ACCELERATOR-DRIVEN THORIUM-CYCLE FISSION: GREEN NUCLEAR POWER FOR THE NEW MILLENNIUM

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In thorium-cycle fission, fast neutrons are used to transmute thorium to fissionable ^{232}U and then stimulate fission. In accelerator-driven thorium-cycle fission (ADTC) the fast neutrons are produced by injecting a symmetric pattern of seven energetic proton beams into a Pb spallation zone in the core. The fast neutrons are adiabatically moderated by the Pb so that they capture efficiently on ^{232}Th, and fission heat is transferred via a convective Pb column above the core. The 7 proton beams are generated by a flux-coupled stack of superconducting isochronous cyclotrons, utilizing a novel form of superconducting rf cavity for acceleration. ADTC offers a green solution to the Earth's energy needs: the core operates as a sub-critical pile and cannot melt down; it eats its own long-lived fission products; a GW ADTC core can operate with uniform power density for a 7-year fuel cycle without shuffling fuel pins, and there are sufficient thorium reserves to run man's energy needs for the next 2000 years.

1. Thorium-cycle fission as a green energy technology

Thorium is the most abundant element beyond lead in the periodic table. It is found in abundance in a number of mineral deposits, notably as monazite sand filling entire deserts and beaches in India and Brazil. The dominant isotope ^{232}Th is stable against spontaneous fission, but it can be transmuted into the fissionable isotope ^{233}U by fast neutron capture (Figure 1a). In 1950 Ernest Lawrence proposed that proton beams could be used to efficiently produce the needed fast neutron flux by spallation on lead (Figure 1b) and thereby harness thorium as an abundant resource for fission power without the need for isotope separation[1]. Such spallation is used today to produce fast neutron beams for research, but it has never yet been harnessed to drive practical fission cores for nuclear power generation. The estimated world reserves of thorium total 2.2 million tons[2]; the present world energy consumption could be provided by ADTC using ~1,000 tons/year; so ADTC could provide the world's energy needs for the next two millennia.

In 1995 Carlo Rubbia proposed a concept for accelerator-driven thorium-cycle (ADTC) fission power in which a ~800 MeV proton beam is injected into a fission core consisting of thorium fuel pins arranged in a molten lead bath[3]. The Pb bath serves

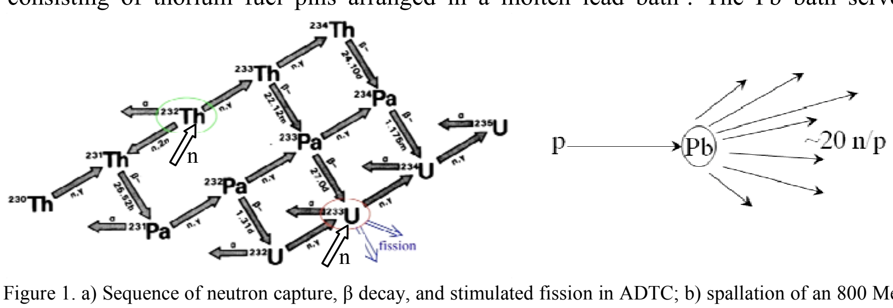


Figure 1. a) Sequence of neutron capture, β decay, and stimulated fission in ADTC; b) spallation of an 800 MeV proton on a lead nucleus to produce ~20 fast neutrons.

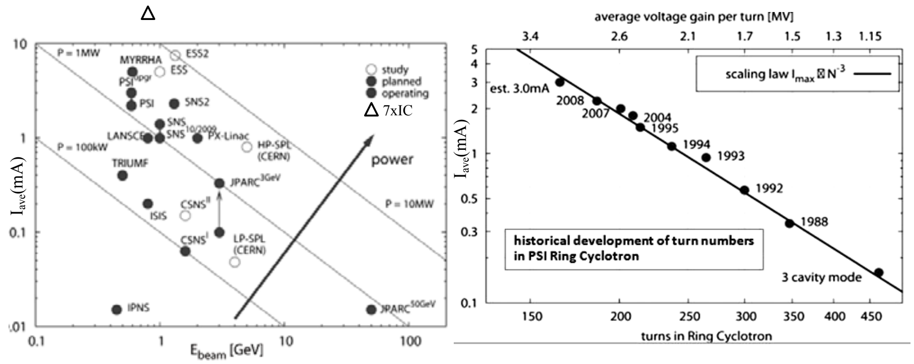


Figure 2. a) Beam current and energy for present and planned high-power proton accelerators and for our ADTC design (7xIC); b) dependence of beam current upon number of orbits in the PSI isochronous cyclotron[6].

multiple functions: *spallation target* to produce fast neutrons, *adiabatic moderator* to gradually reduce the energy of each neutron in successive scatterings to enhance capture on the thorium fuel, and *convective transfer* to transfer heat from fission in the core to steam coils located above the core. Rubbia showed that the adiabatic energy steps by which neutrons slow as they scatter from Pb nuclei maintains equilibrium amongst the fission fragment species and prevents the accumulation of long-lived waste isotopes in the core. This feature is only possible when fission is driven by fast neutrons in a heavy-nucleus moderator, and eliminates a problem that plagues all thermal fission reactors.

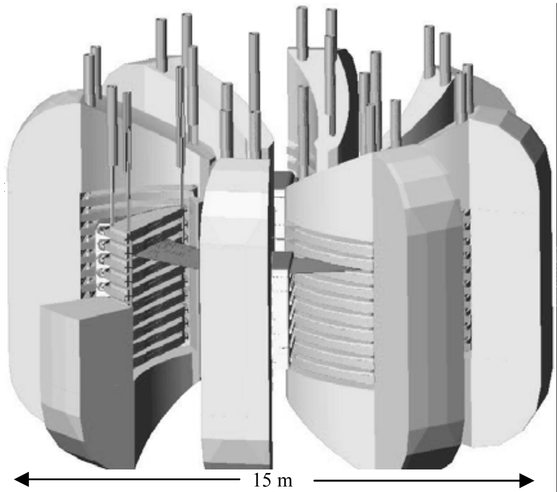
Although Rubbia's concept demonstrated several elegant features of ADTC fission, it did not address several daunting challenges:

A 1 GW ADTC core requires ~10 MW of continuous proton beam. No single accelerator has ever produced that much *beam power* (see Figure 2a).

The fission products that accumulate in the fuel pins are significant absorbers of fast neutrons. If a single proton beam were injected on the central axis of a fission core, *neutron absorption by fission products* would turn off fission in the outer region of the core so fuel pins would have to be shuffled frequently to maintain operation.

Accelerators do not typically operate with the *reliability* that is required for a fission power reactor. Sudden cessation of neutron drive could thermally shock the fuel pin structures and complicate the interface of ADTC for electric power production.

Since that time several accelerator designs have been proposed for ADTC, aimed to deliver the necessary 10 MW beam power in a single beam, some designs based upon superconducting linacs[4], and some upon cyclotrons[5]. The current state of the art for high-power proton accelerators is the 650 MeV isochronous cyclotron (IC) at PSI[6], which produces 2.5 mA beam current, 1.6 MW continuous beam power. The highest-power superconducting linac is the 1.0 GeV SNS[7], which has a design current of 1.4 mA, currently operates with 0.87 mA, and is planning upgrades to ~4 mA. Thus there is today no operating accelerator capable of generating a single beam with the power required for a GW ADTC power plant.



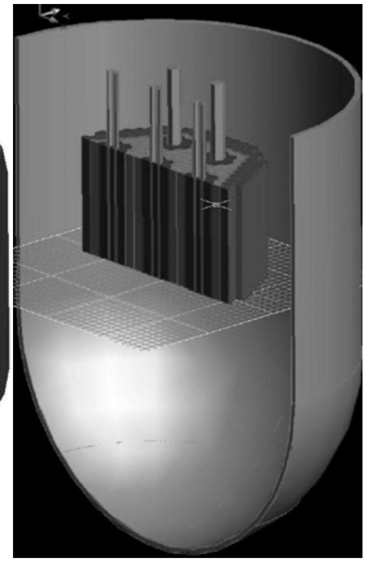


Figure 3. GW ADTC design: a) flux-coupled stack of seven 800 MeV isochronous cyclotrons; b) cross section through Pb-moderated core with seven drive beams.

Figure 2b illustrates an important aspect of the accelerator physics of cyclotrons: the attainable beam current scales as N^{-3}, where N is the number of orbits made by the beam from injection to extraction. This scaling arises from the shift of the betatron tune at injection (produced by the lens action of the space charge depression in the beam, which in turn is proportional to the local circulating charge density) and also to the separation of orbits at extraction. Both phenomena scale with separation between turns ($\sim N^{-1}$), and with beam current ($\sim N^{-1}$), and with the total dwell time of each proton in the IC ($\sim N^{-1}$). It is for this reason that, if one provides ~4 MV/turn rf acceleration to limit N~100, an IC can accelerate ~3 mA of continuous proton beam.

These considerations led us to an alternative design that solves all three problems that plagued Rubbia's earlier ADTC concepts: deliver the necessary beam power using a *flux-coupled stack* of 7 isochronous cyclotrons (Figure 3a, Table 1), and inject the 7 beams in a *6-on-1 symmetric pattern* into the ADTC core (Figure 3b, Table 2) to provide a nearly isotropic flood of spallation neutrons within the core.

2. Flux-coupled stack of isochronous cyclotrons

Each IC in the flux-coupled stack produces 3 mA at 800 MeV, a modest extrapolation from the performance at 650 MeV in the PSI IC. For the ADTC stack configuration the IC design utilizes superconducting coils in the sector magnets and superconducting rf cavities of a novel design for efficient acceleration. The rationale of this approach is to utilize a mature accelerator design, improve it for efficiency and reliability, and replicate it to deliver the necessary power from a common footprint. The injection, rf acceleration, extraction, and beam transport are independent for each accelerator, so that if any one IC were to experience an operating fault the other 6 could continue delivering beam to the

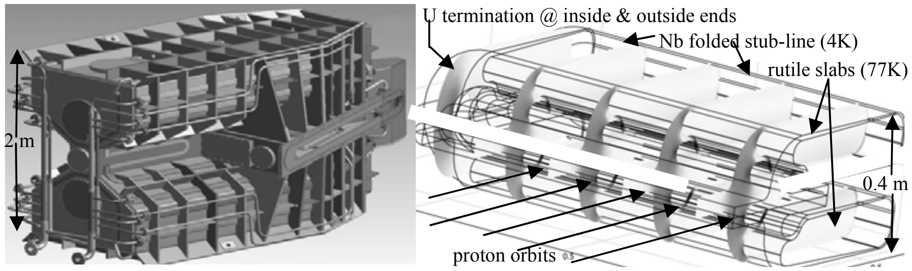


Figure 4. a) 400 kV copper cavity for PSI IC; b) field design of 1 MV dielectric-loaded superconducting cavity to fit in the gap between sectors in each IC.

ADTC core without interruption. If the outage were short term (e.g. arc-down of injection or extraction septum), the missing IC could be restored to operation without interruption of ADTC operation. If a component required access for repair, the ADTC core could continue in service at 85% power until a scheduled downtime was arranged.

The stack concept is motivated by the design of the sector magnets for the Riken superconducting ring cyclotron[8]. In that design each sector magnet consists of a pair of cryogenic coil assemblies (superconducting coil supported on cold-iron pole piece) suspended within a warm-iron flux return yoke. We extend the same principle by stacking 8 coil assemblies to create 7 cyclotron apertures. The flux-coupled magnetics[9] is arranged so that all coil assemblies are approximately buoyant (Lorentz forces in balance above and below). The flux-coupled stack is suspended within the warm-iron yoke using a pattern of low-loss tension supports shown in Figure 3a.

In the flux-coupled stack each pole piece is excited by a coil (6x10 cm^2) of Al-stabilized NbTi superconductor, operating at 4.5 K with an average current density of 30 A/mm^2. The fringe field is shaped using a correction winding and shielded from the superconducting cavities in the gap between sectors. Injection and extraction channels are provided using pole-face windings following the work of Okuno *et al*.[10]

RF acceleration poses a major design challenge for the flux-coupled stack. In all conventional cyclotrons the rf cavities are room-temperature empty copper resonators, whose size is determined by the desired frequency. Figure 4a shows the 50 MHz, 400 kV rf cavity for the PSI IC. It is 2 m high, whereas the spacing between cyclotrons in our flux-coupled stack design is 40 cm!

Figure 4b shows one way to solve this problem. Each cavity is a dielectric-loaded stub-line resonator, symmetric above and below the beam plane. The design shown resonates at 48 MHz and fits in a 40 cm vertical gap and in the shielded gap between sector magnets. The dielectric is high-purity rutile (ε_{ab} = 107, ε_c = 240, $\delta = 7x10^{-6}$ @ 77K). The cavity should produce an accelerating gradient voltage of 1 MV within breakdown limits. The walls are superconducting Nb (4K), the rutile slabs are maintained at 77K. Total heat load for all 7x4 cavities is 1.0 kW @ 4 K, 130 kW @ 80K. Both heat loads can be refrigerated using a commercial helium closed-cycle refrigerator, requiring ~1.5 MW of mains power.

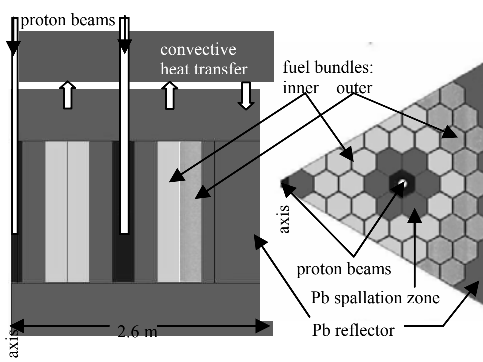


Figure 5. a) side view and b) top view sections of core, center axis at left, showing locations of proton beam tubes, inner and outer fuel bundles, and Pb reflector.

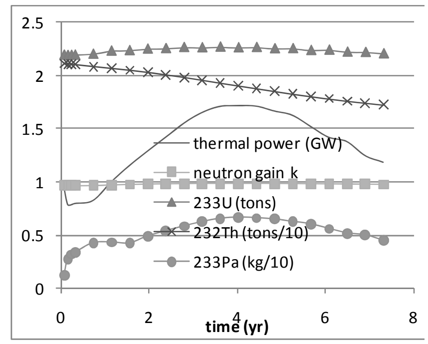


Figure 6. Thermal power, neutron gain, and fuel inventory through life cycle of fuel filling for GW ADTC core.

3. Multi-beam proton drive of the thorium core

Each proton beam traverses a beam tube into the core and is transversely modulated so that protons strike the side walls of the beam tube uniformly along a 50 cm length, providing a line source for spallation. The proton beam energy was chosen to be 800 MeV, providing a fast neutron yield of ~20 n/p. Molten lead is used as moderator, heat transfer medium, and shielding and reflection of neutrons at the core boundaries. The outer radius of the lead is chosen to be large enough to contain the core neutrons.

The proton beams are introduced in a 6-on-1 pattern within the fuel-moderator configuration of the core[11]. The fuel region is subdivided into an inner region and an outer region. The inner and outer fuel regions have the same size fuel bundles (and fuel pin size), but with different pitch between fuel pins (different number of pins per bundle). An oxide fuel composition of 90% ^{232}Th/10% ^{233}U is assumed; the starting ^{233}U fraction provides ~70% of peak power from the outset. Note that the transmutation from ^{232}Th to ^{233}U proceeds through an intermediary of ^{233}Pa, which decays with a half-life of 27 days. Figure 6 shows the thermal power output, the inventories of these nuclei in the core, and the neutron gain k~0.98 through a seven-year life cycle for a 1.5 GW core driven by seven 2 mA proton beams.

The neutronics for a 1.5 GW_{th} core was simulated using MCNPX[12] and SCALE4.3[13]. We selected a neutron gain k = 0.985 (subcritical operation with the neutron balance provided by the proton beams). Optimizing the fuel bundle size to maximize power density yields a bundle size of 18 cm. We then calculated the heat distribution within the core and modeled the convective heat transfer from the core through the molten Pb column to steam heat exchangers located above the core.

The ADTC core can operate for seven years as a sealed system, requiring no access to the core for shuffling fuel rods or other purposes. By contrast, in all other reactor technologies the fuel bundles must be re-shuffled frequently during core lifetime, which complicates securing the core against theft or terrorism.

We calculated what happens if one or all drive beams are lost. If only one beam is lost, the reactor can continue operation with a slightly higher value of k (~0.987) and still maintain uniform power density. If all beams are lost, the fission reaction ceases but the ^{233}Pa inventory decays into ^{233}U over the next month, so that when the reactor is re-started the criticality is just under 1.00. Although k can also be reduced in that situation using B_4C absorber plates, we plan to reduce somewhat the design value for k to ~0.980, so that the core would remain subcritical under all contingencies.

The Pb moderator has sufficient thermal mass that, in the event of a sudden shutdown, meltdown from subsequent decay heat is impossible under any circumstances. Neutrons scattering from the Pb moderator lose energy adiabatically, so all fission products can capture fast neutrons at structure resonance energies. The abundances of all fission products are thereby maintained in equilibrium so that long-lived waste nuclides do not accumulate as they do in thermal reactors.

4. Conclusions

Accelerator-driven thorium-cycle nuclear fission power could be operated using a flux-coupled stack of isochronous cyclotrons feeding seven beams symmetrically into a Pb-moderated thorium core. The required accelerator performance is routinely achieved today. The ADTC design would utilize superconducting magnets and rf to facilitate the stacked configuration, and its 17 MW of beam is sufficient to drive a 2 GW thorium core.

The 6-on-1 drive configuration permits the core to be operated with uniform power density and relatively constant power output for seven years without any access to the core. This feature is unique and opens new possibilities for non-proliferation. The ADTC core can continue to operate if one beam fails without any interruption in core power output or shock to core components. The core can be shut down in the event of all drive beams failing, and then restarted without risk of core shock or criticality. There is no mode of component failure that could lead to meltdown.

Table 1. Parameters of each IC in flux-coupled stack

beam energy:		
injection	200	MeV
extraction	800	MeV
beam current	3	mA
orbit radius:		
injection	3.4	m
extraction	5.0	m
# orbits	100	
rf acceleration:		
# main cavities	4	
frequency	48	MHz
acceleration per cavity	1	MV
# 3rd harmonic cavities	2	
magnetic field in sectors	1.7	Tesla
betatron tunes (horizontal, vertical)	1.9	
vacuum	10^{-9}	Torr

Table 2. Parameters of 7-beam-drive thorium core

thermal power	1.5	GW
proton drive power	7x1.6	MW
Pb moderator, heat xchanger:		
radius, height	2.6, 25	m
mass	5700	ton
thorium core:		
radius, height	1.5, 1	m
fuel bundles:		
pin radius	3.55	mm
pin cladding thickness	0.55	mm
bundle size (flat to flat)	18	cm
#bundles, pins/bundle:		
inner fuel region	6x20,271	
outer fuel region	6x14,331	
total fuel inventory	26.5	tons
fuel cycle between access	7	years

There are sufficient thorium reserves to provide the Earth's energy needs for two millennia. Given these beneficial aspects, it is reasonable to conclude that ADTC should soon become a significant element of energy technology.

Acknowledgments

This work was supported in part by the U.S. Dept. of Energy, grant DE-FG03-95ER40924.

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