with one design producing ~2,000 kg fissile fuel/year, which could support 4 GW_e to 20 GW_e of power reactors.
v) A U.S. DOE status report [33] concluded that nominal electricity costs of HFFRs (coupled with reactors) were 25% cheaper than fast breeder reactors, which were ~40% lower than ADS breeders. To reduce recycling costs, solid fuel elements should be irradiated in the HFFR to build up the fissile content to ~4 wt%, and then transferred for direct use in a conventional reactor, but alternative clad materials would be required, as zirconium alloys would suffer too much damage.

During the 1980s, there was less activity on HFFRs, with a focus on pure fusion systems. During the same period there were reductions in government R&D funding for fusion. This situation started to change during the 1990s, with renewed interest in hybrids, then growing significantly since the year 2000, especially in China [22], the U.S.A. [35], [36], [37], Russia, and South Korea [38]. The majority of activities were proposals, conceptual design studies and associated scoping calculations for HFFRs based primarily on the Tokamak and L-ICF. This was motivated by the accumulated R&D progress, and the final site selection (near CEA-Cadarache in France) and international agreements signed for the ITER project [39] (See Figure 4 a)). In addition, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), which is a large-scale experimental facility to demonstrate net fusion power gain in an L-ICF system was completed after a construction period of ~12 years, with the first large-scale commissioning experiments starting in 2009. The tandem magnetic mirror concept for fusion was dropped by the U.S. in 1986 with the cancellation of the MFTF-B project (Mirror Fusion Test Facility – B) (see Figure 3) in favour of the Tokamak reactor concept, and hence the associated work on hybrid mirror reactors was also abandoned. However, since 2004 there has been a renewed interest in the use of magnetic mirrors for HFFRs [40], [41], again, due to their geometric simplicity, with related work going on in both Russia and Japan. A few highlights over 1983-2012 include:

i) Manheimer [42] argued that a Tokamak-HFFR would be more economical than a pure Tokamak system. The optimum design would use a thick (~150 cm) mixed molten salt blanket (UF_4-ThF_4-BeF_2-LiF), using an ITER-type reactor (~1.5 GW of 14-MeV DT neutrons) as the driver.
ii) Researchers in China [22], [43] reported on scoping studies for experimental and prototype large-scale Tokamak-HFFR's (See Figure 4 b)) with blankets made from U, Pu, MAs, and LLFPs. HFFRs are viewed as a parallel development to pure fusion systems. Different poloidal blanket modules are to be used, with a dual-cooled blanket (DCB). Pu and MAs are to be in carbide form, coated particles in a pebble bed, and cooled with 83%Pb/17%Li. LLFPs are to be coated particles in a pebble bed cooled by helium. Graphite and SiC are used for particle coatings and pebbles.
iii) Researchers at LLNL [45], [46] proposed updated conceptual designs for a hybrid fusion-fission reactor using laser-based inertial confinement fusion, based on the accumulated knowledge and experience in ICF at LLNL since the 1970s, and recent progress on the NIF. The Laser Inertial Fusion Energy (LIFE) engine (see Figure 4 c)) is a new fusion energy system being developed at

LLNL [47]; it could be used as a neutron source for a hybrid system (see Figure 4 d)). It was proposed to use LIFE to support a once-through, closed fuel cycle HFFR. LIFE is used to drive a sub-critical fission blanket to extract most of energy (up to 99%) out of fissile/fertile fuel. Designs using solid PuO_2 or ThO_2 in pebble-type fuel in the blanket and cooled with molten salt were examined. The intent was to use the irradiated pebbles directly in an HTGR, to avoid chemical reprocessing, although the reactor support ratio would be lower (~2 reactors).

4. Conclusions

ADS systems have a high probability for technological success [28]. Within the next 40 years, it is expected that several nuclear nations (e.g., the U.S.A., Europe, Russia, China and Japan) will construct at least one large-scale ADS for MA/LLFP transmutation, to help reduce the inventory and costs associated with the long-term storage of high-level radioactive waste. Technological innovations have the potential to reduce ADS capital and operational costs associated with the accelerator, target, and blanket components. An interesting example of this is the recent work in Japan [20], where a multi-stage DC accelerator for a D-Be neutron source is under investigation.

In spite of the added system complexity with a fissile/fertile blanket, it would seem that HFFRs will be more economical than a pure fusion system [42], given that the technological and performance requirements of the fusion neutron source in the hybrid system are reduced. Higher net fissile fuel production rate of HFFR's, shorter doubling time for fuel (months vs. years) and the larger support ratio of thermal reactors in comparison to fast breeder reactors make the HFFR potentially advantageous to develop [48], [49]. China may develop a HFFR prototype by 2030 to 2050 [22].

There is a push within the international community to develop more modularity, with the capability of rapid and periodic replacement of components in Tokamak and Laser-ICF systems [47]. This approach is being taken to address concerns about capital and operational costs associated with their inherent geometric complexity. Engineering, performance, and operational challenges for Tokamaks were recognized and anticipated more than 30 years ago [50], and they appear to remain [51], [52].

An economical HFFR will require a fusion reactor that is simple to engineer, while meeting the desired Q values ($Q \sim 2$ to 4), and will preferably be a steady-state system to minimize the thermal cycling of components. Alternative fusion concepts have been proposed in the past [50] and could potentially be adapted for use in a hybrid system. One candidate is the magnetic mirror (see Figure 3), which was abandoned by the U.S. in the 1980s due in part to R&D budget cuts, although small-scale R&D has continued in Russia and Japan [53]. Its cylindrical geometry lends itself to easier fabrication, maintenance and operation, along with the incorporation of a blanket [48].

To avoid added operational costs and complexity in the short-term, it may be preferable to design first-generation HFFRs that use solid-fuel blankets that do not require chemical reprocessing of irradiated fissile/fertile fuel [36], [46], [54]. The tradeoff is that the fission reactor support ratio will be reduced. The evolutionary shift to a liquid fuel blanket system with continuous removal of bred fissile fuel and fission products would enable a dramatic increase in the support ratio for HFFRs.

Accelerator-driven systems and hybrid fusion-fission reactors offer potential long-term benefits, by the transmutation of MAs and LLFPs, production of fissile isotopes for nuclear fuel, and direct generation of electrical power. Such systems could help enhance energy safety and security, while protecting the environment through the reduction in high-level radioactive waste.

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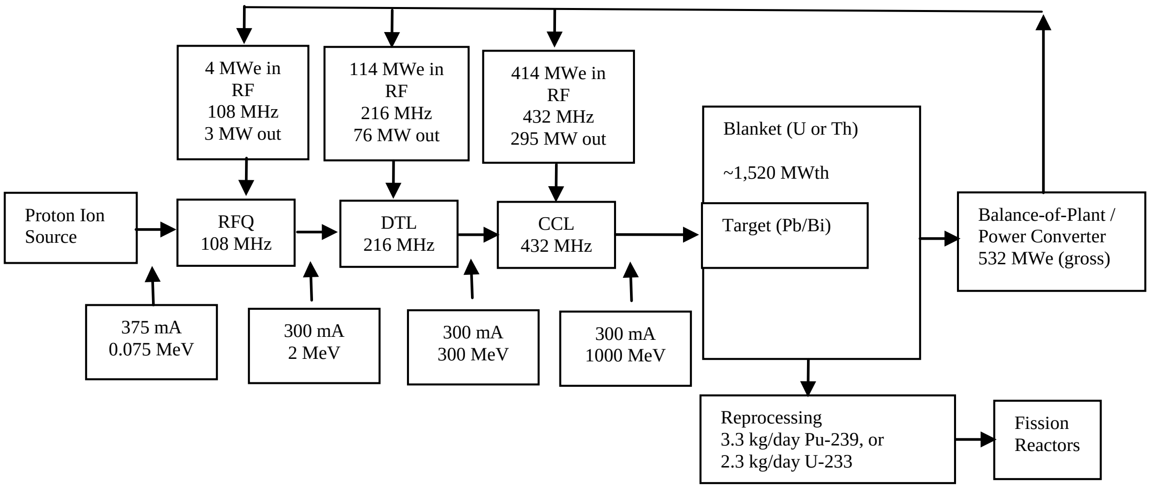


RFQ = Radio Frequency Quadrupole, DTL = Drift Tube Linac, CCL = Coupled Cavity Linac

Figure 1 Block Diagram of AECL’s 1982 Accelerator Breeder Concept (adapted from [5])

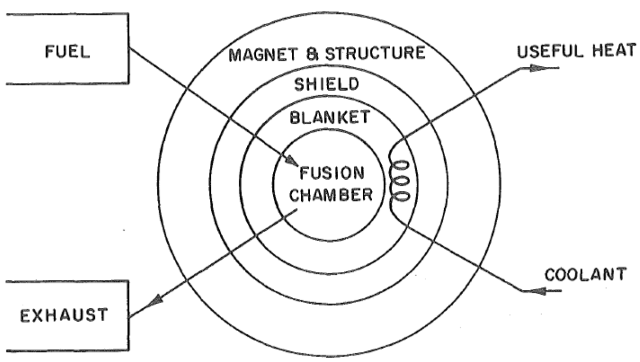
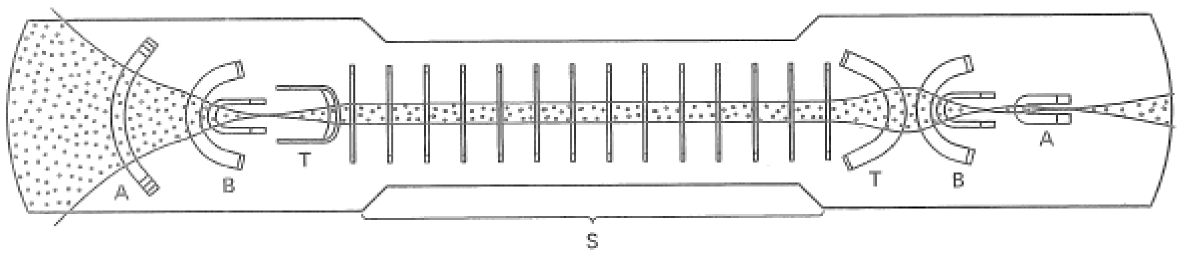
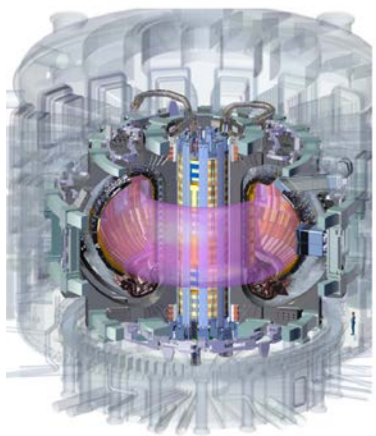


Figure 2 Conceptual Illustration of Fusion-Fission Hybrid Reactor [2]

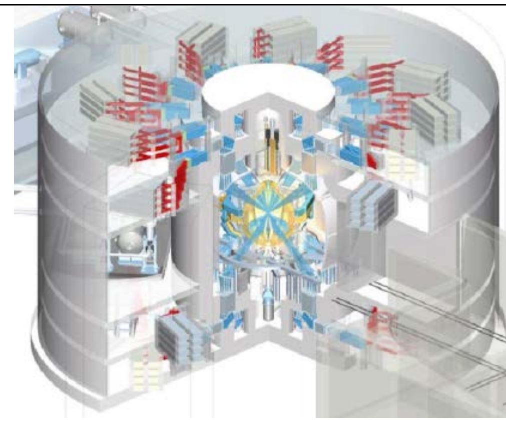


A= Auxiliary End Coil, B= Minimum-B Mirror Coil, T=Transition Coil, S=Central Solenoid

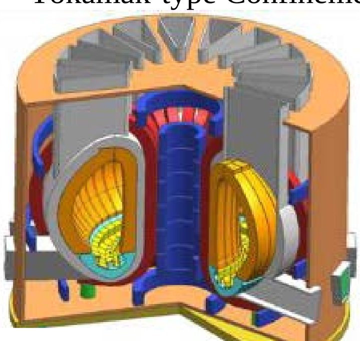
Figure 3 Plan View of MFTF-B Tandem Magnetic Mirror Fusion Reactor ([10], [11])



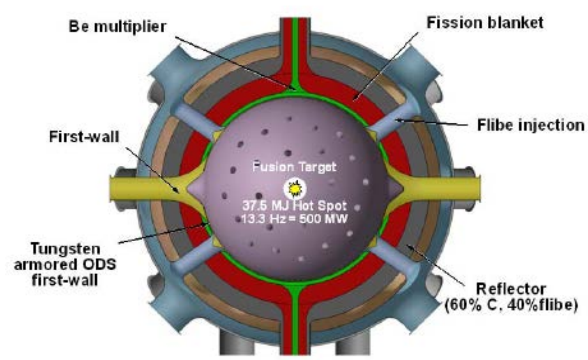
a) ITER – Tokamak-type Confinement [39]



c) LIFE / Laser-based Inertial Confinement [47]



b) Hybrid System Based on Tokamak [22]



d) Hybrid System Based on LIFE [46]

Figure 4 Mainstream Fusion Reactor Concepts for Potential Adaptation for Hybrid Systems

6. Acknowledgements

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