Thorium: an energy source for the world of tomorrow
If, by end of 21st century, people in developing countries are allowed to live as well as we do in Europe today, then, the world power consumption will have to increase by a factor 3 or more.
Burning fossil fuel till the end?

- **Global warming?** Atmospheric CO₂ level higher than ever in the past 15 million years, increasing faster than ever before (IPCC report, March 2014 > 2°C more likely than ≤ 2°C)

- **Air pollution?**
  - Burning coal cost Europe alone 42.8 billion Euros in annual health care expenses (2013 report by the Health and Environment Alliance)
  - The ambient air pollution caused the premature deaths of > 400 000 Chinese in 2013
  - WHO: in 2012 around 7 million people died – 1 in 8 of total global deaths – as a result of air pollution exposure

- **Running out?** The current tendency is to increase the use of fossil fuel

- **Way out? innovate!**
Energy R&D

- Innovation implies investment in both fundamental research and applied research
  - Brings the possibility of (good) surprises
- Relying entirely on wind and solar energy by the end of the century would imply increasing their contribution to the world energy by a factor 130 or more (quite a challenge, and most likely not realistic)
- Energy R&D has to be systematic, without prejudice:
  - Improve energy efficiency, storage, transport, etc.
  - Develop renewable energies
    - Wind, Solar Photovoltaic, Solar thermal, Biomass (E.-D. Schulze)?, Geothermal, Ocean tides, waves, etc.
  - R&D on nuclear fusion (no conceptual solution yet)
    (Magnetic confinement: ITER, Inertial confinement: NIF, Mégajoule)
  - Improve nuclear fission energy (it works already!)
    - Generation IV (critical fast reactors on nuclear industry agenda)
    - Innovative nuclear systems based on thorium
Thorium Energy Conference (ThEC13)

- Organized by the international Thorium Energy Committee (iThEC, http://www.ithec.org)
- Participants from 32 countries, 47 speakers, including some prestigious personalities

Representatives of both India and China cited energy issues as their prime concern and announced strong motivations to do R&D on thorium.

http://indico.cern.ch/event/thec13
China's Energy Challenge

Analysis and forecast on national electric power in China: In 2030, the electricity demand of per person will be about 2KW, total generation capacity will reach about 3000GW, the MW-level power power stations will need 3000.

Europe not representative of the world:
- population to decrease
- little economic growth
- highest standard of living
The increasing worldwide interest in thorium is finally reaching nuclear industry. For the first time, thorium officially mentioned by a French main nuclear actor.

At ThEC13, AREVA and SOLVAY announced an agreement on thorium:

**AREVA and SOLVAY join their know-how to add value to thorium’s entire life cycle**

However, AREVA is only considering an “adiabatic” transition from uranium to thorium (80-100 years), starting by inserting a few thorium fuel elements in a uranium reactor.
Thorium in Light Water Reactors

Thor Energy (The Norwegian Thorium Initiative) collaborates with Westinghouse to carry out thorium fuel tests in the Halden research reactor.

- 2 Rods 85%Th - 15%Pu pellets, ITU, Germany
- 2 Rods 7%Th – 93%UOX, IFE, Norway
- 1 Rod 65%Th – 35%UOX, IFE, Norway
- 1 UOX Reference rod

Halden Research Reactor
Institute for Energy Technology (IFE)
Nuclear fission energy

- **Why is it a priori attractive?:**
  - No CO$_2$, no air pollution (NOx, etc.), concentrated
  - Has the potential to produce abundant (base load) electric energy
  - Nuclear fission technology exists and is well understood
  - Breeding can make it essentially “sustainable” on the human time scale

- **Shortcomings** of the **PRESENT** generation of thermal neutron systems based on uranium:
  - Accidents (Chernobyl, Three Mile Island, Fukushima)
  - Waste management (storage over ≤ one million years is the only option developed so far)
  - Proliferation of nuclear weapons (uranium ≈ military)
  - Sustainability (<100yr at present rate)

- **Can one make nuclear energy acceptable to Society?**
  Can a different nuclear energy based on **thorium** instead of uranium have the potential for eliminating all of the above issues of the present nuclear power scheme?
Thorium ($^{232}\text{Th}_{90}$)

- **Abundant** *(1.2x10^{14} \text{ tons in the Earth’s crust})*, as much as lead, and three to four times more than uranium

- Recovering only one part per million *(10^{-6})*, that is 1.2x10^{8} tons, would provide the present world power consumption of 15 TW, for 18’000 years. “Thorium is a source of energy essentially sustainable on the human time scale” — C. Rubbia @ ThEC13

- **Isotopically pure**, α-decay with a half-life of 14 billion years (almost stable)

- Thorium occurs in several minerals including thorite *(ThSiO$_4$)*, thorianite *(ThO$_2$ + UO$_2$)* and monazite *(Ce, La, Nd, Th)PO$_4$)*. Often a by-product of mining for rare earths *(lanthanides + scandium and yttrium)*, tin, coal and uranium tailings

- Known and estimated resources: $\approx$7x10^6 tons (IAEA); poor indicator because not searched for systematically; $\approx$1000 years at present world energy consumption
Thorium is **fertile**, not fissile, so it can **ONLY be used** in breeding mode, by producing $^{233}\text{U}$ which is fissile.

However, this gives a potential factor 140 gain compared to $^{235}\text{U}$ in PWR (in addition to the factor 3 to 4 in abundance).
Fission energy from $^{232}\text{Th}_{90}$

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Uranium chain

$^{238}\text{U} \rightarrow ^{239}\text{U}$ (half-life 23.45 mn)

$^{239}\text{U} \rightarrow ^{239}\text{Np}$ (half-life 2.3 days)

$^{239}\text{Np} \rightarrow ^{239}\text{Pu}$

Thorium chain

$^{232}\text{Th} \rightarrow ^{233}\text{Th}$ (half-life 22.3 mn)

$^{233}\text{Th} \rightarrow ^{233}\text{Pa}$ (half-life 27 days)

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

Θ decay
Fission energy from $^{232}\text{Th}_{90}$

- Thorium is **fertile**, not fissile, so it can **ONLY be used** in breeding mode, by producing $^{233}\text{U}$ which is fissile.
- However, this gives a potential factor 140 gain compared to $^{235}\text{U}$ in PWR (in addition to the factor 3 to 4 in abundance).
- Thorium dioxide ($\text{ThO}_2$) has the highest melting point (3300 °C compared to 2865 °C for $\text{UO}_2$) of all oxides and is one of the best refractory materials.
- Minimizes nuclear waste production, can be used to destroy existing nuclear waste.

Thorium chain

- $^{232}\text{Th}$: Neutron capture
- $^{233}\text{Th}$: half-life 22.3 mn, β decay
- $^{233}\text{Pa}$: half-life 27 days, β decay, α_f
- $^{233}\text{U}$: fissile

Thorium is **fertile**, not fissile, so it can **ONLY be used** in breeding mode, by producing $^{233}\text{U}$ which is fissile.

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Nuclear Waste

- **TRansUranic elements:** (1.1% of spent fuel) produced by neutron capture and subsequent beta decay; dominated by plutonium. The others are called Minor Actinides

- **Fission Fragments:** (4% of spent fuel) the results of fissions
Nuclear Waste

- TRU constitute by far the main problem [long lifetime – reactivity].
Thorium and nuclear waste

Thorium minimizes nuclear waste production, because it is 7 neutron captures away from plutonium-239.

Used in a fast neutron flux, thorium represents a unique potential for nuclear waste elimination.
Why fast neutrons?

- Advantages of fast neutrons:
  - Favourable to breeding
  - Enhances TRU fission probability
  - No need to separate out Pu! simplifies reprocessing (Pyro-Electro)
  - Reduces captures on FF, extends burnup (better use of fuel)
    (120 GW.day/t achieved in fast electro-breeder at Argonne N.L., and in EA simulation)

- Fast spectrum, implies as little moderation as possible:
  - Sodium or gas used in GENERATION IV
  - Molten salts in MSR
  - Pb or Pb-Bi eutectic in ADS systems
Fission energy from $^{232}\text{Th}_{90}$

- $^{233}\text{U}$ is an excellent fuel for a breeder system

But the other elements in the fuel have to be taken into account ($^{232}\text{Th}$, $^{238}\text{U}$). Thorium + $^{233}\text{U}$ cannot be substituted simply to PWR fuel because of neutron inventory issues (capture rate on thorium and long half-life of $^{233}\text{Pa}$)

CERN Oct 2013
Neutron Captures

Ratio $^{232}\text{Th}(n,g)/^{238}\text{U}(n,g)$

Energy (eV)

Ratio

PWR

Fast Breeders

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How to use thorium in practice?

- Three general options?
  - Thorium blankets around reactors, to breed $^{233}\text{U}$ and introduce $^{233}\text{U}$ in fuel
    \[ n + ^{232}\text{Th} \rightarrow ^{233}\text{Th} \rightarrow ^{233}\text{Pa} \rightarrow ^{233}\text{U} \]
  - Continuously move the fuel out, such as to always have fresh fuel
    - Pebble bed reactors (once through)
    - Molten salt reactors (reprocessing on-line)
  - Accelerator Driven Systems (ADS), providing an external neutron source: this is the solution proposed by C. Rubbia at CERN in the 1990’s
Thorium blanket: Indian strategy

- India, with little uranium resources but a lot of thorium, has the most advanced practical scheme for using thorium (including front-end and back-end of the fuel cycle):
  - Use heavy water reactors (CANDU) or LWR to produce plutonium
  - Use sodium cooled U-Pu fast reactors with a thorium blanket to breed $^{233}\text{U}$
  - Reprocess blankets and manufacture $^{233}\text{U}-\text{Th}$ fuel for advanced fast reactors or heavy water reactors

- The Indian scheme works. However, several issues remain concerning the complexity (three technologies), the sustainability and nuclear waste management.
Pebble bed critical reactors


  - Presented as passively safe, because high temperature systems can be cooled by natural air convection
  - Not discussed at ThEC13

- Several severe issues to be resolved:
  - No containment building if cooling by natural air convection
  - Uses flammable graphite as moderator
  - Produces more high-level nuclear waste than current nuclear reactor designs
  - Relies heavily on pebble integrity and fuel handling (pebble accident in THTR-300)
  - Water ingress is a danger
  - Reprocessing of spent fuel virtually impossible
Molten salt critical reactors

- This is clearly a technology that is concentrating industry’s interest (10 talks related to the subject at ThEC13): China, India, UK, USA, Czech Republic, France, Switzerland
- Pioneered at Oakridge in 1960 (Molten Salt Reactor Experiment, UF4, 7.4MWth)
- Advantages:
  - Liquid fuel allows extending burnup indefinitely, because of reprocessing on-line
  - High temperature (500°C – 600°C), heat produced directly in heat transfer fluid
  - Passive cooling for decay heat removal
- Several severe issues: neutron emission outside core, on-line chemistry failure, corrosion, licencing issues, etc.
- Presently not using a fast neutron spectrum (R&D should be extended to other salts – PbCl₃, to minimize waste)
- There is a particularly well focussed and most ambitious effort in China (Xu Hongjie, Shanghai Institute of Applied Physics)
End of March, the Chinese Government decided that the first fully-functioning thorium MSR reactor should be built within ten years, instead of 25 years, as originally planned.
ADS: the subcritical approach

- A particle accelerator, to provide a neutron source
- A core in which both source neutrons and fission neutrons are at work – restricted here to the case of a moderator allowing for a fast neutron spectrum

Two main areas of physics:
- Neutron production by spallation from the beam
- Neutron transport and interaction in the core

Physics also drives other ADS elements:
- Cooling (possibility of natural convection)
- Electric power production efficiency (go to highest possible temperature)

Physics tested at CERN and well understood

Conceptual phase completed, unlike fusion
A short history of ADS

- The basic process in ADS is nuclear transmutation

- 1919 Rutherford \((^{14}\text{N}_7 + ^4\text{He}_2 \rightarrow ^{17}\text{O}_8 + ^1\text{p}_1)^{210}\text{Po accelerator!}\)

- 1940 E.O. Lawrence/USA and W.N. Semenov/USSR proposed to use a particle accelerator as a neutron source

- 1942 G. Seaborg produced the first \(\mu\)g of \(^{239}\text{Pu}\) with the Berkeley 60 inch cyclotron

- 1950 E.O. Lawrence proposed the Materials Testing Accelerator (MTA) at the Lawrence Livermore Radiation Lab, to produce \(^{239}\text{Pu}\) from Oak Ridge depleted uranium

- 1952 W.B. Lewis in Canada proposed to use an accelerator to produce \(^{233}\text{U from thorium}\) for CANDU reactors (electro-breeder concept)
A short history of ADS

- MTA and Lewis’ projects dropped or slowed down when (a) rich uranium deposits were discovered in the USA, and (b) it was realized that it required several hundred mA of beam intensity, hundreds of MW to produce the beam! \[ Pu, \text{ no amplification} \] today \( \approx \) 10 MW beams seem sufficient

- Renewed interest in ADS in the 1980’s, when the USA decided to slow the development of fast critical reactors (Fast Flux Test Facility @ Argone National Lab.):
  
  - H. Takahashi at Brookhaven National Lab: several proposals of ADS systems (PHOENIX), including the idea of burning minor actinides (Fast neutrons – \( k_s \approx 0.99 \));
  
  - Ch. D. Bowman at Los Alamos: thermal neutron ADS (ATW) with thorium & chemistry on-line for FP and \(^{233}\)Pa extraction;
  
  - Japan launched Options for Making Extra Gains from Actinides (OMEGA, now JPARC) at JAERI (now JAEA).
A short history of ADS

- In the 1990s, Carlo Rubbia gave a big push to the ADS, by launching a vigorous research programme at CERN based on:
  - development of innovative simulation of nuclear systems
  - specific experiments to test basic concepts (FEAT, TARC)
  - construction of an advanced neutron Time of Flight facility (n_TOF) to acquire neutron cross-section data, crucial to simulate reliably any configuration with new materials
- Followed by several proposals for demonstrators

C. Rubbia triggered a major R&D effort on ADS worldwide
Carlo Rubbia’s Energy Amplifier

- Proton accelerator driven **subcritical system**:
  - Fast neutrons ($10^4$ to $10^6$ eV range)
  - Fuel based on thorium rather than uranium (minimize waste, less proliferating)
  - Lead as spallation target, moderator and coolant
  - **Deterministic safety** with passive elements

- C. Rubbia, et al.
  « Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier »,
  CERN/AT/95-44 (ET)

- C. Rubbia et al.,
  « A Realistic Plutonium Elimination Scheme with Fast Energy Amplifiers and Thorium-Plutonium Fuel »,
  CERN/AT/95-53 (ET)

- Jean-Pierre Revol, "An Accelerator Driven System for the Destruction of Nuclear Waste",
The main issue for ADS today is the absence of a demonstrator. This is much more a political issue (funding) than a scientific one.

The technology for a demonstrator with power of \( \approx 100 \text{ MWth} \) is ready.

The physics simulation is available – Impressive measurements at CERN n_TOF

First proposal by C. Rubbia et al., in 1999
Ansaldo engineering design for the Energy Amplifier Demonstration Facility
EA B0.00 1 200 (Jan. 1999)
Simplified model of subcritical systems

- **Theory of subcritical systems** interesting in itself, to get insights into the physics. Properties are quite different from those of critical systems (C. Rubbia, CERN/AT/ET/Internal Note 94-036)

- Neutron flux geometry important to determine the generated power distribution and the uniformity of fuel burnup

- Some simplifying assumptions (uniform material and mono-energetic neutrons, small absorption) to get a basic equation similar to that of a critical reactor, but with an external neutron source term in addition:

\[
\frac{\partial n(\vec{r},t)}{\partial t} = \nu \sum_f \Phi(\vec{r},t) + C(\vec{r},t) - \sum_a \Phi(\vec{r},t) + D \nabla^2 \Phi(\vec{r},t)
\]

- **Fission**
- **Spallation**
- **Absorption**
- **Leakage**
Simplified model of subcritical systems

Example of finite system at equilibrium:

\[
\frac{\partial n}{\partial t} = 0 \Rightarrow \nabla^2 \Phi + \frac{(k_\infty - 1)}{L_c^2} \Phi = -\frac{C}{D}
\]

with \( k_\infty \equiv \frac{\nu \Sigma_f}{\Sigma_a} \); \( L_c^2 \equiv \frac{D}{\Sigma_a} \)

Two regimes corresponding to two classes of solutions:

- \( k_\infty < 1 \): the system is intrinsically subcritical (FEAT experiment: \( k_\infty \approx 0.93 \)) – **Solution is an exponential**
- \( k_\infty > 1 \): subcriticality comes from the lack of confinement, it is a geometrical issue – **Solution is oscillatory** (C. Rubbia’s EA: \( k_\infty \approx 1.2-1.3 \))

\[
C(\vec{x}) = D \sum_{l,m,n} c_{l,m,n} \psi_{l,m,n}(\vec{x}) \Rightarrow \Phi(\vec{x}) = L_c^2 \sum_{l,m,n} \frac{C_{l,m,n}}{1 - k_{l,m,n}} \psi_{l,m,n}(\vec{x})
\]

All modes are excited

Important theorem:

\[
k_{l,m,n} \equiv k_\infty - L_c^2 B_{l,m,n}^2
\]

Fundamental mode subcritical \( \Rightarrow \) all modes are subcritical
Main results from FEAT

$k_\infty < 1$: exponential

3.62 t of natural uranium at CERN PS; $k_{eff} \sim 0.9$
TARC at the CERN PS

- Neutron phenomenology studies in the TARC experiment at the CERN PS (1996-1997).
- Testing both the spallation process and neutron transport in lead.


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334t of pure lead
Neutron multiplication factor

- The neutron multiplication factor whether the accelerator is on or off:

\[ k_{\text{eff}} \approx \frac{\nu \sum f}{\sum a + DB^2} \]

- Non-fission multiplication: For fast neutron systems, (n,xn) reactions on Pb are important, in particular for the source neutrons:

\[ k_s \approx \frac{\nu' \sum f \Phi(\vec{r},t) + C(\vec{r},t)}{\sum a \Phi(\vec{r},t) - D \nabla^2 \Phi(\vec{r},t)} \]

- Change of flux distribution and multiplication in the source:

- Switching off the neutron source not only stops the main power generation, but also moves the system further away from prompt criticality, \( k_s \) to \( k_{\text{eff}} \).
Physics of subcritical systems

- Subcritical systems are insensitive to delayed neutron fraction ($\beta$); safety margin (distance from prompt criticality) is a design choice, it is not imposed by Nature!

- The reactivity changes only very slowly; the beam can be switched off very quickly, reducing $k_s$ to $k_{eff}$. It is possible to choose a higher $k_s$ in order to reduce the load on the accelerator (Takahashi at BNL, $k_s = 0.99$)

### Response to reactivity insertion

The CERN LHC beam can be switched off in 270μs, the CERN SPS in 46 μs, and a smaller accelerator for ADS, even much faster. So the reaction time will not be limited by the accelerator. The typically response time of a critical system to reactivity insertion is of the order of 5 ms.
Advantages of ADS

- **Safety** – a deterministic as opposed to probabilistic approach:
  - Eliminate criticality accidents by making the system subcritical (void coef., T coef., $\beta_{\text{eff}}$ no longer “critical” parameters)
    - This requires an external proton source!
  - Operate system with passive safety elements in addition to avoid core melting or limit its consequences, borrowing features from US advanced fast critical reactor designs;
  - Avoid dangerous coolants such as liquid sodium in Generation IV (use lead)

- **Waste management:**
  - Use (1) fast neutrons, (2) thorium fuel, and (3) recycle long-lived transuranic actinides (TRU) to minimize waste production or destroy existing waste

- **Military proliferation:**
  - Use thorium fuel (very small Pu prod., $^{233}$U very difficult mixture)
  - Avoid Pu separation (Purex), use pyro-electro reprocessing instead (developed for uranium at Argone N.L.)
  - Chemistry on-line in Thorium MSR potentially proliferating ($^{233}$Pa)
ADS @ ThEC13

- Largest number of talks at ThEC13 (17 talks)
- Status of readiness of technologies:
  - Accelerator(s) (cyclotrons, linacs, Fixed Field Alternating Gradient)
  - Spallation targets
  - Core designs
- Presentation of systems:
  - MYRRHA (SCK•CEN, Mol, Belgium)
  - Troitsk (Russia) & CADS (China) for burning minor actinides, and a discussion in India to use ADS to simplify the present thorium utilization scheme
  - Molten Salt ADS (C. Rubbia, Japan, Korea)
- Concrete tests:
  - PSI cyclotron beam (1.4 MW proton beam – 2.4 mA x 590 MeV)
  - 0.8 MW LBE spallation target (MEGAPIE@SINQ (Swiss Spallation Neutron Source), SNS (1.4 mA x 1 GeV, 1.4 MW Spallation Neutron Source at Oakridge N.L.), etc.)
  - Reactivity measurement by beam pulses (Cheol Ho Pyeon, from Korea)
  - Corrosion, material compatibility, etc.
Successful run at PSI 4 months in 2006

Heat Exchanger (Oil)
10 l/s, 5.5 m/s
140-175°C inside

Main Pump
4 l/s, 1.2 m/s
380°C

Guide Tube
4 l/s, 0.33 m/s
380°C

Downcomer
3.75 l/s, 0.33 m/s
230-240°C

Beam Window
380°C outside
330°C inside

Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
380-230°C inside

Bypass Pump
0.25 l/s, 0.2 m/s
230°C

Bypass Tube
0.25 l/s, 1 m/s
230-240°C

Nozzle 1.2 m/s
Beam Window 1 m/s

Design parameters:
- p-beam energy: 575 MeV
- p-current: 1.74 mA
- Heat removal: 650 kW
- Design pressure: 16/10 bar
- Design temp.: 400°C
- Cover gas press: 3.2 bar
- Operation: 1 year
- with max 6000 mAh
- Radiation damage: 20-25 dpa

Dimensions:
- Length: 5.35 m
- Weight: 1.5 t
- LBE-Volume: 89 l
Accelerator Driven Systems

Most important project in Europe, with strong support from the Belgian government:
- partially funded
- no thorium
- will not remain an ADS, will turn into a critical reactor
Industrialized ADS

EA Feasibility Study: Aker ASA and Aker Solutions ASA (2010)

- 1500MWh/600MWe
- Sub-critical core
- Thorium oxide fuel
- Accelerator driven via central beam tube
- Molten lead coolant
- Coolant temp 400-540°C
- 2 Axial flow pumps
- 4 Annular heat exchangers
- Direct lead/water heat exchange

It may be modified to a Minor Actinide burner (ADS)

A Thorium fuelled reactor for power generation

Carlo Rubbia
Other ADS projects

- China, Japan, Korea, Russia, USA, Venezuela and Ukraine
  - 200 kW uranium-based ADS prototype, driven by an electron beam, due for completion in 2014 at the Karkhov Institute of Physics and Technology (KIPT)
  - 10 MW TROISKS ADS, 300 kW proton beam, rearranging existing elements (accelerator, neutron source, etc.)
  - Virginia Nuclear Energy Consortium Authority associated to Jefferson Lab, in the USA, with a view to create a “Science & Technology Center (STC) for the Application of High-Power Accelerators for the Advancement of Innovative Multidisciplinary Science”

Lack of coordination

Lei Yang, IMP, China
Transmutation performance of ADS

- **C. Rubbia’s EA can destroy** 36 kg of TRU/TW\textsubscript{th}.h  
  (A PWR produces 14 kg of TRU/TW\textsubscript{th}.h)

- **Calculations of specific transmutation rates (Y. Kadi)**

  Transmutation rates (kg/TW\textsubscript{th}.h) of plutonium and minor actinides and LLFPs

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>EADF (ThPuO\textsubscript{2})</th>
<th>EADF (UPuO\textsubscript{2})</th>
<th>EADF (UPuO\textsubscript{2})</th>
<th>PWR (UO\textsubscript{2})</th>
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<tr>
<td></td>
<td>ENDF/B-VI</td>
<td>ENDF/B-VI</td>
<td>JENDL-3.2</td>
<td></td>
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<tr>
<td>$^{235}\text{U}$</td>
<td>$+ 31.0$</td>
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<td></td>
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<tr>
<td>Pu</td>
<td>$- 42.8$</td>
<td>$- 7.39$</td>
<td>$- 5.55$</td>
<td>$+ 11.0$</td>
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<td>Np</td>
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<td>$+ 0.25$</td>
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<tr>
<td>Am</td>
<td>$+ 0.24$</td>
<td>$+ 0.17$</td>
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<td>$+ 0.54$</td>
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<tr>
<td>Cm</td>
<td>$+ 0.007$</td>
<td>$+ 0.017$</td>
<td>$+ 0.020$</td>
<td>$+ 0.044$</td>
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<tr>
<td>$^{99}\text{Tc prod}$</td>
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<td>$+ 1.07$</td>
<td>$+ 1.22$</td>
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<td>$^{99}\text{Tc trans}$</td>
<td>$- 3.77$</td>
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<tr>
<td>$^{129}\text{I prod}$</td>
<td>$+ 0.30$</td>
<td>$+ 0.31$</td>
<td></td>
<td>$+ 0.17$</td>
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<tr>
<td>$^{129}\text{I trans}$</td>
<td>$- 3.01$</td>
<td>$- 3.01$</td>
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</tbody>
</table>

C. Rubbia  
CERN/AT/95-58 (ET) 

Reprocessing inefficiency $10^{-4}$ 
Depends on reprocessing efficiency

[Graph showing radioactive decay with time after shutdown, indicating different pathways with and without incineration.]
ADS energy gain

- A source neutron is multiplied by fissions and \((n,\text{xn})\) reactions. Since \(k_s < 1\), neutron production stops after a limited number of generations:

\[
N_0 \left( 1 + k_s + k_s^2 + k_s^3 + k_s^4 + \ldots + k_s^n \right) = N_0 M = N_0 \frac{k_s^{n+1} - 1}{k_s - 1} \approx \frac{N_0}{1 - k_s}
\]

- The energy gain \(G\) is a characteristic of ADS:

\[
G = \frac{\text{Energy produced in } EA}{\text{Energy injected by the beam}} = \frac{0.18 k_s N_0}{\nu (1 - k_s) E_b} = \frac{G_0 k_s}{(1 - k_s)} \approx \frac{G_0}{1 - k_s}
\]

- \(G_0\) includes information from the spallation process (\(G_0 \approx 3\) for uranium; \(G_0 \approx 2.7\) for lead, etc.)

\[
G = \frac{G_0 (E_b, \text{Material, Geometry})}{1 - k_s}
\]
Main results from FEAT

$K_{\infty} < 1$: exponential

Energy gain well reproduced by simulation

$G = \frac{G_0}{1 - k} \sim 30$

$G_0 = 3.1$

$k = 0.895$

3.62 t of natural uranium at CERN PS; $k_{\text{eff}} \sim 0.9$
For a given power output, the energy gain (choice of $k_s$ and $G_0$) determines the accelerator power.

Trade-off between accelerator power and criticality margin.

Possibility of modulating the beam intensity to allow variations in the power output (complementary with a fluctuating renewable energy source).

Neutronics with thorium very favourable compared to uranium $t_{1/2}^{(233\text{Pa})} \sim 27\text{d}$; $t_{1/2}^{(239\text{Np})} \sim 2.3\text{d}$! What was a problem in the use of thorium in critical reactors becomes an advantage in the case of ADS.

![Graph showing energy gain in ADS systems](image)

\[ P_{beam} = \frac{(1 - k_s)}{k_s G_0} P_{ADS} \]

**Marginal of present PWR**

**psi separate turns cyclotron**

(2.4 mA and 1.4 MW, with 0.59 GeV protons).

\[ P_{ADS} = 210 \text{ MW}_{th} \text{ with } k = 0.98 \]

**MYRRHA LINAC**

(\leq 1 to 4 mA and \leq 2.4 MW, with 0.6 GeV protons)

\[ P_{ADS} = 50-100 \text{ MW}_{th} \text{ with } k = 0.95 \]
Accelerator requirements

- In principle, it does not matter how the external neutron source is provided. In practice, for industrial applications, there are a number of well-defined requirements for the accelerator:
  - **Beam particle**: protons
  - **Beam power**: a few to ≈ 10 MW depending on choice of ks value, and power output
  - **Beam Energy**: $E_{\text{beam}} \geq 800$-$900$ MeV
  - **Beam spot size (footprint)**: large on impact on window (studies at JAEA: OK ≤ 0.1-0.2 mA/cm²), MYRRHA has 0.07mA/cm²
  - **Beam losses**: minimize irradiation of the accelerator and of the environment (main issue for any high power beam, not only for ADS); impact on the maintenance and repair
  - **Reliability**: minimize beam trips (multiple sources); the limitation comes mainly from thermal stress in fuel structure. For instance, for MYRRHA:
    - Trip < 0.1 s no limit
    - 0.1 s < Trip < 3 s not more than 100 per day
    - Trip > 3 s 10 in three months
    - Administrative limit if SCRAM event
  - **Beam power stability and control**: 1% fluctuation on beam intensity is 1% fluctuation on the thermal power
Accelerator requirements

- **Large operational range of beam intensity**: to follow demand (factor 10?)
- **Energy efficiency**: maximize fraction of electric grid power stored in the beam. Relevant to overall energy efficiency of system
- **Size of accelerator**: for waste elimination, people might want to fit it on the site of a standard nuclear power plant
- **Cost**: This is very important. One main criticism of ADS is that “the accelerator does not exist and will be too expensive”

- In the end, the solution chosen among LINAC, Cyclotron or FFAG, will be the one best fulfilling these requirements

*H$_2^+$ AIMA Cyclotron w reverse bend and multiple injection, 1.6 MW at 800 MeV* (P.Mandrillon)
Conclusion

- There is no reason to keep thorium out of the energy R&D effort in Europe. Furthermore Europe has all the know-how to do this efficiently.
- The physics of Accelerator-Driven Systems is well understood, conceptual designs exist.
- When taking into account the need for safety, waste management and non-proliferation, thorium in a fast neutron ADS, is an interesting option for energy production and waste elimination.
- It is a challenging innovation but there is no show stopper. Europe cannot afford not to built a “demonstrator” of significant power (MYRRHA?) in order to validate technological solutions.
- iThEC in Geneva is promoting R&D on thorium in general, and on ADS in particular: http://www.ithec.org/
Thank You!

Xu Hongjie

Anil Kakodkar
India – Vast Resources of beach sand minerals
(Ilmenite, monazite, zircon)

P.K. Wattal
BARC, India
RESERVE
Demonstrated **Adiabatic Resonance Crossing** for the elimination of long-lived fission fragments, an idea also proposed by C. Rubbia.
Time dependence

- Diffusion equation (with $\Phi = \beta n$, where $\beta$ is the neutron velocity):

$$\frac{\partial n(\bar{x},t)}{\partial t} = \frac{1}{\beta} \frac{\partial \Phi(\bar{x},t)}{\partial t} = D\nabla^2 \Phi(\bar{x},t) + (k_\infty - 1) \Sigma_a \Phi(\bar{x},t) + C(\bar{x},t)$$

- Case of a neutron pulse, given by $C_0 \delta(t)$, and substituting

$$\Phi(\bar{x},t) = \sum_{l,m,n} \Phi_{l,m,n} \psi_{l,m,n}(\bar{x}) f_{l,m,n}(t)$$

provides an equation for the time dependence:

$$\frac{df_{l,m,n}(t)}{f_{l,m,n}(t)} = -\beta \left[ DB_{l,m,n}^2 + (1 - k_\infty) \Sigma_a \right] dt$$

and the general solution

$$\Phi(\bar{x},t) = \sum_{l,m,n} \Phi_{l,m,n} \psi_{l,m,n}(\bar{x}) e^{-\beta \Sigma_a (1-k_{l,m,n}) t}$$

- Characteristic decay time is shorter as modes become higher. At the criticality limit ($k_{1,1,1}=1$), the mode is infinitely long. Fermi used this to measure the approach of criticality in his Chicago Pile 1 in 1942, and the method is well suited for ADS.
Fossil Fuel Proven Reserves

- Newly discovered resources are also getting more expensive to extract
Energy and pollution in China

- Even though coal accounts for 70% of China’s total energy consumption, China is doing better than most European countries, in terms of CO₂ emissions: no point telling China to stop burning coal ...

<table>
<thead>
<tr>
<th>Country</th>
<th>ton of CO₂ per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>16.94</td>
</tr>
<tr>
<td>Germany</td>
<td>9.14</td>
</tr>
<tr>
<td>Denmark</td>
<td>7.48</td>
</tr>
<tr>
<td>China</td>
<td>5.92</td>
</tr>
<tr>
<td>France</td>
<td>5.04</td>
</tr>
<tr>
<td>World</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Source: IEA 2013 Key World Energy Statistics

- Germany to open 10 new coal-fired power stations in the next two years (Blomberg, Nov. 2013), while at the same time exporting subsidized green electricity (Netherland)
Choice of the accelerator type: Linac versus cyclotron

In principle both accelerator types can deliver the required proton beam for ADS applications. However, the nature of each — one compact unit for an isochronous cyclotron, a sequential modular structure for the linac — brings both advantages and disadvantages.

Due to its recirculation nature, a cyclotron is compact and cost effective. However, it lacks every form of redundancy which is crucial for fault tolerance. Hence, a cyclotron will not reach the wanted level of availability, and furthermore an upgrade of its beam energy is not a realistic option.

Linacs on the other hand, can be built as a sequence of many independent accelerating structures (RF cavities), which is a highly modular situation. It is this modularity that makes such a linac particularly well suited to tackle the availability issue. In case of failure of a single accelerating module, independently controlling the RF amplitude and phase of the adjacent modules creates the conceptual possibility of recovering the beam within a short time. Furthermore, increasing the final beam energy is obtained by merely adding accelerating modules.

For these reasons MYRRHA favours the linac option.

Linac versus cyclotron

<table>
<thead>
<tr>
<th>LINAC</th>
<th>CYCLOTRON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large space requirement (few hundred m long) but light</td>
<td>Compact but heavy</td>
</tr>
<tr>
<td>Expensive</td>
<td>Cheaper in construction</td>
</tr>
<tr>
<td>Less efficient power conversion</td>
<td>More efficient power conversion</td>
</tr>
<tr>
<td>Modularity provides redundancy</td>
<td>No intrinsic redundancy</td>
</tr>
<tr>
<td>Upgradable in energy</td>
<td>Difficult to upgrade in energy</td>
</tr>
<tr>
<td>Straightforward beam extraction</td>
<td>Difficult extraction and related beam losses</td>
</tr>
<tr>
<td>Capable of high beam current (100 mA)</td>
<td>Modest beam current capability (5 mA)</td>
</tr>
</tbody>
</table>
Realistic ADS system

Today one can simulate in great detail any realistic system of this type (LHC experiments have up to 30 million volume elements in their simulation)

- The physics is extremely well known!
- Use passive safety – physics does not fail!
- Neutron data are improving

Strategic importance of n_TOF at CERN!
Neutron cross section data

- Develop precise and predictive simulation, requires precise input data:
  - n_TOF facility at CERN

Frank Gunsing

$^{232}$Th(n,γ)
The energy problem

If the rest of the world is allowed to live as well as we do in Europe today, then the energy production of the world will have to be increased by a factor of 3 or more, by the end of this century, when the world population will likely approach 11 billion individuals (from 15 TW to ≥ 50 TW). Most of the population increase is expected in developing countries. *Europe is not representative of the world!*

“Visualization from Gapminder World, powered by Trendalyzer from www.gapminder.org.”

See Prof. Hans Rosling’s lecture
Architecture of an ADS system

Example of the generic 1500 MW\textsubscript{th} system (Energy Amplifier), designed and simulated by C. Rubbia et al. (CERN/AT/95-44 (ET))

\begin{itemize}
\item 645 MW\textsubscript{e} \rightarrow \text{OUTPUT}
\item 675 MW\textsubscript{e}
\item 29 MW\textsubscript{e}
\item 12.5 MW
\item 1500 MW\textsubscript{th}
\item \(\eta_{\text{el}} \sim 45\%\)
\end{itemize}

\(\eta \sim 43\%\)

\(k = 0.98\)

\(G = G_0/(1-k)\)
Critical versus Subcritical Systems

Chain Reaction

Nuclear Cascade

Effective neutron multiplication factor

\[ k = \frac{\text{Production}}{\text{Absorption} + \text{Losses}} \]

Self-sustained process:

- \( k = 1 \) (if \( k < 1 \) the Reactor stops)
- \( k > 1 \) (the Reactor is supercritical)

\[ \Rightarrow \text{The time derivative of the power kept equal to zero by control} \]

Energy gain (G)

\[ \text{Energy gain (G)} = \frac{\text{Energy produced by EA}}{\text{Energy provided by beam}} = \frac{G_0}{1 - k} \]

Externally driven process:

- \( k < 1 \) (\( k = 0.98 \))

\[ E_{\text{tot}} = G \times E_p \]

\[ \Rightarrow \text{Constant Energy Gain} \]

\[ N_0 \left( 1 + k^1 + k^2 + k^3 + k^4 + \ldots + k^n \right) = N_0 \frac{k^{n+1} - 1}{k-1} \approx \frac{N_0}{1-k} \]
R&D in Europe

Many projects carried out since the EU FP5 and FP6 (Eurotrans) in the field of partitioning and transmutation. All aspects covered.
Several *Molten Salt ADS* concepts were discussed: Carlo Rubbia, Toshinobu Sasa and Laszlo Sajo-Bohus.

**MS ADS**

**ADMS ?**

---

**Toshinobu Sasa**

**Carlo Rubbia**

jpr/Varenna-2014
Detailed simulation
From Pu to asymptotic Th-U mixture

The appropriate $k < 1$ value is adjusted with the help of control bars

Impressive demonstration of compensation mechanism allowing extended burnup

Carlo Rubbia
Abstract

- **Title**: Thorium: An energy source for the world of tomorrow?

- **Abstract**: To meet the tremendous world energy needs, systematic R&D has to be pursued to replace fossil fuels. The ThEC13 conference organized by iThEC at CERN last October has shown that thorium is seriously considered by developing countries as a key element of their energy strategy. Developed countries are also starting to move in the same direction. How thorium could make nuclear energy (based on thorium) acceptable to society will be discussed. Thorium can be used both to produce energy and to destroy nuclear waste. As thorium is not fissile, one elegant option is to use an accelerator, in so-called “Accelerator Driven Systems (ADS)”, as suggested by Nobel Prize laureate Carlo Rubbia. CERN’s important contributions to R&D on thorium related issues will be mentioned as well as the main areas where CERN could contribute to this field in the future.
Contents

• The **energy problem**: a global issue
• Review of **R&D on thorium technologies** (ThEC13 thorium conference)
• Possible ways of using **thorium**
• Accelerator Driven Systems (**ADS**)
• CERN contributions to ADS
How much thorium for 1 GWe?

- Calculating the amount of thorium needed for producing 1 GW of thermal energy during one year is a straightforward calculation, based on the fact that the energy released as heat per fission is about 189 MeV (see later).

- Calculating the amount of thorium needed for producing 1 GW of electrical energy during one year requires one basic assumption:

  For 1.5 GW of thermal power, 645 GW of electrical power are sent to the Grid (see later)
Energy in fission reactions

- (1) Kinetic energy of fission fragments: 167 MeV
- (2) Prompt (< $10^{-6}$ s) gamma ray energy: 8 MeV
- (3) Kinetic energy of fission neutrons: 8 MeV
- (4) Gamma ray energy from fission products: 7 MeV
- (5) Beta decay energy of fission products: 7 MeV
- (6) Energy as antineutrinos ($\bar{\nu}_e$): 7 MeV

Adding 1, 2, 4 and 5 (clearly neutrinos do not deposit heat, and fission neutrons are mostly absorbed to induce fissions), one gets:

189 MeV for the contribution to the heat deposition per fission
Energy flow in EA

This is the result of a detailed simulation using particle physics methods, starting from single protons in the beam.
Amount of thorium

• To produce 645 GWe in a EA requires a thermal power of 1500 MW. Energy during one year:
  \[ 1500 \times 10^6 \times 365 \times 24 \times 3600 = 4.73 \times 10^{16} \text{ Joules} \]

• Number of fissions (1 eV = 1.6x10^{-19} J):
  \[ 4.73 \times 10^{16} / (189 \times 10^6 \times 1.6 \times 10^{-19}) = 1.564 \times 10^{27} \text{ fissions} \]

• The number of \(^{232}\)Th atoms consumed to have one \(^{233}\)U fission is about 1.127 (see later)

• The mass of \(^{232}\)Th used to produce 1.564\times10^{27} fissions is (molar mass of \(^{232}\)Th is 232.0381 g/mole, and one mole = 6.022\times10^{23} atoms):
  \[ (1.127 \times 1.1564 \times 10^{27} / 6.022 \times 10^{23}) \times 232.0381 = 6.79 \times 10^5 \text{ g} = 679 \text{ kg} = 0.679 \text{ t} \]
Thorium for 1 GWexYear

- 645 GWe for one year requires **0.679 ton** of thorium in C. Rubbia’s Energy Amplifier, hence for producing 1 GWe during one year takes **1.05 ton** of thorium.

- Note that to produce **1 GW** of thermal energy during one year requires only **0.453 ton** of thorium (6.79 kt of thorium per year for the entire world power consumption of 15 TW).

- Given that the density of thorium is **11.7 g/cm³**, it takes a cube of thorium of side \( a = 33.8 \text{ cm} \) to produce 1 GWth during one year!
Thorium in the Earth’s crust

• According to Wikipedia, the Earth’s crust contains $1.2 \times 10^{14}$ tons of thorium.

• Recovering only one part per million ($10^{-6}$) of this, that is $1.2 \times 10^{8}$ tons, would provide the present world power consumption of 15 TWth, for almost 20’000 years:
  
  $1.2 \times 10^{14} \times 10^{-6} / 6.79 \times 10^{3} = 1.77 \times 10^{4}$ years
  
  $\approx 18’000$ years.

• Thorium is a potentially sustainable source of energy on the human time scale.
Annual production of a 900MWe PWR

On suppose un rendement de 33% et un facteur de charge de 70% (7,9 TWh $\rightarrow$ 5,5 TWh); typiquement 225kg de TRU et 745 kg de FF.

<table>
<thead>
<tr>
<th>Electricité</th>
<th>5,5 milliards de kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustible usagé (à 33,000 MWd/t)</td>
<td>21,5 t de UO₂</td>
</tr>
<tr>
<td><strong>Actinides</strong></td>
<td></td>
</tr>
<tr>
<td>Uranium $^{238}$U (avec 1,1% de $^{235}$U)</td>
<td>20 620 kg</td>
</tr>
<tr>
<td>Plutonium $^{239}$Pu, $^{241}$Pu (71%)</td>
<td>20 400 kg</td>
</tr>
<tr>
<td>Actinides mineurs (Np, Am, Cm, etc.)</td>
<td>209 kg</td>
</tr>
<tr>
<td><strong>Fragments de fission (total)</strong></td>
<td>16 kg</td>
</tr>
<tr>
<td><strong>Fragments de fissions à vie longue</strong></td>
<td>745 kg</td>
</tr>
<tr>
<td><strong>Déchets de classe A</strong> (Gaines, matériaux</td>
<td>50 kg</td>
</tr>
<tr>
<td>structurels, etc.)</td>
<td></td>
</tr>
</tbody>
</table>

100 – 200 m³
Pyro-electric reprocessing

- Electrolysis of molten salt solution. Actinides are separated out. Method already tested in the case of Uranium at Argone National Lab (99.99% efficiency achieved). Plutonium remains combined with minor actinides (Np, Am, Cm, etc.). Simpler, nothing goes to the environment (no water) unlike Purex, small dimensions, not proliferating.
Destruction of nuclear waste

- In a system where elements can be both created and generated, the concentration reaches an equilibrium after a certain time.
CONSOMMATION NETTE DE PU / UNITÉ D’ÉNERGIE (kg/TWhe)

POURCENTAGE DE PLUTONIUM DANS LE MÉLANGE

Destruction
Production

Réacteur rapide Uranium-Plutonium
Transmutation of LLFF

\[
{}^{99}\text{Tc} \quad (t_{1/2} = 2.1 \times 10^5\ \text{ans}) + n \rightarrow {}^{100}\text{Tc} \quad (t_{1/2} = 15.8\ \text{s}) + \gamma \text{ prompts}
\]

ARC maximise le taux de capture de neutrons

\[
{}^{100}\text{Ru}^* \rightarrow {}^{100}\text{Ru} \quad (\text{stable}) + \gamma' s
\]

174\mic{\text{s}}

92\mic{\text{s}}

Thermique

Section Efficace de Capture du \(^{99}\text{Tc}\)

Energie du Neutron (eV)

Section Efficace (barns)