Sustainable Thorium Energy for the World

Nuclear energy based on thorium and controlled by a proton accelerator instead of uranium in a critical reactor

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Science and Sustainability: Impacts of Scientific Knowledge and Technology on Human Society and its Environment
Pontifical Academy of Sciences
25-29 November 2016, Casina Pio IV, Vatican City
Sustainable energy

• A source of energy that will last long enough for an innovative technology to provide a replacement, while its impact on the environment can be reasonably managed
  – Sustainability requires R&D to ensure that the next innovation will come on time
  – The research effort must include fundamental research, as it is fundamental research that drives innovation
  – Investing in R&D implies also investing in education
One of Society’s biggest challenges: transition to a zero carbon society

• It does not make sense to burn fossil fuels (coal, oil, gas) till the end of supply for several reasons:
  – **Global warming**: more and more consensus that anthropic carbon emission is a problem

![CO2 levels over the last 10,000 years](image)
One of Society’s biggest challenges: transition to a zero carbon society

- **Air pollution:** immediate, real, and a very costly major problem

  "Air pollution poses the single largest environmental health risk in Europe today”

  *European Environment Agency*

  - Burning coal cost Europe alone 43 billion Euros in 2014 health care expenses (Heinrich Böll Stfitung);
  - 1.6 M deaths per year in China due to air pollution (Rohde, Muller, Berkeley);
  - 1 in 8 of total global deaths are the result of air pollution exposure (WHO).

- **Better use of oil:** plastics, rubber, paint, glue, drugs, cosmetics, detergents, ...
However, as they are cheap and abundant, the current tendency is still to increase fossil fuel consumption!
World Primary Energy Consumption

- Replacing 86% of the primary energy consumption is a huge challenge
A different nuclear energy?

- **Solutions must come from R&D.** R&D must be systematic, it must not exclude the nuclear fission domain

- **Nuclear fission energy is abundant, energy-intensive**
  (1 ton of thorium ≈ 3 million tons of coal), can ensure **base load electricity** production, emits **no greenhouse gases or air pollution, could be made sustainable**
  - If it were not for **accidents, waste management, proliferation issues**, nuclear energy would be ideal

- **Question: Can nuclear energy be made acceptable to society?**

- **Present nuclear energy technology was not chosen** to be acceptable:
  - **Uranium fuel cycle**: to produce plutonium for nuclear bombs
  - **Pressurized Water Reactors (PWR)**: to fit on a boat

- **Is there a better way of exploiting nuclear energy?**
  - Yes, with “**Thorium fuel in fast neutron Accelerator-Driven Systems (ADS)**”
Comment on nuclear waste

- Regardless of national policies, the problem of nuclear waste management must be solved.
- The added requirement of retrievability makes the geological repository strategy more questionable.

Transuranium elements (TRU): chemical elements with atomic numbers greater than 92 (the atomic number of uranium).

⇒ the idea is to use thorium fuel to destroy a large fraction of this waste.
Thorium: $^{232}\text{Th}$, 142 neutrons, 90 protons

- Thorium occurs mostly in monazite ($\text{Ce, La, Nd, Th})\text{PO}_4$, often a by-product of rare earth mining, found also in tin, coal and uranium tailings.

- **Excellent physical properties**: Higher melting point of metallic state ($1750^\circ\text{C}$) compared to ($1130^\circ\text{C}$) for uranium and of $\text{ThO}_2$ ($3300^\circ\text{C}$) compared to $\text{UO}_2$ ($2800^\circ\text{C}$). $\text{ThO}_2$ has better thermal conductivity and smaller expansion coefficient than $\text{UO}_2$:
  - Higher margins for design and operation as nuclear fuel.

- **Abundant**, as much as lead, three to four times more than uranium and **broadly distributed over the world**:
  - Known and estimated resources: $6.3\times10^6$ tons, probably more ($\approx 2500$ years of world electric energy consumption*);
  - “Thorium is a source of energy essentially sustainable on the human time scale”

*World electrical power consumption $\approx 2.5$ TW
Fission energy from thorium

- Thorium is **fertile**, not fissile, so it can **ONLY** be used in breeding mode (to produce $^{233}\text{U}$ which is fissile) – **inconvenience that can be turned into an advantage**
Fission energy from thorium

- $^{232}\text{Th}$ chain analogous to $^{238}\text{U}$ chain (Superphenix type of reactor / GEN IV)

**U-Pu Breeder**

$^{238}\text{U}$ → $^{239}\text{U}$ (fertile) → $^{239}\text{Np}$ (fissile) → $^{239}\text{Pu}$ (fissile)

- $^{239}\text{U}$ decay, $t_{1/2} = 22.45$ mn
- $^{239}\text{Np}$ decay, $t_{1/2} = 2.3$ d

**Th-U Breeder**

$^{232}\text{Th}$ → $^{233}\text{Th}$ (fertile) → $^{233}\text{Pa}$ (fissile) → $^{233}\text{U}$ (fissile)

- $^{233}\text{Th}$ decay, $t_{1/2} = 22.3$ mn
- $^{233}\text{Pa}$ decay, $t_{1/2} = 27$ d
Fission energy from thorium

- However, breeding gives a factor 140 gain compared to $^{235}\text{U}$ in PWR (in addition to the factor 3 to 4 in abundance): potentially ≈ 500 times more abundant than $^{235}\text{U}$

The $^{235}\text{U}$ isotope represents only 0.7% of natural uranium

- Neutron capture
- $^{232}\text{Th} \rightarrow ^{233}\text{Th}$
- $\beta$ decay $t_{1/2} = 22.3$ mn

- $^{233}\text{Th} \rightarrow ^{233}\text{Pa}$
- $\beta$ decay $t_{1/2} = 27$ d

- $^{233}\text{Pa} \rightarrow ^{233}\text{U}$
- fissile

PWR  Th-U Breeder
Breeding nuclear fuel

To make breeding possible, the number of neutrons produced per neutron absorbed must be larger than 2.

\[ \frac{f}{f + c} > 2 \]

Breeding \(^{233}\text{U}\) is most efficient with fast neutrons.

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Thorium and nuclear waste

- Thorium minimizes nuclear waste production and is proliferation resistant.
- In a fast neutron flux, TRU can be eliminated while producing energy.

Thorium chain in a fast neutron flux

Entry door to nuclear waste production

Thorium chain in a fast neutron flux

- (n, γ) capture
- β-decay ≤ 10 years
- Fission
- (n, 2n) (E_n ≥ 6 MeV)

Revol/PAS/Nov.28.2016
How to use thorium in practice?

• One cannot simply replace uranium fuel with thorium fuel

• What are the options?
  – Use thorium blankets around fast critical reactors to breed $^{233}\text{U}$ and introduce $^{233}\text{U}$ as fuel in new critical reactors (India’s strategy)
  – Continuously move the fuel, such as to always have fresh fuel
    • Pebble bed critical reactors
    • Molten salt critical reactors
    • Traveling wave critical reactor? (yet to be developed)
  – Provide an external neutron source to maintain the chain reaction: Accelerator-Driven Systems (ADS)
Proposal to use a particle accelerator as a neutron source by E.O. Lawrence/USA and N.N. Semyonov/USSR in 1940

- Beam inserted from the top
- Neutrons produced by spallation
- Runs in subcritical mode (no criticality accident)
- Flexibility in the choice of fuel, including TRU from nuclear waste
Basic concepts carefully validated 1990s

FEAT@ CERN PS

3.62 t of natural uranium at CERN PS; \( k_{\text{eff}} \approx 0.9 \)

TARC@CERN PS

334 t of pure lead
Paul Scherrer Institute (PSI) at Villingen, Switzerland:
– proton beam power of 1.3 MW
– Today, designs exist to reach a power of 10 MW

High-power (> 1 MW) proton beams exist
High-power spallation neutrons sources

MEGAPIE target @ PSI

Target Head Feedthroughs
Target Shielding
Expansion Tank
Main EMP Flowmeter
Bypass EMP Flowmeter
Upper Target Enclosure
Main Guide Tube
Bypass Flow Guide Tube
LBE Leak Detector
Central Rod Heaters and Neutron Detectors
T91 Lower Liquid Metal Container
Lower Target Enclosure

SNS in the USA with 1.4 MW on target (1 GeV, 1.4 mA)

Successful 4 month run at PSI, Switzerland, in 2006, 1 MW

ESS under construction at Lund (5 MW at 2 GeV)
The most developed design. MYRRHA should be the flagship of ADS projects, however:
– only partially funded* (injector up to 100 MeV recently approved)
– not before 2025?
– no thorium in the plans
– will not remain an ADS, will be turned into a critical reactor

*Europe spent 600 billion Euros on renewable energies, from 2005 to 2013 (Bloomberg New Energy Finance)
China ADS project: ADANES

- Accelerator-Driven Advanced Nuclear Energy System (ADANES) led by Wenlong Zhan (CAS), as a complete energy system, integrating nuclear waste transmutation, nuclear fuel multiplication and energy production, aiming at 1000 MWe.

- Includes a systematic R&D program on the various elements of the system.

Two injector solutions developed in parallel (IMP Lanzhou and IHEP Beijing)

CIADS: INITIAL FACILITY

250MeV@10mA
5-10MW in 2022

RESEARCH FACILITY

DEMO FACILITY

dense granular target (DGT)
iThEC’s initiative: Use an existing facility at INR Troitsk for ADS phase 3

Existing pulsed neutron source

ADS experimental cell

Existing INR Infrastructure

– Proton linac (design: 600 MeV, 300 kW)
– Spallation neutron source
– Pit on a beam line to host a subcritical core
– Infrastructure (to manipulate radioactive material)

5 years at 4% of the cost of MYRRHA
But initial funding for approval not yet found
iThEC’s initiative: An innovative cyclotron for ADS

• **Project baseline:** one stage superconducting cyclotron, 600 MeV, 6 mA (3.6 MW)
  – High reliability through redundancy
  – High efficiency
  – Lower cost

• **Proposal to be submitted to EU H2020** "*Future and Emerging Technologies (FET)*" programme, a collaboration between CERN, iThEC, PSI, AIMA (France), ASG (Italy), Hydromine Nuclear Energy (Italy), and Nuclear-21 (Belgium)

• **Other applications of high-power accelerators:**
  – Production of new alpha emitters for medicine (TRT and TAT), and other radioisotopes
  – High intensity beams for fundamental research
Arriving at a zero carbon society in a sustainable way, requires innovation, hence a systematic R&D effort, including nuclear fission energy.

Fast neutron accelerator-driven systems (ADS) using thorium fuel offer the possibility to transmute a major part of the long-lived nuclear waste and produce energy.

Thorium is a potentially sustainable source of energy for the future.

The availability of high power proton beams will bring further benefits to society, in particular in the production of new medical radioisotopes.