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TITLE : ENERGY CONCEPTS FOR THE 21st CENTURY
TIME : 20, 21, 22, 23 & 24 March, from 11.00 to 12.00 hrs
PLACE : Auditorium, bldg 500

ABSTRACT

The series is composed of five lectures:

- Current ideas concerning wind energy.
- Fundamental research and the energy problem. Examples of how fundamental research feeds innovation. Global energy trends and their consequences for the future.
- Can nuclear energy contribute to the global solution of the energy problem? How does the Energy Amplifier work? Can nuclear waste be eliminated?
- Experimental tests of new concepts at CERN: The FEAT and TARC (Transmutation by Adiabatic Resonance Crossing) experiments.
- Other fields of applications of the TARC effect, in particular in medicine, fundamental research and space travel. Present and Future of R&D on ADS systems.
Energy Concepts for the 21st Century

P.Hjuler Jensen
Danish Research Establishment Risø, DK

CONTENT


The presentation gives a overview over the following:

The wind energy development world-wide is presented addressing development in capacity and economy.

The technology development is presented through the development in concepts, size, efficiency reliability.

Finely a technology forecast for wind energy development worldwide is presented.
Status end 1998
Installed capacity in Denmark

Accumulated capacity

End 98: 1460 MW

Avg. new turbine capacity

MW

Private Utility

kW
Wind Turbine Size
Type approved machines on the Danish market

- Largest
- Average
- Smallest

[Graph showing kW and years from 1981 to 1997]
World Market for Wind Turbines

- 20 years track record for commercial wind turbines
- Average annual growth of 40% between 1991 to 1997
- Wind turbines in more than 50 countries
- Increasingly more countries have ambitious wind energy programmes
- Competitive international market for equipment and finance

Source: BTM-consult

![Graph showing the installed capacity of wind turbines from 1990 to 2000. The y-axis represents the year, and the x-axis represents the installed capacity in MW. The chart indicates a steady increase in installed capacity over the years.]
Wind Turbine sizes

% of annual sales in numbers

22-30 kW
55-75 kW
90-100 kW
150-250 kW
300-400 kW
450-600 kW
Installation Type and Payment Rate

- Single ownership installation
- Joint ownership installation

85% of utility net selling price
70% of utility net selling price
Wind Turbine Economy - Danish Marked

![Graph showing the cost of wind energy in Danish Marked from 1981 to 1997. The cost decreases from approximately 1.4 DKK/kWh in 1981 to about 0.2 DKK/kWh in 1997.](image-url)
Industry Progress Ratio

Each time accumulated volume double costs decrease 20%

- Reduction of costs of equipment ~ 10 - 20%
- Better siting ~ 0 - 10%
Cost of Wind Energy
Danish Government’s Cost Expectations

20 years, 5% interest rate
Source: AKF & Danish Energy Agency
Energy 21
The Danish Government's New Plan of Action

Some Targets In Energy 21
- 20% reduction of CO₂ emissions from 1988 to 2005
- 50% reduction of CO₂ emissions before 2030
- 12 - 14 % of renewable energy by 2005 (100 PJ)
- 35% renewable energy by 2030 (235 PJ)

Targets for Wind Energy
- 1500 MW wind turbines by 2005 (200 MW off-shore)
  12% of electricity consumption
- 5500 MW wind turbines by 2030 (4000 MW off-shore)
  50% of electricity consumption

http://www.ens.dk/stat/eindex.htm  http://www.ens.dk/e21uk
Off-shore Windfarms

Available off-shore sites
1. South of island of Læsø
   ▲ 43 km² + 438 km²
2. Horn’s Reef
   ▲ 41 km² + 94 km²
3. Rødsand / Gedser Reef
   ▲ 39 km² + 157 km²
4. Omø Shallows (Vindeby)
   ▲ 51 km² + 107 km²

Total area ~ 1000 km²
Total potential ~ 8000 MW

Status
- Two demonstration farms
  ▲ Vindeby (Omø Shallows, 4)
  ▲ Tønø Knob (T)
- Plan-of-action: July 1st 1997
- Ongoing feasibility studies:
  ▲ Rødsand / Gedser Reef
  ▲ Middelgrunden
    (Copenhagen harbour)
- Substantial cost reduction for new 100 - 200 MW projects
  ▲ 55-60% compared to Vindeby
Wind Resources

Wind resource studies
On project basis Risø offers training and quality control of wind resource studies all over the world.
Typically, Risø trains local institutions, helps during the project and assures the quality of the result.

Short-term prediction
Electrical utilities with a high penetration of wind energy need to know in advance the production from their wind farms. Risø has developed and verified a method to this end. The method predicts the wind-farm-produced power 36 hours ahead, every 6 hours.

WAasP
The Wind Atlas Analysis and Application Program
- The standard in wind resource calculation and micro-siting.
- More than 500 users in more than 60 countries.

European Wind Atlas
- A hand-book describing the European wind resource.
- Describes the Wind Atlas Methodology, which is the basis of most wind atlases in the world.

Due diligence / second opinion
To secure the investment in a wind farm project, reliable estimates of the production are needed.
Risø offers independent state-of-the-art calculations of the wind resource. This service is being used by investors, banks and insurance companies world-wide.

Risø National Laboratory, Denmark
Aeroelastic Design

Rise develops and uses advanced computational tools to establish the relevant design load basis and assists in finding the optimal design of components and complete wind turbines.

Aerodynamics
Three-dimensional Navier-Stokes computations of the airflow are very useful in the development of simpler and computationally inexpensive engineering models. In combination with numerical optimisation, aerodynamic engineering models are used to design new wind turbine airfoils followed by experimental verification in the wind.

Structural dynamics
Finite element analysis and experiments (both full scale and in test stands) give information on strength, mode shapes, eigenfrequencies, stability and damping properties of the different parts composing a wind turbine.

Aeroelasticity
The combination of aerodynamics and structural dynamics into aeroelastic codes allows prediction of the extreme and fatigue loads that a wind turbine experiences during its lifetime.

New concepts
The traditional three-bladed concept is continuously improved, but also new concepts are examined. An example is the two-bladed, dynamically flexible wind turbine that sways in the wind as a straw minimising the loads.

Riso National Laboratory, Denmark
Electrical Design and Control

Control strategies
- Optimisation of pitch control and rotor speed control versus structural loads, production through modelling and testing.
- Flexibility and power quality.
- Storage control for wind power smoothing.

Electromechanical components
- Analysis of generator types, specially designed for wind turbine applications.
- Application of latest technology of power converters for grid connection of wind turbines.

Hybrid systems
- Integration of wind power in electrical power supply systems.

Power quality
- Specification and development of power station characteristics of large wind farms.
- Power quality for grid connection of wind farms in weak grids - e.g. large wind farms in India.
- Statistical calculations to investigate alternatives to grid reinforcements - e.g. voltage dependent power control of wind turbines.
- Development of methods for standardisation and verification of power quality for wind turbines.
Testing & Measurements

The Test & Measurement Group

has a world leading experience in measurements on wind turbines and testing of blades and components. Our Sønder Test Centre in West Denmark and a coming test site in Northwest Denmark are expected to be the main test facilities going into the next century.

Accredited measurements

Accredited measurements for private and public customers are performed according to the European Standard EN 45001.

1. Mechanical Load Measurements
   - The direct way to determine structural safety limits
   - Validation of load calculations
   - Determination of loads under specific conditions

2. Power Curve Measurements

3. Blade Tests
   - Static tests
   - Fatigue tests

Standardisation of testing procedures

Participation in R&D projects within the European programmes JOULE and SMT (Standards, Measurements and Testing) to support the international standardisation work.

Membership of committees under IEC and CENELEC is our contribution to standardisation of measurement procedures, and as a member of the International MEASNET-organisation we guarantee high quality and international recognisable measurements.
Blade testing

Static blade tests
Accredited Static Load Tests performed at the Sparkær Centre consists of the standard parts:
- Determination of physical properties
- Determination of natural frequencies
- Flapwise proof test
- Edgewise proof test

Strain gauges in a number of 60 - 120 are applied to the blade skin and internal blade structure, and the blade is bolted to the test rig. Structural damping and natural frequencies are measured.

For a flapwise proof test 5 or 6 loading clamps are attached to the blade, and loads are introduced in all points simultaneously.

Loads are introduced by remote controlled electric hoists or hydraulic systems, and forces are measured by load cells.

Deflections are measured by electric remote sensors. Edgewise test is normally performed in two directions: Against and in the rotor thrust direction.

The strain values measured on the blade surface often indicate that structural buckling in the blade skin is building up, although difficult to spot at an early stage.

Accreditation

Having tested rotor blades since 1984 the Sparkær Centre, as part of the Test and Measurement Group, was in 1998 accredited according to the European Standard EN 45001 "General Criteria for the Operation of Testing Laboratories".

The accredited measurements are:
- Static Blade Tests
- Fatigue Blade Tests
- Determination of Natural Frequencies
Certification of Wind Turbines

The Secretariat for Type Approval
is accredited by DANAK for compliance with DS/EN 45011 for product
certification of wind turbines, and offers certification for compliance with the
following regulations:

- Technical criteria for the Danish Approval Scheme for Wind Turbines.
- Dutch type approval with reference to Technical Criteria NVN 11400.
- German Gutachten with reference to "Technischer Baubestimmungen,
  Einführung der Richtlinie für Windkraftanlagen".
- International Standard for Wind Turbine Generation Systems - Wind
  Turbine Certification IEC 61400-22.

DNV - Det Norske Veritas
The Secretariat for Type Approval has a formalised co-operation with
Det Norske Veritas (DNV) - one of the largest international classification
societies, and thus supplementing the state research institute Risø.
Risø wind energy activities

Wind turbine of tomorrow
Light and flexible structural design, full control of rotational speed, individual adaptive control of pitch angles, fully controllable electronic grid connection. Risø investigates the perspectives of different concepts, optimising the operation with respect to costs, energy production, power quality and lifetime, giving the lowest overall price per kWh.

Loads and lifetime
Reducing the wind turbines weight and price without affecting the safety and lifetime requires a detailed knowledge of the nature of the wind, the aerodynamics, the structural behaviour, loads and stresses. Risø is in the front with a combination of state-of-the-art research, models and experiments.

Approval Schemes
Risø plays a key role in developing, formulating and specifying international design bases and standards for wind turbines. The Danish Approval Scheme, developed and maintained by Risø for the Danish Energy Agency, acts as a well proven scheme in the international standardisation work.

Wind power utilisation
With the rapidly increasing contribution from wind power, Risø investigates in advance operation and regulation of wind power plants and the electric network in order to optimise the value of the installed wind power capacity, and maintain a high power quality.

Consultancy services
Risø carries out consulting work, feasibility studies, project planning etc. on commercial basis. Risø offers national and international training activities for industry, institutes, planners, consultants etc. within all wind energy aspects.
International consultancy services

Wind power projects
- Institution building projects
- Test station building
- Project design and formulation
- Feasibility and appraisal studies
- Wind measurements and data analysis
- Wind resource assessment
- Wind atlas analysis and wind mapping
- Wind farm siting, layout and production estimation
- Power system analysis and design
- Technical specifications and tendering
- Economic analysis and cost of energy calculation
- Uncertainty analysis and evaluation
- Second opinion assessment of wind farm projects
- Project implementation planning
- Energy planning with wind energy

Training activities
Riso develops, conducts and builds adapted training activities in wind energy technology, wind resource assessment, feasibility of wind energy projects, wind turbine testing and certification - carried out on location or at Riso.

References
Baltic countries, Bulgaria, Czech Republic, EU-countries, Russia, Scandinavia
Algeria, Egypt, Jordan, Kuwait, Libya, Morocco, Syria
Cape Verde, Somalia, South Africa, Tanzania
India, Indonesia, Korea, Mongolia, Nepal, China
USA, Chile, Mexico
Australia, Cook Islands, Fiji, Tonga
Items Discussed in Rome in 1961

Cost's dependency of
- Concept and design
- Number of blades 1,2,3,4, -
- Turbine size and spec. power
- Simple versus sophisticated concepts (Gedser/Hütter)
- Direct driven generators
- New materials (plastics)
- Market volume
- Local production
- Accelerated tests
Concepts Presented in Rome 1961

All imaginable concepts were presented

French
Andreau-Enfield
Site: Grand Vent
100 kW
Downwind

Danish
Juul’s design
Site: Gedser
200 kW, 24 m
Stiff and heavy

German
Hütter’s design
Site: near Stuttgart
100 kW, 34.8 m
Highly flexible

American
Jacob’s design
Site: All over America
3 kW, 4.5 m
Light design

+ many others
<table>
<thead>
<tr>
<th>Concepts</th>
<th>Future</th>
</tr>
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<tbody>
<tr>
<td>Rome 1961</td>
<td>Dublin 1997</td>
</tr>
<tr>
<td>All imaginable concepts presented</td>
<td>No new concepts</td>
</tr>
<tr>
<td>Few on the market</td>
<td>Greater variety on the market</td>
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</tbody>
</table>

- **Aerodynamical and structural knowledge**
  - Only very simple designs could be based on calculations
  - We are increasingly able to rely on modelling in design

- **Computer modelling**
  - No computers
  - Modelling available for highly flexible structures
  - Computers available
  - Faster computers

- **Measurement**
  - Simple measurement techniques
  - Fast computer based measurement techniques
  - Verification of designs available

<table>
<thead>
<tr>
<th>Markets</th>
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<tr>
<td>Few markets</td>
<td>Large, stable markets</td>
</tr>
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</table>
Future Wind Turbine Concepts

Higher structural flexibility
- Development of better load simulation codes
  - Faster computers
  - Lighter designs

Higher drive-train flexibility
- Development of var. speed and pitch
- Cheaper power electronics
  - Better grid impact

Higher control flexibility
- Development of control systems for site specific design and operation
  - Adaptive grid connection
# Changing Reasons for Wind Power

<table>
<thead>
<tr>
<th>Era</th>
<th>Context</th>
<th>Driving factors for wind power</th>
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<tbody>
<tr>
<td></td>
<td><strong>1970s</strong></td>
<td><strong>1990s</strong></td>
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<tr>
<td></td>
<td>• Energy supply uncertainties</td>
<td>• Cheap Oil</td>
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<td></td>
<td>• Unstable oil prices</td>
<td>• Environmental concerns</td>
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<td></td>
<td>• Planned energy sectors</td>
<td>• Re-structuring energy sectors</td>
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<td><strong>2010s</strong></td>
<td><strong>2010s</strong></td>
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<td></td>
<td>• OPEC's safety of demand</td>
<td>• Diversified supply</td>
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<td></td>
<td>• Stable fossil prices</td>
<td><strong>Economical and energy policy issues</strong></td>
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<td></td>
<td>• New energy sector structure</td>
<td>• Wind energy is competitive</td>
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<tr>
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<td>• ?????</td>
<td>• Wind energy is clean and safe</td>
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<td></td>
<td><strong>Driving factors for wind power</strong></td>
<td><strong>Economical and energy policy issues</strong></td>
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<tr>
<td></td>
<td>• Energy policy issues</td>
<td>• Wind energy is competitive</td>
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<tr>
<td></td>
<td>• Wind energy is a domestic source of energy</td>
<td>• Wind energy is clean and safe</td>
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<td><strong>Environment and industry policy issues</strong></td>
<td><strong>Economical and energy policy issues</strong></td>
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<tr>
<td></td>
<td>• Green house gas mitigation technology</td>
<td>• Wind energy is competitive</td>
</tr>
<tr>
<td></td>
<td>• New jobs, new technology</td>
<td>• Wind energy is clean and safe</td>
</tr>
<tr>
<td></td>
<td>• Wind energy is clean and safe</td>
<td><strong>Economical and energy policy issues</strong></td>
</tr>
</tbody>
</table>
Environmental Requirements
for future wind turbine technology

Planning issues
- Less noise
- Less reflections
- Integration in the landscape
- “Stealthing”? 

→ More planning related limitations and requirements

Developer or buyer issues
- Life-cycle analyses
- Re-cycling of all parts
- Other “political consumer” requirements

→ Environmental certification
Problems to be Solved

- Today, wind power is only competitive at some sites
- Significant visual impact
- Public acceptance/“Not-In-My-Back-Yard” dilemma
- Uncertainty within utilities and financial organizations
European Targets

Commission's White Paper for a Community Strategy and Action Plan

- Renewable energy by 2010
  - 12% penetration of renewables in the Union by 2010 (6% today)

Wind energy contribution
International Perspektives

Status end 1998: 9,600 MW

WEC, FDV for 2000: 10 - 15,000 MW

World Energy Council for 2020:
- Current policy scenario (1½ %): 180,000 MW
- Ecologically driven scenario (5 %): 474,000 MW

1 MW ~ 1 mio. USD
EWEA Targets - 1997

Year
2000
2010
2020

MW
8,000
40,000
100,000
CERN Academic Training
March 21, 22, 23 and 24th, 2000

Cours/Lecture Series

Energy Concepts for the 21st Century

Jean-Pierre Revol
(CERN)

Contents

Lecture 1: Fundamental research and the energy problem.

Lecture 2: Can nuclear energy contribute to the global solution of the energy problem? How does the energy amplifier work? The First Energy Amplifier Test (FEAT). Transmutation of TRans-Uranian elements (TRU).

Lecture 3: The Transmutation by Adiabatic Resonance Crossing (TARC) experiment. Transmutation of long-lived fission fragments using ARC with the Energy Amplifier.

Lecture 4:

a) Other fields of applications of the TARC effect: [Medicine and industry, Fundamental Research (nTOF), Space Travel, etc.]

b) Present and Future of R&D on ADS systems.
CERN ACADEMIC TRAINING

ENERGY CONCEPTS FOR THE 21ST CENTURY

Particle physics contribution to the elimination of nuclear waste

Jean-Pierre Revol

Progress in particle accelerator technology makes it possible to use a proton accelerator to eliminate nuclear waste efficiently. The Energy Amplifier (EA) proposed by Carlo Rubbia and his group is a subcritical fast neutron system driven by a proton accelerator. It is particularly attractive for destroying, through fission, transuranic elements produced by present nuclear reactors. The EA could also transform efficiently and at minimal cost long-lived fission fragments using the concept of Adiabatic Resonance Crossing (ARC) recently tested at CERN with the TARC experiment. The ARC concept can be extended to several other domains of application (production of radioactive isotopes for medicine and industry, neutron research applications, etc.).

1 Introduction

The research work presented here is an exceptional contribution for a laboratory such as CERN, in principle devoted entirely to fundamental research. However, the Energy Amplifier (EA) [1] is an innovative approach to nuclear energy, and it should come as no surprise that such an innovation results from fundamental research which has always been a main driving engine of innovation. Examples are legion and well known; one of the most recent, the World-Wide Web, was invented at CERN and not by the much more powerful and resourceful computer industry.

Because particle physicists, interested in discovering the ultimate structure of matter, have pushed particle accelerator technology as far as they have, it is possible today to consider using a proton accelerator to drive a new type of nuclear system, with very attractive properties.

Today, the world is facing an extremely difficult challenge, that of producing sufficient energy to sustain economic growth without ruining the ecological equilibrium of the planet. The massive use of fossil fuels has allowed the Western World to reach an unprecedented level of wealth. Unfortunately, if the rest of the Earth's population were to carry out the same energy policy, the entire planet would be in serious trouble. There is, therefore, a moral obligation for developed countries to provide new energy sources for the entire world in order to minimize global warming and other pollution effects.

If an acceptable solution is found, it will certainly be the result of systematic R&D and in this context, nuclear energy should be part of this R&D. The present nuclear energy programme is meeting growing public opposition world-wide because of three main reasons: (a) the association with military use and the fear of nuclear weapon proliferation; (b) the fear of accidents such as Chernobyl (1986 prompt-supercritical reactivity excursion) and Three Mile Island (1979 loss-of-coolant accident resulting in a core meltdown); (c) the issue of the back-end of the fuel cycle (nuclear waste management: at this time only deep geological storage is seriously envisaged).

Obviously, nuclear power, without these drawbacks would be ideal as it does not release greenhouse gases nor other chemical pollutants (NOx, SOx, etc.), nor dust particles, nor even radioactive particles as coal ashes do. Therefore, the real
question facing scientists today is: Is it possible to transform nuclear energy production in such a way as to make it acceptable to society? Nuclear energy is a domain that has essentially seen no significant fundamental R&D since the end of the 1950s when the first civil power plants came into operation. There have been many technological improvements, mainly with the purpose of improving safety. However, we have seen that even these were not sufficient.

The concept of the EA was proposed by C. Rubbia and his group specifically as an answer to the concerns raised by current nuclear energy production. The present EA version is optimized for the elimination of the nuclear waste, as it is considered to be the most pressing issue in the Western World. In developing countries such as China and India, where there is virtually no nuclear waste, a version of the EA optimized for energy production, adapted to the detailed needs of the country and with minimized waste production, is the more appropriate solution. It is interesting to note that the Chinese Government has just approved the first phase of an R&D project on an EA system for energy production.

2 Nuclear waste

Transuranic elements (TRU) and fission fragments (FF) are the two main components of nuclear waste representing respectively 1.1% and 4% of spent nuclear fuel. TRU, which are produced by neutron capture in the fuel eventually followed by decay, can only be destroyed by fission, while FF can only be destroyed by neutron capture; therefore, different methods will have to be used to eliminate them. As the long term radiotoxicity of waste (Figure 1) is clearly dominated by TRU, the EA has been designed to destroy them with the highest efficiency.

![Figure 1: Time evolution of the potential radiotoxicity (relative to uranium ore) of the two main components of nuclear waste for PWR spent fuel, obtained with the ORIGEN2 code.](image)

3 The Energy Amplifier

The Energy Amplifier is a subcritical system, driven by a proton accelerator and using fast neutrons (Figure 2). A complete description of all the features of the EA can be found in Ref. [1]. One of the main characteristics is the presence of $10^4$ tons of
molten lead used as a target for the protons to produce neutrons by spallation, as a neutron moderator, as a coolant to extract heat by natural convection and as a radioactivity containment medium.

![Diagram](image)

**Figure 2:** Schematics of the 1500 MWth Energy Amplifier standard unit [1]. The main vessel is about 25 m high and 6 m in diameter. The proton beam is injected vertically, through a vacuum pipe to produce spallation neutrons at the level of the core.

### 3.1 Why fast neutrons?

The choice of lead as a neutron moderator to obtain the hardest possible neutron energy spectrum is deliberate. This is dictated by the need to optimize the fission probability of TRU. Indeed, in the fast neutron flux provided by the EA all TRU can undergo fission, a process which eliminates them, while in a PWR thermal neutron flux many TRU do not fission and thus accumulate as waste (Figure 3).

In addition, as the capture cross section of neutrons on FF is smaller for fast neutrons than for thermal neutrons (Figure 4), and since neutron capture on FF is the main limitation to long burnups, in a fast neutron system the efficiency with which the
fuel can be used will be much higher than in a PWR. Typically it is hoped to reach burnups of 150 GW\texttimes day/t (a burnup of 200 GW\texttimes d/t was achieved in the fast EBR2 system at Argonne National Laboratory).

![Graph](image)

**Figure 3:** Comparison of fission and capture probabilities of actinides for thermal and fast neutron fluxes.

![Graph](image)

**Figure 4:** Fraction of neutron captures on fission fragments (FF) for thermal and fast neutron fluxes, as a function of burnup. The maximum burnup for a PWR is indicated.

3.2 **Subcriticality and the accelerator**

The proposed system [1] has a neutron multiplication coefficient (k) of 0.98. The sustainability of the nuclear fission reactions is made possible because of the presence of an external source of neutrons provided by the proton beam. The working point is far below criticality, which ensures that the system remains subcritical at all times, implying that, by construction, accidents of the Chernobyl type are impossible. The traditional $k_{\text{eff}}$ of the system itself (with beam turned off) is even smaller than $k$ (of the order of 0.97). The energy amplification in the system, defined as the ratio between the energy produced in the EA and the energy provided by the beam, can be parametrized as $G_0/(1-k)$, where $G_0$ is a constant characterizing
the spallation process. This aspect of the system has been studied in the FEAT experiment [2] at CERN where it was shown that this energy gain is well understood and that, not only is it independent of the proton beam intensity, but it is also independent of the beam kinetic energy if above about 900 MeV. This fortunate feature means that the accelerator can be of relatively modest size (Figure 5). All experts agree that the present accelerator technology can provide the required beam power (10 to 20 mA at 1 GeV) with either linac or cyclotron solutions [3]. Examples already exist of high power accelerators which are planned or have been considered in various parts of the world:

- the PSI (Switzerland) cyclotron now running at 1.4 mA, 590 MeV, 0.826 MW [4];
- the proton linac for the Los Alamos Neutron Science Centre (LANSCE) running up to 1.5 mA, 0.8 GeV and 1 MW of average power [5];
- both the USA and Europe had projects to build linacs to produce tritium: (TRISPAL at CEA (France): 600 MeV, 40 mA, 24 MW and LANL (USA): 1 GeV, 100 mA, 100 MW). Even though tritium is no longer officially on the agenda, accelerator developments are continuing;
- Japan is also considering a high intensity proton source as part of their new Neutron Science Project [6].

The system needed to drive an EA represents only a reasonable extrapolation of what has already been achieved in current accelerator technology.

![Diagram of cyclotron layout](image)

Figure 5: The full cyclotron high intensity accelerator layout proposed to drive a $k = 0.98$ EA [1].

In practice, the choice of accelerator technology may be coupled with the strategy for the EA system. If the strategy is to destroy waste on a nuclear power plant site, then the cyclotron with its smaller size (Figure 5) has a clear advantage (it is easier not to have to extend the power plant site, and easier for control and safety of the accelerator, cost effectiveness).

Several other technical advantages can be found in favour of the cyclotron as compared to a linac:

- One can achieve high efficiency (50%), as the current in RF cavities would be about 100 times (100 turns) the extraction current, implying that most power is in the RF cavities (which have reached 70% efficiency), keeping the losses relatively small.
- There is no need for SC cavities, keeping the technology simple.
- The reliability may be better than in linacs which need many more control elements (reliability decreases strongly with an increase in the number of parts).
- In a warm linac the small aperture is a problem for the beam losses, which in addition are not localized (a superconducting linac is difficult below 400 MeV because of the problem of making short niobium-coated superconducting cavities). In cyclotrons, beam losses are expected to be small and localized. Machine elements are accessible as soon as it comes to a halt (this is the case at PSI).

![Energy Amplification Scheme](image)

*Figure 6:* The energy amplification scheme in the standard EA system as proposed in Ref. [1].

An important achievement of the FEAT experiment was the validation of the innovative simulation developed by the EET group at CERN of energy amplification in accelerator driven subcritical systems. This gives confidence in the choice of the main parameters of a system where less than 5% of the electric power needs to be recirculated during its operation (Figure 6).

### 3.3 Destruction of nuclear waste: TRU

The general strategy consists of using as fuel thorium mixed with TRU as opposed to uranium with plutonium as proposed in fast critical reactors, such as SuperPhenix.

The availability of an external neutron source, thanks to the accelerator, and the availability of a fast neutron energy spectrum, thanks to the choice of lead as moderator, allows the sustained operation of a subcritical device with wide flexibility in the choice of fuel. Pure thorium does not fission, but it is $^{233}$U bred from $^{232}$Th which can produce energy through fission. In practice, seeds are needed to provide fissions at the startup of the system, and for this purpose any fissionable element will do: $^{233}$U from a previous EA fuel load or $^{235}$U extracted from natural uranium or military $^{239}$Pu or simply TRU, which is precisely the main component of the waste we wish to destroy. Therefore, it is possible, in an EA, to destroy TRU by fission, a process which produces energy and makes the method economically attractive. TRU represent potentially about 40% of the energy that a PWR delivers while producing these TRU.

Thorium is an attractive fuel because it exists in relatively large quantities in the Earth's crust (at least five times more abundant than uranium), it is isotopically pure (no enrichment is needed), all of it is used in the EA as compared to only 0.7% of $^{235}$U in a PWR and it is about 5 neutron captures away from the TRU one wants to destroy, ensuring that it can work in a mode where it destroys more TRU than it produces.
Nombre de documents à scanner :

Numéros des documents :
AT 0000 0771 / CERN 90-05
C17-900070212

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Figure 7a: Net plutonium consumption per unit energy in a uranium-plutonium fast breeder (CAPRA [7]) as a function of plutonium concentration. Note that the unit is kg/TWxh electric and not thermal.

Figure 7b: Evolution as a function of burnup of the stockpile of the main elements present in the EA fuel [1].

It is easy to see why a thorium system would be much more practical than a uranium system for the destruction of TRU. The high equilibrium concentration (15%) of plutonium in uranium type systems (Figure 7a) forces the use of extremely large plutonium enrichment, which would make these systems extremely dangerous, while in an EA, equilibrium concentrations of the order of $10^{-5}$ (Figure 7b) naturally ensure a high burning rate for reasonable TRU concentrations.

A study [8] carried out for the Spanish Government, based on a practical example, showed that a 1500 MW$_{th}$ EA could destroy a net amount of 34 kg of TRU per TW$_{th}$ of thermal energy produced. In comparison, a PWR, on the contrary, produces 14 kg of TRU per TW$_{th}$.

It is expected that the reprocessing needed to extract TRU from spent fuel should be much simpler than what is needed to extract plutonium from spent fuel for MOX, as performed in the La Hague factory (PUREX process). A pyroelectric reprocessing method [9] developed at the Argonne Laboratory in the United States collects all TRU on a single electrode; this is sufficient since all of them fission and do not need to be separated from one another.
3.4 Why not a critical system using thorium?

Critical reactors using thorium fuel have worked in the past [10], motivated by the prospect of a high neutron yield per neutron absorbed which $^{233}\text{U}$ offers over the whole neutron energy range, only slightly surpassed by $^{239}\text{Pu}$ for fast neutrons. However, there is a price to pay for breeding $^{233}\text{U}$. It is the production of $^{233}\text{Pa}$ which has a large neutron capture cross-section and must be compensated by a higher enrichment in fissile material. Also, $^{233}\text{U}$ fissions produce more $^{135}\text{Xe}$ (direct yield 1.4% for $^{233}\text{U}$ versus 0.3% for $^{235}\text{U}$) and samarium precursors ($^{147}\text{Nd}$, $^{149}\text{Pm}$) than $^{235}\text{U}$. These isotopes represent a significant fraction of the total neutron absorption by fission products. At mid-cycle they account for more than 50% of the total fission product absorption.

Finally, the effective fraction of delayed neutrons ($\beta_{\text{eff}}$) of $^{233}\text{U}$ is less than half of that of $^{235}\text{U}$, leading to a smaller safety margin. This goes against our strategy of a different approach to safety in the choice of a subcritical system. In a critical system, the effective neutron multiplication coefficient ($k$) is maintained equal to one by active control and feedback. The resulting safety of the system is then defined in terms of the probability for the system to become (or not to become) supercritical ($k > 1$), as happened in Chernobyl in 1986. The probability of such an accident occurring may be very small, but is not zero. In a subcritical system, the effective neutron multiplication coefficient is smaller than one by construction. Therefore, the resulting safety aspect is a deterministic one. The system is and remains subcritical at all times and Chernobyl type accidents are simply impossible.

Furthermore, the availability of an external neutron source in an EA allows greater flexibility in the choice of fuel than in a critical system, particularly relevant for TRU burning.

3.5 Destruction of nuclear waste: Long-Lived Fission Fragments (LLFF)

In a system such as the EA, where TRU are destroyed, the long term ($\geq 500$ years) radiotoxicity of the waste becomes dominated by LLFF (Figure 8). This residual level of radiotoxicity could perhaps be tolerated, since it is lower than the level of radiotoxicity of coal ashes corresponding to the production of the same quantity of energy. However, since the main LLFF ($^{99}\text{Tc}$ and $^{129}\text{I}$) can be soluble in water and therefore have a non-zero probability over a time-scale of million of years of contaminating the biological chain with hard-to-predict long term effects, it may be wise to destroy them also.

In order to provide such an option, Carlo Rubbia has proposed to use Adiabatic Resonance Crossing (ARC) [12] (Figure 9) to enhance the neutron capture probability, turning for instance a $2.1 \times 10^5$ year half-life $^{99}\text{Tc}$ into $^{100}\text{Tc}$ decaying quickly ($t_{1/2} \sim 15.8$ s) into stable $^{100}\text{Ru}$. The TARC experiment at CERN [13] has shown that one can indeed use the peculiar (small elastic collision length $\lambda \sim 3$ cm and small elastic $\Delta E/E$) kinematic of neutrons in pure lead (the most transparent to neutrons of all heavy elements) to maximize the neutron capture probability, making optimum use of prominent resonances in the neutron capture cross-section. Note that $^{129}\text{I}$ and $^{99}\text{Tc}$ which were studied in TARC represent 95% of the LLFF volume. The results from TARC imply that one could actually destroy $^{99}\text{Tc}$ and $^{129}\text{I}$ in the lead in the vicinity of the EA core, where conditions are such that one can destroy about twice as much of these elements as is produced over the same time period in the EA core. This possibility to transmute LLFF in a parasitic mode, around an EA core, may be an additional incentive to eliminate LLFF, a process which, unlike the elimination of TRU producing energy, does not pay.
Figure 8: Evolution of the potential radiotoxicity of nuclear waste for PWR, EA and coal burning power station, showing that in the EA, the long-term radiotoxicity can be 4 orders of magnitude smaller than in a PWR in open cycle and is dominated by LLFF if no further incineration is performed (adapted from Ref. [11]).

Figure 9: Illustration of the Adiabatic Resonance Crossing principle, showing how the presence of lead transforms the spallation neutron energy distribution into a flat flux distribution of slowing down neutrons, with iso-lethargic steps smaller than the width of cross-section resonances where they will be captured with high probability. A sketch of the 334 ton TARC lead volume is also shown.
3.6 Medical applications

A second important application domain of ARC is the production of radioisotopes for medical applications [12]. The same technique (TARC), which is very efficient for destroying fission fragments can also be used to induce any other type of nuclear transmutation (ie. radioisotope production), providing an attractive alternative to production with nuclear reactors. A relatively small system free of all the complications of running a critical nuclear reactor has many advantages, as it would:

– favour local radioisotope production thanks to the small size of the system (activator on the hospital site);
– favour the possibility of using shorter-lived isotopes, resulting in a much smaller dose to the patient [example: $^{128}$I (25m) instead of $^{131}$I (8j)];
– avoid long (costly) transportation allowing smaller doses at the production site;
– allow flexibility in the choice of neutron source according to need: high intensity accelerators (cyclotron) [industrial production of $^{99m}$Tc ($t_{1/2} = 6$ h) from the decay of $^{99}$Mo ($t_{1/2} = 65$ h)] to radioactive neutron sources [low activity applications]. In TARC, we successfully tested the idea of using natural molybdenum which contains 24.13% of stable $^{98}$Mo to produce $^{99m}$Mo simply by neutron capture, instead of extracting $^{99}$Mo from the spent fuel of a nuclear reactor.

These applications were considered sufficiently important that CERN has now obtained a patent [14] on medical radioisotope production based on ARC.

4 Conclusion

One should not forget that fundamental research is a strong driving force in innovation and that it can lead to potential solutions of some of the most difficult problems facing our society at the beginning of the third millennium. In particular, nuclear energy could make an important contribution to the solution to the energy problem and it would be a mistake to exclude it, a priori, from fundamental R&D.

The Energy Amplifier, based on physics principles well established by dedicated experiments at CERN, is the result of an optimization made possible by the use of an innovative simulation code validated in these experiments (FEAT and TARC).

This experimental programme has generated new applications in various fields: medical applications for which CERN now owns a patent, research with the approved CERN TOF facility [15], and other surprising ideas such as a nuclear engine [16] for deep space exploration.

All of which come as an additional reward for those who have been involved in this project.

References


Indian Point No 1 Reactor: 270 MWel. PWR, using $^{232}$ThO$_2$-$^{235}$U, stopped because 95% enriched uranium was too expensive;
High Temperature Gas Cooled Reactor, 40 MWel. using $^{232}$ThO$_2$-$^{235}$U, at Peach Bottom, Pa, USA (1966-1974);
Light Water Breeder Reactor, 60 MWel. using $^{232}$Th-$^{233}$U, Shippingport, Pa, USA (shut down in 1982 after reaching a burnup of 60 GWd/t).


CERN ACADEMIC TRAINING

"Energy Concepts for the 21st Century"

Selected Bibliography

The Energy Amplifier


Transmutation of TRUs


The FEAT experiment


The TARC experiment and its applications


Accelerator developments


The CERN Time of Flight Facility


A new nuclear space engine


Technical Working Group and related matters


[3] Benoît Giraud (FRAMATOME), Luciano Cinotti (ANSALDO), Brian Farrar (NNC), "Preliminary Engineering Requirements on Accelerators for ADS",


European Parliament document


Books and notes on Nuclear Reactor physics


Papers on the energy problem and on science


A large number of technical notes have also been produced by the EET Group which can be obtained through the EET secretariat: Catherine Di Maio (75138)
ENERGY CONCEPTS FOR THE 21ST CENTURY

J.-P. Revol (CERN)

LECTURE 1

CERN ACADEMIC TRAINING
March 21-24, 2000
LECTURE OUTLINE

Lecture 1: Introduction on fundamental research and the energy problem.


Lecture 3: The Transmutation by Adiabatic Resonance Crossing (TARC) experiment. Transmutation of long-lived fission fragments using ARC with the Energy Amplifier.

Lecture 4: Other applications of the TARC effect. [Medical and industrial, Fundamental Research (CERN Time Of Flight Facility), Space Travel]. Present and future of R&D on ADS systems.
CERN ACADEMIC TRAINING

ENERGY CONCEPTS FOR THE 21ST CENTURY

Particle physics contribution to the elimination of nuclear waste

Jean-Pierre Revol

Progress in particle accelerator technology makes it possible to use a proton accelerator to eliminate nuclear waste efficiently. The Energy Amplifier (EA) proposed by Carlo Rubbia and his group is a subcritical fast neutron system driven by a proton accelerator. It is particularly attractive for destroying, through fission, transuranic elements produced by present nuclear reactors. The EA could also transform efficiently and at minimal cost long-lived fission fragments using the concept of Adiabatic Resonance Crossing (ARC) recently tested at CERN with the TARC experiment. The ARC concept can be extended to several other domains of application (production of radioactive isotopes for medicine and industry, neutron research applications, etc.).

1 Introduction

The research work presented here is an exceptional contribution for a laboratory such as CERN, in principle devoted entirely to fundamental research. However, the Energy Amplifier (EA) [1] is an innovative approach to nuclear energy, and it should come as no surprise that such an innovation results from fundamental research which has always been a main driving engine of innovation. Examples are legion and well known; one of the most recent, the World-Wide Web, was invented at CERN and not by the much more powerful and resourceful computer industry.

Because particle physicists, interested in discovering the ultimate structure of matter, have pushed particle accelerator technology as far as they have, it is possible today to consider using a proton accelerator to drive a new type of nuclear system, with very attractive properties.

Today, the world is facing an extremely difficult challenge, that of producing sufficient energy to sustain economic growth without ruining the ecological equilibrium of the planet. The massive use of fossil fuels has allowed the Western World to reach an unprecedented level of wealth. Unfortunately, if the rest of the Earth’s population were to carry out the same energy policy, the entire planet would be in serious trouble. There is, therefore, a moral obligation for developed countries to provide new energy sources for the entire world in order to minimize global warming and other pollution effects.

If an acceptable solution is found, it will certainly be the result of systematic R&D and in this context, nuclear energy should be part of this R&D. The present nuclear energy programme is meeting growing public opposition world-wide because of three main reasons: (a) the association with military use and the fear of nuclear weapon proliferation; (b) the fear of accidents such as Chernobyl (1986 prompt-supercritical reactivity excursion) and Three Mile Island (1979 loss-of-coolant accident resulting in a core meltdown); (c) the issue of the back-end of the fuel cycle (nuclear waste management: at this time only deep geological storage is seriously envisaged).

Obviously, nuclear power, without these drawbacks would be ideal as it does not release greenhouse gases nor other chemical pollutants (NOx, SOx, etc.), nor dust particles, nor even radioactive particles as coal ashes do. Therefore, the real
The Energy Amplifier (EA) was an exceptional research activity for CERN.

Why should an idea such as the Energy Amplifier come from CERN and not from nuclear industry?

Basically for the same reason, why was the World Wide Web invented at CERN and not by IBM or Microsoft, or any other computer company.

History shows clearly that it is fundamental research which is the main engine of innovation, even more so, that the development of a civilisation is strongly linked to its support of fundamental research (i.e. pre-medieval Arabic civilisation).

*Man is by nature curious, and it is his curiosity which has been the prime mover of progress in our knowledge of the Universe, of the constituents of matter and of life which are the main objects of fundamental scientific research*
Some classic examples:

- Old: Faraday (first half of nineteenth century)
- Recent: the World Wide Web (invented at CERN)
- Medical applications of particle detectors (PET, NMR, etc.)
- Even more recent: applications of TARC concept (CERN patent) [medical, research, space travel] ⇒ the trend continues!

The Energy Amplifier fits well within this framework:

*Because particle physicists, interested in discovering the ultimate structure of matter, have pushed the accelerator technology as far as they have, it is possible today to use a proton accelerator to drive a new type of nuclear system with very attractive properties*
Plate 1: Michael Faraday by Thomas Phillips. See letter 1339
quote about Michael Faraday from:

"The Correspondence of
MICHAEL FARADAY"
Volume 3 (1841–December 1848)

Edited by Frank A J L James
Published by the Institution of Electrical Engineers
Short Run Press Ltd., Exeter (1996)

As with his direct work for government departments, the state of Faraday’s health did not prevent him from continuing to provide extensive advice to Trinity House\textsuperscript{80}. Some of this entailed analysing water from various lighthouses\textsuperscript{81}. Less mundanely, Faraday considered a proposal to use electricity to light buoys, but dismissed this proposal as impractical\textsuperscript{82}. However, during the 1840s most of Faraday’s efforts for Trinity House were directed towards the problem of ventilation. He commenced investigating this in February 1841 following his visit to St Catherine’s Lighthouse on the Isle of Wight. The problem facing Faraday was how to remove from the lighthouse lantern the products of combustion that condensed on the outer glass which thus reduced the amount of light emitted. Faraday worked on developing a chimney which would carry away these products without at the same time interfering with the light emitted by the flame. He had a chimney installed in St Catherine’s Lighthouse\textsuperscript{83} which, judging by the graphic description provided by the keeper two years later, proved very successful\textsuperscript{84}. But Faraday realised that there were other sources of moisture in the lighthouse which he was also able to eliminate\textsuperscript{85}. His continued investigation of ventilation systems required him to visit the South Foreland Lighthouse on the Kent coast on several occasions\textsuperscript{86}. In this process he developed a new design of chimney, which he made over, in 1842, to his brother, Robert, who patented it the following year\textsuperscript{87}; the only invention of Faraday’s to be patented. This chimney was quite successful and it was installed in buildings other than lighthouses including the Athenaeum\textsuperscript{88} and Buckingham Palace where, as the \textit{Times} noted, Faraday’s lamp illuminated Princess Helena’s christening\textsuperscript{89}. The tasks that Faraday undertook for the state reduced, as he was perfectly well aware, the amount of time he could devote to research.
Some classic examples:

- Old: Faraday (first half of nineteenth century)
- Recent: the World Wide Web (invented at CERN)
- Medical applications of particle detectors (PET, NMR, etc.)
- Even more recent: applications of TARC concept (CERN patent) [medical, research, space travel] ⇒ the trend continues!

The Energy Amplifier fits well within this framework:

Because particle physicists, interested in discovering the ultimate structure of matter, have pushed the accelerator technology as far as they have, it is possible today to use a proton accelerator to drive a new type of nuclear system with very attractive properties.
For all these reasons, it is very important to ensure strong support for fundamental research: a difficult task for politicians:

One cannot predict if something practical will come out of a given research, what it will be and when it will happen ⇒ Long term?

Scientific culture in society is very limited and is not improving (even at government level: i.e. background of ministers; Max Perutz's complaint). There is a lot of superstition (i.e. university poll), stimulated by the press (Sept. 1999 Tokaimura accident in Japan, more than a thousand times as many articles than for a coal mine (fossil fuel) accident in Lugansk, Ukraine, where 80 people died last March 14)
The fact that fundamental science is concerned with the study of the Universe in which we live, and that its only purpose is the search for knowledge, does not mean that scientists should isolate themselves from the very society which is supporting their activity.

Help promote scientific culture, contribute to science education, help prepare society for the ever increasing role of science in solving its problems.

Whenever possible, help resolve society's problems. In our particular case, the main problem of concern is the "Energy Problem", one of the great challenges facing us in the next 50 years.
A few elements of the energy problem

- A very complex problem, because of the implications in many areas: economy, politics, ecology, psychology, etc.
  - no complete discussion possible here

- Energy consumption of the world will increase as a result of two main factors:
  - Energy consumption per capita grows with economic development. Inevitable closing of the gap in per capita consumption between developed and developing countries
  - The world population is growing in a spectacular way, mainly in developing countries where economical growth is great
Approximate per capita consumption of energy as a function of time [R. A. Knief, 1992]. Energy for food gathering has been supplemented sequentially by that for household use (initially heating), organised agriculture, industry and transportation.
Source: International Atomic Energy Agency (1994)

Relative To North America
World Population (Million Inhabitants)
RELATIVE TO NORTH AMERICA
TOTAL ENERGY CONSUMPTION (GJ/PERSON/CAPITA)
Fig. 1. Population growth rate in South-East Asia versus annual energy use per capita in tons of oil equivalent. 1971-1992 data, 1993-2010 predictions. Curves are theory.
Electricity Consumption as a Percentage of Total Energy Consumption

% of Total Energy

Year

OECD
WORLD
CEE/CIS
DCs
Electricity, GDP and energy growth in developing countries

All values normalized to 1.0 in 1970
If developing countries were to reach the per capita energy consumption of the USA, the increase would be enormous. Assuming they only reach the European level (45% of the USA) by the year 2100, then the energy consumption would have to increase by a factor 6! from the present 13 TWatt-year. Firm predictions are very difficult to make.

The Chinese government estimates that China electricity production needs to be increased by a factor of 6 to 7 in the next 30 years. The problem is somewhat worse in India. Both of them represent about half the world population. How should they do it?
World Energy Challenge

- Annual world energy consumption:
  \[4 \times 10^{20} \text{ Joule} \sim 13 \text{ TW} \times \text{year} \sim 380 \text{ quad} \sim 9600 \text{ MTOE}\]
  34\% \text{ electricity}, 5.5\% \text{ nuclear} \quad (1 \text{ quad} = 10^{15} \text{ btu} = 1.06 \times 10^{18} \text{ Joule})

- Challenge: How to continue producing this large amount of energy and how to increase production in the future to satisfy legitimate economical growth without destroying the ecological equilibrium of our planet?

- Environment impact: If present practices continue, the pollution of the Earth will be dramatic, with very unpleasant consequences:
  - CO\text{2}, CH\text{4}, etc. \Rightarrow \text{ global warming } \Rightarrow \text{ rise in sea level, climate instability (greater energy stored in the Earth's atmosphere), outburst of epidemic illnesses, etc.}
  - SO\text{x}, NO\text{x}, ashes, dust, etc. \Rightarrow \text{ air and water pollution (acid rains)}
  - Nuclear waste and nuclear accidents \Rightarrow \text{ potential pollution which would be irreversible on the human scale}
Correlation* of CO₂ and Temperature Variation from 160,000 years before present to 2100

*From the study of ice at the Pole
(Source: H. Lehmann, Wüppertal Institut für Klima, Umwelt, Energie)
Variation of the global mean temperature between 1860 and 1995

ΔT (°C)

Year

1850  1880  1910  1940  1970  2000

Measurements (IPCC, 1995)
Model
Estimate of Emissions due to Electric Energy Generation (ton/GWatt×hour)

<table>
<thead>
<tr>
<th>Source</th>
<th>SO₂</th>
<th>NOₓ</th>
<th>PM</th>
<th>CO₂</th>
<th>VOC</th>
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<tr>
<td>Nuclear</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>

SO₂ : Sulfur Dioxide  
NOₓ : Nitrogen Oxydes  
PM : Particles of matter of diameter < 10 microns (particulate matter)  
CO₂ : Carbon Dioxide  
VOC : Volatile Organic Compounds
Les gaz à effet de serre

Oxyde d’azote
Méthane 15%
CFC 19%
Dioxyde de carbone (CO2) 55%
Autres

Sources: Agence Internationale de l’énergie / «Le Monde»

Quand un habitant de l’ex-URSS dépense 6,5 francs, il génère une production de CO2 de 2,3 kg.
La même somme dépensée en Belgique génère presque 600 grammes, et en France 417,300 grammes.
How to face the challenge?

- Dominant recipe (Rio, Kyoto, Berlin, etc.): reduce CO₂ emissions by (1) energy conservation and efficiency measures, (2) increasing the use of renewable energies and reducing coal consumption (shift towards gas):
  
  - gas usage + 55%, Coal production + 66% from 1992 to 2010 (OECD, 1995): the current course is not towards what ministers are hoping for
  
  - despite the welcome gradual progress in the effectiveness of renewable energies OECD experts expect in the foreseeable future only a very modest share of renewable energies (not due to lack of money or conspiracy but to the dispersed nature of these energy sources – solar, wind and the long time needed to develop new sources)

- Even if the present agreements are kept, this will be insufficient to prevent CO₂ from rising.
Figure 4.1. Alternative emission time paths and associated costs

Global carbon emission paths

Billion tons of carbon

Ppmv

Atmospheric CO$_2$ concentrations

Percentage of world GDP

Costs of stabilising atmospheric CO$_2$ concentrations at 500 ppmv by 2100

Relative fuel efficiencies

- Coal: 3700 tons → 13600 t of CO₂, ≥ 200 t SO₂, 200 t NOₓ, dust, 100 GW×day of greenhouse heat
- PWR: 266 kg nat. Uranium → 30 kg of waste [high activity, long-lived, sub-critical (fissionable), proliferating]
- Energy Amplifier: 1.06 kg Thorium → (Fission Fragments: same activity as burnt Thorium, same radio-toxicity level as coal ashes after 500 years, non-fissionable, non-proliferating)

1 Gwatt of electric power requires:
- 3 million tons of coal per year
- 20 km² of solar cells
- 200 km² of windmills
- 2000 km² of fast growing trees
- 700 kg of thorium per year in the Energy Amplifier
No good solution exists at present. New methods will have to be invented to produce sufficient energy in an economically competitive and ecologically acceptable way. On the long term ($\geq 50$ years) fossil fuels are bound to be exhausted anyway. Only prediction: If a solution is found to the energy problem, it can only come from a systematic fundamental R&D program.

The energy problem is a global problem. Developed countries have a moral duty to help developing countries in this research effort. The "don't do as I did" attitude will not work!

The Energy Amplifier studies started at CERN in the belief that all sources of energy will have to contribute, but that nuclear energy should play an important role for several main reasons:

1. Nuclear energy has the potential to satisfy the demand for many centuries (breeding is needed)

2. A higher rate of growth in urban population will limit the role of renewable energies (solar, wind, etc.) which demand large areas

$\Rightarrow$ Nuclear energy must not be excluded from R&D
Nuclear Energy: some elements of history

- Initially nuclear energy was a physicist's business: physicists were the first to understand the tremendous energetic potential of atomic nuclei (Fission: O. Hahn, F. Strassman, O. Frisch, L. Meitner 1938-39; first atomic pile: E. Fermi 1942).

- In the 1960's a certain euphoria led the world to believe that nuclear energy was ready as the solution to the energy problem. As a consequence, fundamental research stopped, to be replaced by 40 years of technological developments.

- The resulting nuclear industry has shown its limitations. It must change. This implies fundamental R&D.

- In fact, competition from low cost alternatives may be the main influential factor in the phasing out of present nuclear energy!
Figure 8. Efficiency Trends.
Nuclear Fission Energy is facing growing public opposition for several reasons:

- Association with military use (World War II, present stock pile of nuclear weapons, weapon proliferation, etc.)
- Accidents (Chernobyl [1986], Three Mile Island [1979], etc.)
- Issue of back-end of the fuel cycle (waste management)
Transuranic elements and Fission Fragments are the major components of the radioactive waste generated in nuclear fuel cycles:

TRansUranic elements (TRU's) (1.1 %: Np, Pu, Am, Cm, Bk, etc.) the result of neutron capture in the fuel and subsequent decay (i.e.: \( n + ^{238}\text{U} \rightarrow ^{239}\text{U} (t_{1/2} \sim 23 \text{ mn}) \rightarrow ^{239}\text{Pu} \), etc.). (~100 t/year of \(^{239}\text{Pu}\) produced in the world + Military Pu)

Fission fragments (~4%) produced in the fission process.
### Production of nuclear waste (Actinides)

**Annual**

<table>
<thead>
<tr>
<th>(1995)</th>
<th>1 PWR of 1 GWe</th>
<th>France (59 GWe, 54 PWRs)</th>
<th>World *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy produced</td>
<td>6 TWe×h</td>
<td>359 TWe×h</td>
<td>2130 TWe×h</td>
</tr>
<tr>
<td>Uranium (0.9 % 235U)</td>
<td>20 t</td>
<td>1200 t</td>
<td>7100 t</td>
</tr>
<tr>
<td>Pu</td>
<td>200 kg</td>
<td>12 t</td>
<td>71 t</td>
</tr>
<tr>
<td>Np</td>
<td>10.4 kg</td>
<td>620 kg</td>
<td>3690 kg</td>
</tr>
<tr>
<td>Am</td>
<td>9.8 kg (≥ 5 yrs)</td>
<td>590 kg</td>
<td>3480 kg</td>
</tr>
<tr>
<td>Cm</td>
<td>0.8 kg</td>
<td>48 kg</td>
<td>285 kg</td>
</tr>
</tbody>
</table>

**München, 19 März 1997**

62.8 GWe 1997
## Annual Waste Production in France

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity per inhabitant</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toxic Waste</td>
<td>7 million de tons</td>
<td>180 million tons</td>
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<tr>
<td>Nuclear Waste</td>
<td>60,000 tons</td>
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</tr>
<tr>
<td>Long-Lived Nuclear Waste</td>
<td>1000 tons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>116 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 g</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 tons</td>
<td></td>
</tr>
</tbody>
</table>
It is to respond to these concerns raised by present nuclear energy that Carlo Rubbia and his group have proposed the Energy Amplifier (initially an extrapolation of compensating calorimeter technique):

*Can nuclear energy change in such a way that it becomes acceptable to society?*

In the western world the main concern is nuclear waste, therefore, the present version of the Energy Amplifier is optimized for the destruction of nuclear waste. In other parts of the world (China, India) where there is no nuclear waste another version of the Energy Amplifier, optimized for energy production and adapted to local needs would be more appropriate.
Nuclear Waste

- Transuranic elements and Fission Fragments are the major components of the radioactive waste generated in nuclear fuel cycles:

  - TRansUranic elements (TRU's) (1.1 %: Np, Pu, Am, Cm, Bk, etc.) the result of neutron capture in the fuel and subsequent decay (i.e.: \( n + ^{238}\text{U} \rightarrow ^{239}\text{U}(t_{1/2} \sim 23 \text{ mn}) \rightarrow ^{239}\text{Pu} \), etc.). (~100 t/year of ^{239}\text{Pu} produced in the world + Military Pu) \( \Rightarrow \) destroyed by Fission

  - Fission Fragments (FF) (~4%) produced in the fission process. \( \Rightarrow \) destroyed by neutron capture
ENERGY CONCEPTS FOR THE 21ST CENTURY

J.-P. Revol (CERN)

LECTURE 2

CERN ACADEMIC TRAINING
March 21-24, 2000
The energy problem is a global problem, on the scale of the entire planet. We are all inside the test tube! At present, the availability of cheap and abundant energy in developed countries is not a sufficient excuse not to have to worry about clean and safe energy production for the rest of the world and for the future.

Developed countries must help developing countries. If not, there will be disasters: uncontrolled increase of pollution and global warming and the possibility of major nuclear accidents in developing countries.

Nuclear fission energy is needed. The Energy Amplifier study is an attempt at putting nuclear energy back into fundamental research to answer the question:

Can nuclear energy change in such a way that it becomes acceptable to society?
Today, in the western world, the main concern is long-lived nuclear waste. For instance, in France (60 nuclear reactors, 80% of electric power production) the French Parliament has acted:

December 30, 1991 Bataille/Curien law with the following objectives:

- develop methods allowing the separation and transmutation of long-lived radioactive elements
- study the possibility of reversible or irreversible deep geological storage sites
- study methods of packaging for long term surface storage

as a consequence the SeParation et INcineration (SPIN) programme (CEA) was launched

PURETEX (1991–2000) with the goal of a reduction by at least 2/3 of the volume of waste produced by reprocessing (improvement of PUREX)
ACTINEX (1991–2006) with the goal of a reduction by a factor 100 to 1000 of the radiotoxicity of the waste, through separation and incineration of long-lived elements.

Transmutation of nuclear waste with Accelerator Driven Systems (ADS), also called hybrid systems (in France) should be part of that effort. In the USA, the name is Accelerator Transmutation of Waste (ATW) to insist that the purpose is waste elimination and nothing else.
A brief history of Accelerator Driven Systems

The idea of producing neutrons by spallation with an accelerator has been around for a long time:

In 1950, Ernest Lawrence at Berkeley proposed to produce plutonium from depleted uranium from Oak Ridge. The Material Testing Accelerator (MTA) project was abandoned in 1954.

In 1952, W. B. Lewis in Canada proposed to use an accelerator to produce $^{233}$U from thorium, in an attempt to close the fuel cycle for CANDU type reactors.

Renewed interest in the 1980's and beginning of the 1990's, in particular in Japan (OMEGA project at Japan Atomic Energy Research Institute), and in the USA (Hiroshi Takahashi et al. proposal of a fast neutron hybrid system at Brookhaven for minor actinide transmutation and Charles Bowman a thermal neutron molten salt system based on the thorium cycle at Los Alamos)
In November 1993, Carlo Rubbia proposed, in an exploratory phase, a first Thermal neutron Energy Amplifier system based on the thorium cycle, with a view to energy production. As it became clear that in the western world the priority is the destruction of nuclear waste (other sources of energy are abundant and cheap and pollution is of little concern), the system evolved towards that goal, into a Fast Energy Amplifier. More specifically, C. Rubbia and his group have:

- defined a clear strategy for destroying TRU
- produced new simulation tools validated by experiments (FEAT and TARC)
- used the simulation tools to optimize the parameters of a system to eliminate TRU
Committee Report - House Rpt. 105-749
MAKING APPROPRIATIONS FOR ENERGY AND WATER
DEVELOPMENT FOR THE FISCAL YEAR ENDING
SEPTEMBER 30, 1999, AND FOR OTHER PURPOSES

Associated Bill -- H.R.4060

"...to conduct a study of accelerator transmutation of waste (ATW) technology. The Department is to
establish, in coordination with its laboratories, a road map for the development of ATW technology. The road
map should identify the technical issues that must be resolved, a proposed time schedule and program to
resolve these issues, and the estimated cost of such a program. The road map should also consider and propose
collaborative efforts with other countries developing ATW technology and other programs developing
accelerator technology. In addition, the report should include an assessment of the institutional challenges of
this program, the impact this technology could have on the civilian spent nuclear fuel program, areas of
development which could have benefits to other ongoing programs, and the estimated capital and operational
life cycle costs to treat civilian spent nuclear fuel."

Page master: Pam Novak
Last updated: February 15, 1999

http://www.pnl.gov/atw/legis.html
Congress, in the Fiscal Year 1999 Energy and Water Appropriation Act, (see legislation) has directed the Department of Energy (Office of Civilian Radioactive Waste Management) to carry out a study of the Accelerator Transmutation of Waste (ATW) and to prepare, before the end of the fiscal year, a roadmap for its development.

This website is a tool to focus and integrate the efforts of a team of international and domestic scientists, disseminate information about the effort, and allow the team of international and domestic scientists to collaborate.

- What is ATW?
- Why study ATW?
- What are the technical challenges?

The graphic below shows the linkages among the four ATW Technical Working Groups. Clicking on a group name will take you directly to the page for that technical working group.
Minister’s Advisory group meeting: list of participants

Austria: H. Rauch, R. W. Reiter
Belgium: P. D’Hondt
Denmark: H.B. Moller
Finland: M. Bjornberg
France: H. Flocard, R. Pellat
Germany: G. Heusener, K. Kugeler
Portugal: J. C. Soares
UK: P. Storey
Spain: F. Aldana, J. M. Martinez Val
Sweden: P.E. Ahlstroem
Italy: P. Fasella, G. Gherardi, E. Iarocci, A. Marino, C. Rubbia
CONCEPTUAL DESIGN OF A FAST NEUTRON OPERATED
HIGH POWER ENERGY AMPLIFIER

C. Rubbia, J.A. Rubio, S. Buono\textsuperscript{1)}, F. Carminati, N. Fiétier\textsuperscript{2)}, J. Galvez, C. Gelès, Y. Kadi, R. Klapisch, P. Mandrillon\textsuperscript{2)}, J.P. Revol and Ch. Roche

Abstract

The basic concept and the main practical considerations of an Energy Amplifier (EA) have been exhaustively described in Ref. [1]. Here the realisation of the EA is further explored and schemes are described which offer a high gain, a large maximum power density and an extended burn-up, well in excess of 100 GW × day/t corresponding to about five years at full power operation with no intervention on the fuel core. Most of these benefits stem from the use of fast neutrons, as already proposed in Ref. [2].

The EA operates indefinitely in a closed cycle, namely the discharge of a fuel load, with the exception of fission fragments, is re-injected in the sub-critical unit with the addition of natural Thorium to compensate for the burnt fuel. After many cycles an equilibrium is reached, in which the Actinide concentrations are the balance between burning and “incineration”. The fuel is used much more efficiently, namely the power obtained from 780 kg of Thorium is roughly the same as the one from 200 tons of native Uranium and a PWR (33 GW × day/t of burn-up). The probability of a criticality accident is suppressed since the device operates at all times far away from it. Spontaneous convective cooling by the surrounding air makes a “melt-down” leak impossible.

An EA module consists of a 1500 MW\textsubscript{th} unit with its dedicated 1.0 GeV proton accelerator of 12.5 mA. A compact, highly reliable and modular Cyclotron has been designed. A plant may be made of several such modules. For instance a cluster of three such modular units will produce about 2,000 MWe of primary electrical power. A relevant feature of our design is that it is based on natural convection to remove the heat generated inside the core. The EA is a large, passive device in which a proton beam is dumped and the heat generated by nuclear cascades is extracted, without other major elements of variability. The delivered power is controlled exclusively by the current of the accelerator. The fuel needs no access during the whole burn-up and it may be kept sealed up as a non-proliferation safeguard measure. Contrary to Fusion, there are no major technological barriers.

After \(700\) years the radio-toxicity left is about \(20,000 \times\) smaller than the one of an ordinary Pressurised Water Reactor (PWR) for the same energy. Geological storage (\(10^6\) years) is virtually eliminated or at least strongly reduced \([\leq 500 \text{ Ci/(GW} \text{e} \times \text{y})\) after 1000 years]. It could be further reduced \((< 35 \text{ Ci})\) “incinerating” some of the nuclides. Radioactivity dose to individuals truncated to 10,000 years and due to operation is about 1/330 of the one of PWR and about 1/33 of Coal burning.

Geneva, 29th September, 1995

\textsuperscript{1)} Sincrotrone Trieste, Trieste, Italy
\textsuperscript{2)} Laboratoire du Cyclotron, Nice, France
In lead, a 3.5 GeV/c (2.75 GeV of kinetic energy) proton produces 100 neutrons. A spallation neutron costs about 27 MeV.
The EA is intrinsically safe. Safety is a deterministic feature as opposed to a probabilistic one in critical reactors. In addition to the control offered by the reactor, it has several passive safety features, some of them borrowed from advanced USA reactor designs:

- natural convection of molten lead and a Reactor Vessel Air Cooling System (RVACS) protects against core meltdown
- many containment barriers (cladding, molten lead vessel, containment vessel, containment dome and lead itself)
- lead overflow possibility to introduce heat conduction to the outer wall of main lead vessel and to stop the beam

In the worst case (huge earthquake?) you could lose the EA, but with no significant impact on the environment. Lead is an excellent radiation containment medium.
### Table 4.1 - Main parameters of the Energy Amplifier

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Thermal Power/unit</td>
<td>1500</td>
</tr>
<tr>
<td>Primary Electric Power</td>
<td>625</td>
</tr>
<tr>
<td>Type of plant</td>
<td>Pool</td>
</tr>
<tr>
<td>Coolant</td>
<td>Molten Lead</td>
</tr>
<tr>
<td>Sub-criticality factor $k_*$ (nominal)</td>
<td>0.98</td>
</tr>
<tr>
<td>Doppler Reactivity Coefficient, $(\Delta k/\Delta T)$</td>
<td>$-1.37 \times 10^{-5}$</td>
</tr>
<tr>
<td>Void coefficient (coolant) $\Delta k/\Delta \rho/\rho$</td>
<td>$+0.010$</td>
</tr>
<tr>
<td>Nominal energetic Gain</td>
<td>120</td>
</tr>
<tr>
<td>Accelerator re-circulated Power</td>
<td>30</td>
</tr>
<tr>
<td>Fraction Electric Power re-circulated in Accel.</td>
<td>0.0465</td>
</tr>
<tr>
<td>Control Bars</td>
<td>none</td>
</tr>
<tr>
<td>Scram systems(3)</td>
<td>CB4 rods</td>
</tr>
<tr>
<td>Seismic Platform</td>
<td>yes</td>
</tr>
</tbody>
</table>

#### Main Vessel

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross height</td>
<td>30 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>6 m</td>
</tr>
<tr>
<td>Material</td>
<td>HT-9</td>
</tr>
<tr>
<td>Walls thickness</td>
<td>70 mm</td>
</tr>
<tr>
<td>Weight (excluding cover plug)</td>
<td>2000 ton</td>
</tr>
<tr>
<td>Double Liner</td>
<td>yes</td>
</tr>
</tbody>
</table>

#### Proton Beam and Spallation Target

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator type</td>
<td>Cyclotron</td>
</tr>
<tr>
<td>Number of beams</td>
<td>1</td>
</tr>
<tr>
<td>Accelerator overall efficiency$^{33}$</td>
<td>43%</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>1.0 GeV</td>
</tr>
<tr>
<td>Nominal current</td>
<td>12.5 mA</td>
</tr>
<tr>
<td>Nominal beam Power</td>
<td>12.5 MW</td>
</tr>
<tr>
<td>Maximum current</td>
<td>20 mA</td>
</tr>
<tr>
<td>Spallation Target material</td>
<td>Molten Lead</td>
</tr>
<tr>
<td>Beam radius at spallation target</td>
<td>7.5 cm</td>
</tr>
<tr>
<td>Beam window</td>
<td>Tungsten, 3.0 (1.5) mm</td>
</tr>
<tr>
<td>Max. power density in window</td>
<td>113 W/cm²</td>
</tr>
<tr>
<td>Max. Temp. increase in window</td>
<td>137 °C</td>
</tr>
<tr>
<td>Window expected lifetime</td>
<td>$\geq 1$ year</td>
</tr>
</tbody>
</table>

$^{33}$Beam power/Mains Load
### Fuel Core

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial fuel mixture</td>
<td>ThO₂ + 0.123³UO₂</td>
</tr>
<tr>
<td>Initial fuel mass</td>
<td>28.41 ton</td>
</tr>
<tr>
<td>Cladding material</td>
<td>low act. HT-9</td>
</tr>
<tr>
<td>Specific power</td>
<td>52.8 W/g</td>
</tr>
<tr>
<td>Power density</td>
<td>523 W/cm³</td>
</tr>
<tr>
<td>Average Fuel Temperature</td>
<td>908 °C</td>
</tr>
<tr>
<td>Maximum Clad Temperature</td>
<td>707 °C</td>
</tr>
<tr>
<td>Dwelling time (eq. @ full power)</td>
<td>5.0 years</td>
</tr>
<tr>
<td>Average Burn-up</td>
<td>100.0 GW d/t</td>
</tr>
</tbody>
</table>

### Breeder Core

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial fuel mixture</td>
<td>ThO₂</td>
</tr>
<tr>
<td>Initial fuel mass</td>
<td>5.6 ton</td>
</tr>
<tr>
<td>Cladding material</td>
<td>low act. HT-9</td>
</tr>
<tr>
<td>U²³³ stockpile at discharge</td>
<td>242.7 kg</td>
</tr>
<tr>
<td>Power density at end cycle</td>
<td>3.0 W/g</td>
</tr>
</tbody>
</table>

### Primary cooling system

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate weight of the coolant</td>
<td>10,000 ton</td>
</tr>
<tr>
<td>Pumping method</td>
<td>Nat. Convection</td>
</tr>
<tr>
<td>Height convection column</td>
<td>25 m</td>
</tr>
<tr>
<td>Convection generated primary pressure</td>
<td>0.637 bar</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td>4 × 375 MW</td>
</tr>
<tr>
<td>Decay heat removal</td>
<td>RVACS</td>
</tr>
<tr>
<td>Inlet temperature, Core</td>
<td>400 °C</td>
</tr>
<tr>
<td>Outlet temperature, Core</td>
<td>600 °C</td>
</tr>
<tr>
<td>Coolant Flow in Core</td>
<td>53.6 ton/s</td>
</tr>
<tr>
<td>Coolant speed in Core, average</td>
<td>1.5 m/s</td>
</tr>
</tbody>
</table>

### Decay Heat Passive Cooling (RVACS)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riser channel gap width</td>
<td>18 cm</td>
</tr>
<tr>
<td>Downcomer channel gap width</td>
<td>57 cm</td>
</tr>
<tr>
<td>Trigger Temperature</td>
<td>500 83.5 64.5 °C</td>
</tr>
<tr>
<td>EA Coolant max Temperature rise</td>
<td>17.5 11.2 9.5 hours</td>
</tr>
<tr>
<td>Outlet air Temperature (@ max. temp.)</td>
<td>273 302 334.3 °C</td>
</tr>
<tr>
<td>Outlet air Speed (@ max. temp.)</td>
<td>13.4 14.2 15.2 m/s</td>
</tr>
<tr>
<td>Air flow Rate (@ max. temp.)</td>
<td>52.8 56.1 60 m³/s</td>
</tr>
<tr>
<td>Extracted Heat (@ max. temp.)</td>
<td>8.57 9.65 10.84 MW</td>
</tr>
</tbody>
</table>
Why fast (high energy) neutrons?

Several strategic reasons linked to physics ...
TRansUranic elements (TRU's) representing 1.1% of the spent fuel (Np, Pu, Am, Cm, Bk, etc.) are the result of neutron capture in the fuel and subsequent decay:

\[ n + ^{238}\text{U} \rightarrow ^{239}\text{U}(t_{1/2} \sim 23 \text{ mn}) \rightarrow ^{239}\text{Pu}(t_{1/2} \sim 24110 \text{ y}) \]  \[ (n,\gamma) \]

\[ n + ^{239}\text{Pu} \rightarrow ^{240}\text{Pu}(t_{1/2} \sim 6564 \text{ y}) \]  \[ (n,\gamma) \]

etc.

Transuranic elements dominate the long-term radiotoxicity of the waste:

⇒ TRU can only be destroyed by fission and the Energy Amplifier has been optimized precisely to do this
Chain Reaction

Effective neutron multiplication factor

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

Self-sustained process:
- \( k = 1 \) (if \( k < 1 \) the Reactor stops)
- \( k > 1 \) (the Reactor is supercritical)

⇒ The time derivative of the power kept equal to zero by control

Nuclear Cascade

Critical Reactor

Energy Amplifier

High Energy Proton
(1 GeV)

External driven process:
- \( k < 1 \) (\( k = 0.98 \))
- \( E_{\text{tot}} = G \times E_p \)

⇒ Constant Energy Gain
Allowed Operational Safety Margin

Maximum distance from Prompt Criticality

PWR  SPX  CAPRA  Ac Burner  JAERI  EA (k=0.98)  EA (k=0.96)
Subcriticality and Energy Amplification

"$k_{source} = 0.98$"

$\Rightarrow$ Chernobyl type accidents are impossible
WHY SO MANY EXPONENTIALS?
Carlo Rubbia

We neglect the fine structure of the critical assembly and assume a fictitious material with uniform properties. The basic diffusion equation can be written for mono-energetic or thermal neutrons as

$$D\nabla^2 \phi - \Sigma_t \phi + S = \frac{\partial n}{\partial t}$$

where $S$ is the source term, namely the rate of production of neutrons per cm$^3$ per sec, $D$ is the diffusion coefficient and $\Sigma_e$ the macroscopic absorption cross section, all averaged over the Uranium-water mixture. This formula is strictly applicable only for mono-energetic neutrons and then only at distances greater than two or three mean free paths from strong sources, absorbers or boundaries. It is approximately valid in our case since there are no strong absorption. Since the system is in a steady state $\delta n/\delta t=0$ and the equation becomes

$$D\nabla^2 \phi - \Sigma_e \phi + S = 0$$

Let $k_\infty$ be the number of neutrons produced at each absorption in the Uranium-water mixture. The source term will then be $S = k_\infty \Sigma_e$, leading to the equation

$$D\nabla^2 \phi - \Sigma_e \phi + k_\infty \Sigma_e = 0$$

Upon dividing by $D$ and rearranging terms, the result is

$$\nabla^2 \phi - \frac{1-k_\infty}{L^2} \phi = 0$$

where $L$ is equal to $D/\Sigma_e$. This equation has different behaviour according to the sign of $1-k_\infty$ term. In the case of a reactor, which one expects to become eventually critical, namely $k \geq 1$, one has to assume obviously $k_\infty > 1$. Note that $k = k_\infty P$, where $P \leq 1$ is the geometrical escape probability.
SPATIAL DISTRIBUTION OF THE NEUTRON FLUX

Distance from Centre (arbitrary units)

Neutron Flux (arbitrary units)

Fission neutrons $k = 0.9$

Spallation neutrons

Critical Reactor neutrons
Energy Amplification

Energy production: by fission amplifying, by a factor $1/(1-k)$ the number of neutrons produced by the spallation process:

$$G = \frac{\text{Energy Produced by EA}}{\text{Energy Provided by Beam}} = \frac{G_0}{1-k}$$

The dependence on $K$ comes from the physics of neutron multiplication

$$N_0 \left(1 + k + k^2 + k^3 + k^4 + ... + k^n\right) = N_0 \frac{k^{n+1} - 1}{k-1} \approx \frac{N_0}{1-k}$$

The $G_0$ constant contains the spallation information: $G_0 \sim 3$ for uranium, $G_0 \sim 2.7$ for lead.
Example of FEAT experiment (CERN):

On a uranium target, one 1 GeV proton produces 40 spallation neutrons which in turn produce (for $k = 0.9$) $40 \times 10 = 400$ neutrons from fission.

40% of these neutrons also produce fissions (160 fissions), the energy produced is $160 \times 0.200 = 32$ GeV, and the energy gain is: $G \approx 32/1 = 32$ (G0 $\sim 3$ for uranium).

If $\eta El \sim 43\%$, the corresponding electric energy (13.76 GeV) is more than sufficient to drive the accelerator which uses 2 GeV ($\eta \sim 50\%$).
The FEAT experiment:

EXPERIMENTAL DETERMINATION OF THE ENERGY GENERATED IN NUCLEAR CASCADES BY A HIGH ENERGY BEAM

CEN, Bordeaux-Gradignan, France • CIEMAT, Madrid, Spain • CSNSM, Orsay, France • CEDEX, Madrid, Spain • CERN, Geneva, Switzerland • Dipartimento di Fisica e INFN, Università di Padova, Padova, Italy • INFN, Sezione di Genova, Genova, Italy • IPN, Orsay, France • ISN, Grenoble, France • Sincrotrone Trieste, Trieste, Italy • Universidad Autónoma de Madrid, Madrid, Spain • Universidad Politecnica de Madrid, Madrid, Spain • University of Athens, Athens, Greece • University of Basel, Basel Switzerland • University of Thessaloniki, Thessaloniki, Greece

Funded by European Union
**SPANISH THERMOMETER**

*First Test*

22.09.94

---

**Results**

Intensity: $1.45 \times 10^4$ protons/pulse

14.4 seconds between pulses

$P_{\text{beam}} = 3.7 \text{ GeV}c$

---

![Graph showing temperature changes over time with beam on and off](image)

- **Beam OFF**
  - $U_1$ Slope: 709 ± 4μK/min
  - $Pb$ Slope: 279 ± 3μK/min

- **Beam ON**
  - $U_1$ Slope: 251 ± 3μK/min
  - $U_2$ Slope: 919 ± 4μK/min

---

**Detector**

- Diameter: $\phi = 1 \text{ cm}$
- Weight: $W = 55.40 \text{ g}$

---

**URANIUM BAR**

- Diameter: $\phi = 0.8 \text{ cm}$
- Weight: $W = 53.78 \text{ g}$
Time dependence of fission rate

Detector distance: 35 cm.
FEAT EXPERIMENT AT CERN PS


\[ G = \frac{G_0}{(1 - k)} \approx 30 \]

where \( G_0 \approx 3 \)
and \( k \approx 0.9 \)
ENERGY AMPLIFIER: ENERGY BALANCE

625 MW_e \rightarrow \text{OUTPUT}  
\text{Accelerator}  
(\eta \sim 50\%)

645 MW_e \rightarrow 20 MW_e 
\rightarrow 10 MW \rightarrow \text{Energy Producing Unit}  
(\eta_{el} \sim 43\%)

1500 MW_{th}
Experts agree it is possible today to build accelerators able to drive an Energy Amplifier. Only a reasonable extrapolation of existing technologies is needed:

- the PSI (Switzerland) cyclotron now runs at 1.4 mA and 590 MeV (0.826 MW)
- Both USA and Europe have (had) projects to build LINACs to produce Tritium: (TRISPAL at CEA (France): 600 MeV, 40 mA, 24 MW and LANL (USA): 1 GeV, 100 mA, 100 MW)
- Japan is also considering a high intensity proton source as part of their new Neutron Science Project

"The accelerators which would be required in connection with subcritical reactor systems are state of the art in that they can be designed and built with low technological risk ..."

W.K.H. Panofsky, May 1998
The choice of accelerator technology may be coupled to the strategy for the EA system. Cyclotron preferred by C. Rubbia's group:

Can get high efficiency (50%), as current in RF cavities is about 100 times (100 turns) the extraction current, implying that most power is in the RF cavities (which have 70% efficiency), keeping the losses relatively small.

Reliability may be better than in LINACs which need many more control elements (reliability decreases with the number of parts).

If the strategy is to destroy waste on the nuclear power plant site, then the smaller size is a clear advantage (easier not to have to extend the site, better for control and safety of the machine). Compact size is also a commercial advantage.

No need for SC cavities, keeping the technology simple.
Longitudinal SC effects in H.-A.1p1/turns of the 380 MeV booster cyclotron.
Time structure at 70.4 Mhz (14.2 ns)

Injector extraction: 20 deg or 0.8 ns

380 MeV injection: 36 deg or 1.4 ns

380 MeV extraction: 12 deg or 0.5 ns

1200 MeV extraction: 6 deg or 0.25 ns
Variation du $K_{src}$ et de $I_p$ en fonction du Taux de Combustion (Benchmark IAEA)

$< K_{src} > \approx 0.979$

$< \text{Intensité Proton} > \approx 14.8 \text{ mA}$
OUTLINE

- TRU elimination (continued) + REMARK ON WINDOW
- Adiabatic Resonance Crossing
- The TARC experiment
- Elimination of Long-Lived Fissions Fragments using ARC
Fission all actinides (TRU)

⇒ fast neutron spectrum

⇒ choice of lead as moderator

Additional advantage: long burnups (longer exposure time for TRU, fewer reprocessings, higher duty cycle, etc.)

Minimise TRU production / allows high TRU burning rates

⇒ choice of natural thorium as fuel

⇒ external neutron source (accelerator)

Additional advantage: can have subcritical system (no Chernobyl type accident)
Table 11. Asymptotic yields of the EA module as Incinerator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power, thermal</td>
<td>1500 MW</td>
</tr>
<tr>
<td>Nominal k value</td>
<td>0.97</td>
</tr>
<tr>
<td>Burn-up/cycle</td>
<td>120 GW × day/t</td>
</tr>
<tr>
<td>Fuel Power density</td>
<td>160 Watt/g¹</td>
</tr>
<tr>
<td>Fuel refill period</td>
<td>2.0 EFPY</td>
</tr>
</tbody>
</table>

Overall performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRU incineration rate</td>
<td>402 kg/year ³⁴ U²³₃</td>
</tr>
<tr>
<td>²³³U-rich Uranium mix production rate</td>
<td>175 kg/year</td>
</tr>
<tr>
<td>TRU → ²³³U conversion (atom by atom)</td>
<td>0.435</td>
</tr>
</tbody>
</table>

Refill composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh TRU’s</td>
<td>0.85 ton</td>
</tr>
<tr>
<td>Fresh Thorium</td>
<td>0.74 ton</td>
</tr>
<tr>
<td>Residue of previous (actinides ≠ Û)</td>
<td></td>
</tr>
<tr>
<td>-Thorium</td>
<td>5.35 ton</td>
</tr>
<tr>
<td>-Rest</td>
<td>2.26 ton</td>
</tr>
<tr>
<td>Fuel metal total initial mass</td>
<td>9.2 ton</td>
</tr>
</tbody>
</table>

Discharge composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovered U-mix</td>
<td>0.35 ton</td>
</tr>
<tr>
<td>Fraction ²³³U in U-mix</td>
<td>0.94</td>
</tr>
<tr>
<td>Fission Fragments</td>
<td>1.24 ton</td>
</tr>
</tbody>
</table>

The recovered Uranium is slightly dropping as the consequence of the smaller amount of Thorium in the fuel, also tending to an asymptotic value of slightly less than 350 kg. The addition of fresh TRU’s is also essentially constant of the order of 800 kg, after the first large excess required to start up the cycles, which is over 2 tons. The fresh Thorium initially very small also tends to about 700 kg.

The cumulative distribution of these amounts is shown in Figure 18. Note the linear rises in the cumulative amount of TRU’s processed and of the

¹ Heavy Metal.
ELECTROREFINING

- Actinide Elements are Separated from Fission Products for Recycle in Fresh Fuel Elements
  - >99.9% recovery
  - plutonium is combined with all minor actinides (Np, Am, Cm) and an approximately equal amount of uranium
  - contamination of fuel product with rare earth fission products

- Fission Products are Separated and Immobilized for Disposal
- Removal of Actinides from High-Level Waste
NUCLEAR: OPEN CYCLE

Natural Uranium (0.7% U-235)

266 kg for 1 GW x day

Isotopic Separation

Enriched Uranium (3.3% U-235)

Depleted Uranium (0.25% U-235)

PW-REACTOR

CRITICAL PROBABILISTIC SAFETY

33 GW x Day/t access every 6 months

30 kg for 1 GW x day

WASTE

1) Very high activity
2) Very long lived
3) Sub-critical (fissionable)
4) Proliferating (1% Pu)

Cost: 2.5$/GJ (Large installations)

ENERGY AMPLIFIER

NOT CRITICAL DETERMINISTIC SAFETY

>100 GW x day/t access every 5 years

Thorium-Uranium Mix (9% U-233)

Fission Fragments

Activated materials

74 gr Sr-90
137 gr Cs-135 (most offending)

SECULAR COOLDOWN ON SITE

Alternate route for Most offending Radio-nuclides

56 gr Tc-99
115 gr Cs-135
27 gr I-129 (most offending)

Coal ashes radio-toxicity level after < 500 years

WASTE

1) Same activity as burnt Th
2) non Fissionable
3) No proliferation

EA: CLOSED CYCLE ON SITE
Typical temperature and velocity fields in the spallation zone

\[ I_p = 6 \text{ mA} \]

**Temperature**
- Absolute
  - Local Max: 599
  - Local Min: 470

**Velocity**
- Component V
  - Local Max: 1.999
  - Local Min: -0.4013

Energy Amplifier Project
## Target main options

<table>
<thead>
<tr>
<th>Element</th>
<th>Reference Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam energy</td>
<td>600 MeV</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>2÷6 mA</td>
</tr>
<tr>
<td>Beam shape</td>
<td>Circular spot of 7.5 cm radius</td>
</tr>
<tr>
<td>Beam distribution</td>
<td>Parabolic</td>
</tr>
<tr>
<td>Target coolant</td>
<td>Pb-Bi eutectic at 180-260 °C</td>
</tr>
<tr>
<td>Target coolant circulation</td>
<td>Natural convection (eventually enhanced by gas injection)</td>
</tr>
<tr>
<td>Window material</td>
<td>HT-9 steel</td>
</tr>
<tr>
<td>Coolant mass flow rate</td>
<td>~200 kg/s</td>
</tr>
</tbody>
</table>
Typical temperature and stresses distributions on the internal and external fibres of the beam window.
Beam interruption effects: maximum temperature and Von Mises stress during the beam interruption transient.
Free surface calculations on the windowless target geometry: preliminary results (CFX)

\[ mfr = 100 \text{ Kg/s} \quad \text{mfr} = 135 \text{ Kg/s} \]
(PEC) SECONDARY BUILDING

48.00
Locale 3.7.7

26.00
Locale 3.6.1

19.25
Locale 3.5.1

14.80
Locale 3.5.1

10.32
Locale 10.3.2

(PEC) REACTOR BUILDING

5.00
Locale 1.4.2

N.FORE

(3D) LOOP LAYOUT
The interface between the proton beam and the molten lead

- The window is a major element of the Energy Amplifier. However, its failure would have no catastrophic consequences.

- Technological R&D is being carried out, in the framework of the Energy Amplifier demonstrator engineering design. The material considered for the demonstrator (standard solution) is ferritic steel, with no Nickel:
  - CRS4 (Sardinia): design and simulation
  - CEA (France): water loop scale 1 for fluid dynamic studies
  - FZK (Germany): Lead-Bismuth loop, scale 1 for T & velocity
  - CERN: possible future study in a proton/neutron beam?

- Free surface target (Window-less solution) studies:
  - CRS4/Sardinia (simulation and design); MYRRHA Mol/Belgium (water model); U. of Torino/Italy (water model); CIRCE ENEA Brasimone/Italy (Full scale Pb-Bi loop); CERN: future beam studies?
Destruction of nuclear waste
Fission Fragments

Gamma Radiation

(neutron)

233U

Transmutation by Adiabatic Resonance Crossing

CERN Academic Training, March 21-24, 2000
Fission Fragments activity and toxicity after 1000 years of cool-down in a Secular Repository

(Values are given for 1 GWe x year)

<table>
<thead>
<tr>
<th>Radio-isotope</th>
<th>Half-Life (years)</th>
<th>Activity @ 1000 yr</th>
<th>Ingestive Toxicity (Sv)</th>
<th>Mass (kg)</th>
<th>Dilution Class A (10CFR61) (m3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>^{129}I</td>
<td>1.57 x 10^7</td>
<td>2.11 x 10^5</td>
<td>33.79</td>
<td>8.09</td>
<td>17.847</td>
</tr>
<tr>
<td>^{99}Tc</td>
<td>2.11 x 10^5</td>
<td>1.187</td>
<td>19.58</td>
<td>1.43</td>
<td>178.47</td>
</tr>
<tr>
<td>^{126}Sn</td>
<td>1.0 x 10^5</td>
<td>34.12</td>
<td>27.67</td>
<td>16.61</td>
<td>947.65</td>
</tr>
<tr>
<td>^{135}Cs</td>
<td>2.3 x 10^6</td>
<td>39.32</td>
<td>9.65</td>
<td>3.20</td>
<td>39.32</td>
</tr>
<tr>
<td>^{93}Zr</td>
<td>1.53 x 10^6</td>
<td>26.11</td>
<td>18.75</td>
<td>6.5 x 10^5</td>
<td>0.745</td>
</tr>
<tr>
<td>^{79}Se</td>
<td>6.5 x 10^5</td>
<td>0.30</td>
<td>2.38</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Concentration factors for $^{99}\text{TcO}_4^-$ in marine organisms as determined in laboratory experiments using $^{95m}\text{TcO}_4^-$ (T.M. Beasley & H.V. Lorz)
Neutronics in Lead is understood

![Graph showing neutron energy and cross-section for natural lead](image)

- Cross-section (barns)
- Neutron Energy (eV)

Legend:
- Elastic
- Capture

Natural Lead
Adiabatic Resonance Crossing

Unique properties of Lead from the point of view of neutronics:

- Small capture probability ($\lambda_{\text{mig.}} \sim 1.2$ m);
- High elastic collision probability ($\lambda_{\text{el}} \sim 3$ cm), independent of $E_n$
- Small "Lethargy" kinematics of elastic collisions [below threshold for inelastic processes, (n, 2n), (n,3n), etc.]:

$$\frac{E_2}{E_1} = \frac{m_n^2 + m_{\text{Pb}}^2}{(m_n + m_{\text{Pb}})^2} + \frac{2m_n m_{\text{Pb}} \cos \theta}{(m_n + m_{\text{Pb}})^2} \approx 1 - \varepsilon$$

$\Rightarrow$ $E_2$ bounded: $\alpha E_1 \leq E_2 \leq E_1$; where:

$$\alpha = \frac{(m_{\text{Pb}} - m_n)^2}{(m_{\text{Pb}} + m_n)^2} \approx 0.98$$

$\Rightarrow \frac{E_2}{E_1}$ independent of energy and close to 1
The concept of Lethargy:

\[ \Delta u = -\ln \left( \frac{E_2}{E_1} \right) \equiv \frac{\Delta E}{E} \quad \text{[if } \frac{\Delta E}{E} \ll 1] \]

\[ \langle \Delta u \rangle \equiv \xi = 1 + \frac{\alpha}{1 - \alpha} \ln(\alpha) \approx 9.6 \times 10^{-3} \]

\[ \frac{E_2}{E_1} \] independent of energy \( \Rightarrow \Delta u \) independent of energy

\[ \Delta u \] independent of energy and constant elastic cross-section and captures negligible \( \Rightarrow \) flat neutron flux distribution in isolethargic bins [\( \ln(E) \) bins with \( \Delta(\ln(E)) \sim 1\% \)]:

A spallation neutron surviving the Lead capture resonances cannot, in its "adiabatic" slowing down, miss a resonance energy such as that of \(^{99}\text{Tc}\) at 5.6 eV. Therefore, it has a high probability to be captured on such resonance.
$^{99}\text{Tc}$ ($t_{1/2} = 2.1 \times 10^5 \text{ ans}$) + n $\rightarrow ^{100}\text{Tc}$ ($t_{1/2} = 15.8 \text{ s}$) + $\gamma$ prompt (1)

$^{100}\text{Ru}^* \rightarrow ^{100}\text{Ru}$ (stable) + $\gamma$'s (2)

Neutron Capture Cross-Section of $^{99}\text{Tc}$

174$\mu$s
92$\mu$s

neutron slowing down
Adiabatic Crossing of the 5.6 eV Resonance of $^{99}$Tc

Iso-lethargic steps
$\xi = 9.6 \times 10^{-3}$
TARC Proposal

EXPERIMENTAL STUDY OF THE PHENOMENOLOGY OF SPALLATION NEUTRONS IN A LARGE LEAD BLOCK

(CERN/SPSLC95-17; SPSLC/P291)

TARC Collaboration:

CEN, Bordeaux-Gradignan, France
CEDEX, Madrid, Spain
CERN, Geneva, Switzerland
Dipartimento di Fisica e INFN, Università di Padova, Padova, Italy
INFN, Sezione di Genova, Genova, Italy
IPN, Orsay, France
ISN, Grenoble, France
Sincrotrone Trieste, Trieste, Italy
Universidad Autónoma de Madrid, Madrid, Spain
University of Athens, Athens, Greece
University of Basel, Basel Switzerland
University of Thessaloniki, Thessaloniki, Greece
Universidad Alfonso X el Sabio, Madrid, Spain
Universidad Politecnica de Madrid, Madrid, Spain

(Financed by the European Union)
Side view of the TARC experimental area showing the details of the beam line. In the slow extraction mode the two station beam hodoscope is introduced in the beam line where indicated.
Fluka neutron source for 2.5 GeV/c protons

$E_n \leq 1\text{ MeV}$
$|x| \leq 2\text{ cm}$
TARC EXPERIMENT

Monte Carlo simulation of neutrons produced by a single 3.5 GeV/c proton

(147 neutrons, 55035 scatterings)

With 1 GeV protons and an accelerator current of 10 mA, as in the Energy Amplifier, the multiplication factor would be $2 \times 10^{16}$ per second!

[TARC Final Report to the European Union, 4th Framework Programme Contract F141-CT96-009]
Neutron Energy – Time correlation

As a result of the peculiar kinematics of neutrons in lead, a strong correlation exists between the time at which a neutron is observed and its energy:

$$t = \frac{2 \ell_{el.}}{\xi} \left[ \frac{1}{v} - \frac{1}{v_0} \right]$$

and if time is long enough ($v_0 \gg v$):

$$t \approx \frac{2}{\xi} \times \frac{\ell_{el.}}{v} \approx \frac{5.7 \text{ m}}{v}$$

\[
\begin{align*}
\ell_{el.} & \sim 3 \text{ cm} \\
\xi & \sim 0.01
\end{align*}
\]
CeF₃ Scintillator Set-up

\[ n + ^{99}\text{Tc} \rightarrow ^{100}\text{Tc} + \text{Prompt } \gamma \text{'s} \]

\( \Phi = 56 \text{ mm} \)

CeF₃ (Thickness: 2 mm; Area: 20×20 mm²)

Photo-Multiplier tube (XP2020) with Quartz window

Al Foil (20 μm)

Sample
Energy-Time correlation: \[ E = \frac{K}{(t + t_0)^2} \]

Data: \[ K = 172 \pm 2 \text{ keV} \times \mu s^2 \]

Monte Carlo: \[ K = 173 \pm 3 \text{ keV} \times \mu s^2 \]

Typically: \( \Delta E/E = 8\% \) at 1 keV and \( 1.3 \% \) at 5.6 eV

\[(12.3 \mu s) \quad (175 \mu s)\]
\[ N(\frac{E}{<E>}) \sim \frac{3\xi}{8\pi} \exp\left(-\frac{3\xi}{8} \left(\frac{E}{<E>} - 1\right)^2\right) \]

\[ N(E) \sim \frac{2n}{\pi} \frac{1}{kT} \sqrt{\frac{E}{kT}} \exp\left(-\frac{E}{kT}\right) \]

Elastic scattering process, for \( t \gg t_0 \)

Thermal distribution for \( E \ll 2 \text{ eV} \)

\[ \frac{\Delta E}{E} = 2\left(\frac{\xi}{3} + \frac{kT}{4E}\right)^{1/2} \approx 11.4\% \left(1 + \frac{2}{E(\text{eV})}\right)^{1/2} \]

- Ta: 4.28 eV
- Au: 4.906 eV
- Ag: 5.19 eV
- Tc: 5.584 eV
- In: 9.07 eV
- Ag: 16.30 eV
- Tc: 20.30 eV
- Mn: 337.00 eV

Analytical theory

M.C. simulation

Relative energy dispersion vs. Neutron energy (eV)
TARC SIMULATION

Fluence (d\(\phi/d\ln E\)) (n/cm\(^2\)/10\(^9\) protons)

Simulated fluence
No lead captures

Simulated fluence
With captures

\[ \frac{d\phi_n}{dE} = \frac{\alpha}{E^{\nu_2}} \left( \frac{\nu_2}{\nu_1} \right) e^{-\frac{\nu_2}{\nu_1}} e^{-\frac{E}{\nu_1}} \]

Neutron Energy (eV)
General layout of the CERN T7 experimental area. Top view showing the beam line, the lead assembly, the concrete shielding and the Rabbit system. The GE detection and data acquisition room labelled EP27D.
$^{99}$Tc and Background Spectra from TARC Experiment

Counts / 0.27 keV / 50 min

$^{99}$Tc Bremsstrahlung

662 keV (98Tc)
661 keV (137Cs)
745 keV (98Tc)

Run_8 & Run 49 (Background)
100\textsuperscript{Tc} Spectrum from TARC Experiment

Run_9 (x = 0, y = 60, z = 12.5 cm)
Figure 8.19

HPGe 1 539 KeV peak (Run 26)

Half life of $^{100}$Tc = 15.9 ± 0.4 s
$n + ^{129}\text{I} (1.57 \times 10^7 \text{ y})$ 

129I Transmutation

$^{129}\text{I} (t_{1/2} = 9 \text{ min})$

$^{130m}\text{I}$

$84\% \text{ IT}$

$^{130}\text{I} (t_{1/2} = 12.36 \text{ h})$

$16\% \beta^-$

$100\% \beta^-$

$^{130}\text{Xe}$ (stable)

- Graph showing number of counts vs. photon energy (KeV) for different elements.
- Activation number 7 (Hole 3, Z = + 7.5 cm)
- Rate for counting 6 multiplied by 10.
- Lines for counting #1 and #6.
Normalized Spectra

Flux, arbitrary units

Breeder
Spall. target
Fuel

Iron Vessel
Lead diffuser

Neutron kinetic Energy, eV
Monte Carlo simulation of the neutron fluence in the lead outside the Energy Amplifier core after introduction of 2.7 mg/cm$^3$ of $^{99}$Tc.

C. Rubbia, CERN/LHC/97-04 (EET)
ENERGY CONCEPTS FOR THE 21ST CENTURY

J.-P. Revol
(CERN)

LECTURE 4

CERN ACADEMIC TRAINING
March 21-24, 2000
Applications of the TARC effect
  Medical isotope production
  The CERN Time Of Flight facility
  A nuclear space engine

Status of the Energy Amplifier project in Europe

Conclusion
Medical Applications of the TARC concept

- The same technique (Adiabatic Resonance Crossing), which is very efficient for destroying Fission Fragments can also be used to induce any other type of nuclear transmutation (ie. radioisotope production), providing an attractive alternative to nuclear reactors:
  - favours "local" production thanks to the small size of the system (activator on the hospital site)
  - favours the possibility of using short-lived isotopes, resulting in a much smaller dose to patient [ex: $^{128}$I (25m) instead of $^{131}$I (8j)]
  - Avoids long (costly) transportation allowing smaller doses at the production site
  - Allows flexibility in the choice of neutron source according to need: high intensity accelerators (cyclotron) [industrial production $^{99}$Mo($^{99m}$Tc)] to radioactive n sources [low activity applications]

Ref.: C. Rubbia, CERN/LHC/97-04 (EET) & patent taken by CERN
EFFECT OF CARBON BUFFER ON THE ACTIVATOR FLUX ENERGY SPECTRA

Figure 9
General Principle of the Activator
Adapted from C. Rubbia, CERN/LHC/97-04 (EET)

Reflector (Pb)

Activation Region

Beam (p ord)

Moderator Region (C)

Low Energy Beam or Radioactive Source

Source or Target (³Be, ⁷Li)

Buffer Layers (Pb)

50 cm

High Power Beam and Spallation Neutrons

Activator Ensemble

Beam Channel

Pipe Pb Flow

Pb molten

Window

Heat Exchanger

Heating
Irradiation of Molybdenum – Run 767

Counts in 10000 sec.

Photon Energy (KeV)

99mTc 99Mo

1000

100

10

99Mo 101Mo 101Tc

32Mo 44Mo 95Mo 96Mo 97Mo 98Mo 100Mo

32Mo 44Mo 95Mo 96Mo 97Mo 98Mo 100Mo

44.26\% 78.25\% 15.82\% 16.68\% 19.55\% 34.13\% 8.63\%
THE SAMPLE BECOMES NATURALLY VERY PURE - ONLY $^{99}$Mo AND $^{99m}$Tc!
99\textsubscript{Mo} production from natural molybdenum (stable isotopes: 92\textsubscript{Mo}, 94\textsubscript{Mo}, 95\textsubscript{Mo}, 96\textsubscript{Mo}, 97\textsubscript{Mo}, 98\textsubscript{Mo}, 100\textsubscript{Mo})

First Activation: 98-Mo captures

Ratio Data / Monte Carlo

Gamma Energy (keV)

0.0 100 200 300 400 500 600 700 800
Asymptotic activated yield for different elements as a function of the neutron source strength

C. Rubbia, CERN/LHC/97-04 (EET)

1. $^{127}\text{I} \rightarrow ^{128}\text{I}$
2. $^{98}\text{Mo} \rightarrow ^{99}\text{Mo}$
3. $^{130}\text{Te} \rightarrow ^{131}\text{I}$
4. $^{127}\text{I} \rightarrow ^{128}\text{I}$

Source neutron yield (n/sec)

Beryllium Target

Spallation source

(100 MeV protons; 5 mA)
An innovative simulation was developed for the EA, using Monte Carlo techniques:

- Based on FLUKA for the spallation process and high energy transport ($E_n \geq 20$ MeV).

- Incorporating both neutron transport and nuclear element evolution and using detailed and updated nuclear data (100 Mbytes) ($E_n$ from 20 MeV down to thermal energies).

- Allowing the description of complicated geometries and material composition.

- Using special techniques (parallelisation, kinematics, $\sigma$, etc.) to be fast enough and provide sufficient statistics (20 $\mu$s/event/CPU).

Such a complex simulation had to be validated. It was one of the main goals of FEAT & TARC. [until now this simulation of a nuclear system is unique].

SEE CERN YELLLOW REPORT 99-11
- Calculational Scheme

General architecture of the EA-MC Monte Carlo simulation of neutron transport and element evolution

![Diagram showing the flow of the calculation process]

- Materials & Geometry
- Fluka run
- Neutrons < 20 MeV Spallation Products Released Energy
- FLUKA step
- Endf/B-6 cross sections and spectra
- Cross sections merging
- Neutron transport for a given time (+activation)
- Time evolution and materials update
- Nuclear database
- Monte Carlo step
- Analysis code
- Neutron collision file Materials evolution data

Energy Amplifier Project

Yacine Kadi
91-Pa-233
(n,\gamma)
Research Applications

- There is a severe lack of reliable nuclear data: "a simulation can never be better than the quality of data which are used as input". While current strategic elements are relatively well known, there is insufficient data to explore, systematically and with high precision, the parameters of new systems (Accelerator Driven Systems, etc.). Fundamental research on stellar nucleosynthesis, nuclear physics, dosimetry etc. also requires better data.

- The TARC method can provide a high intensity neutron source for various research applications, in particular in the field of nuclear cross-section measurements, allowing unprecedented energy resolution ($\Delta E/E \sim 10^{-4}$) over a very broad neutron energy spectrum and with intense short neutron pulses advantageous to reject background. Strong interest in tests of nuclear models and in providing reliable data for simulation of technologies involved in the elimination of nuclear waste.

- Such a facility (nTOF) has received strong support from the European Commission and has been approved by CERN, to start operating this year. It will make use of existing infrastructures (TT2A old PS transfer line to ISR).
\[
t = \frac{2\lambda_{el}}{v} \left[ \frac{1}{v} - \frac{1}{v_0} \right] \approx \frac{5.7 \text{ m}}{v} \implies \lambda \approx t \times v \approx 5.7 \text{ m} \pm 31 \text{ cm}
\]

\[
\frac{\Delta E}{E} = 2 \left( \frac{\xi}{3} + \frac{k_T}{4E} \right) \approx 11\% \Rightarrow \frac{\Delta v}{v} \approx 5.5\%
\]

Sample to be Measured & Detector

\[ t = T \]

Proton beam

Source

\[ v = \text{neutron speed} \]

Time of Flight \( t_{TOF} \)

\[ t_{TOF} = L/v \]

Flight path = \( L \)

\[ \Delta \lambda \]

\[ \lambda \]

Effective neutron path used in energy determination

\[ \Delta \lambda = \Delta \lambda / T \]

\[ \Rightarrow \text{The velocity } v \text{ of the neutron is derived from the "effective neutron path" } v = (\lambda + L) / T \text{ with an uncertainty } \Delta v = \Delta \lambda / T. \]

\[ \Rightarrow \text{The parameter which has to be made as small as possible is } \Delta \lambda \]
If at the exit of the Lead target, the neutron speed $v$ is abruptly reduced by a large factor, for instance with a hydrogen rich moderator slab, $\Delta \lambda = v \Delta t$ will be correspondingly reduced.

Note that the time fluctuations $\Delta t$ of the moderation process are essentially unchanged, because of the small thickness of the hydrogen layer.

The hydrogen moderator removes also the "Lead glitches"

Consequently $\Delta \lambda$ goes from 31 cm to 1.7 cm. Reaching a $10^{-4}$ energy resolution required $L = 3$ km without hydrogen, it now only requires of the order of 200 m.

the price of a lower average energy spectrum, as suitable for the measurements at lower energies.
Characteristics of the CERN Neutron TOF Facility

The CERN accelerator complex, allowing a TOF distance up to $L = 213$ m, is characterised mainly by **six practically unique features**:

■ A high neutron flux exceeding $3 \times 10^{10}/L^2$ [n/cm$^2$/pulse] for the standard CERN-PS intensity, allowing for targets of very modest mass.

■ An excellent energy resolution in the neutron energy determination by TOF, namely $\langle \Delta E/E \rangle = 3.5 \times 10^{-2}/L$ [m].

■ A very broad energy spectrum, covering **simultaneously** the whole energy domain of interest, over eight orders of magnitude, from 1 eV to over 250 MeV.

■ Small intrinsic photon (0.14 γ/n) and charged particle (0.2 c/n) contamination, much suppressed by TOF & $B_{field}$.

■ The much smaller repetition rate (< 1/2.4 sec$^{-1}$) of the CERN PS eliminates the problems of time overlaps at the measuring station due to successive bunches.

■ The accidental background due to radioactive targets is also very much reduced because of the high bunch intensity and repetition rates at the CERN-PS.
A As result of a general trade-off between the neutron flux $\Phi_n$ and the $\Delta\lambda$ resolution, we have chosen:

$$R = 40 \text{ cm}, \ H = 40 \text{ cm} \ and \ W_{\text{mod}} = 4 \text{ cm}$$

For $E_n < 10^5 \text{ eV}$ (resonance domain), the bunch width $\Delta t_B$ does not affect the TOF energy resolution.

$Iso$ lethargic $\Phi_n$ over 8 orders of magnitude!
A HIGH RESOLUTION SPALLATION DRIVEN FACILITY AT
THE CERN-PS TO MEASURE NEUTRON CROSS SECTIONS IN
THE INTERVAL FROM 1 eV TO 250 MeV.

C. Rubbia, S. Andriamonje\textsuperscript{1}, D. Bouvet-Bensimon\textsuperscript{1}, S. Buono\textsuperscript{2}, R. Cappi,
P. Cennini, C. Gelès, I. Goulas, Y. Kadi, P. Pavlopoulos\textsuperscript{3},
J.P. Revol, A. Tzima\textsuperscript{4}, V. Vlachoudis\textsuperscript{4}

Abstract

The design of innovative Accelerator-Driven Systems (ADS) for incineration of nuclear waste, energy production and radio-isotope activation for medical applications as well as many other subjects in Nuclear Physics, requires a knowledge as complete and as precise as possible of cross sections for neutron induced processes.

The spallation mechanism is a remarkably powerful source of neutrons: in a Lead spallation target, one 24 GeV proton may produce as many as 760 neutrons. The CERN PS accelerator is capable of accelerating $2 \times 3 \times 10^{13}$ ppp, resulting in as many as $2 \times 10^{16}$ neutrons at each pulse. This extraordinarily prolific source can be concentrated in short time pulses which are typically of the order of $\pm 10$ ns, offering the added feature of a tremendous potential accuracy in the time of flight (TOF) determination of the neutron energy.

To the very small time uncertainty of the source one has to add the fluctuations in the moderating time needed to produce a wide initial neutron spectrum capable of covering the full extent of the energy domain in which cross sections need to be measured. It is a fortunate circumstance that the moderation in a high A material (the spallation target) occurs in a large number of steps in which the energy loss is small ($\leq 1\%$). Hence the time fluctuations in the slowing-down process are also small, since the moderation time is strongly correlated with the energy of the outgoing neutron.

These features, already exploited in the TARC experiment, permit a very accurate TOF measurement of the incoming neutron energy. The rich initial source offers, at a measuring station located at the distance L, a flux of $2.8 \times 10^5/L^2$(km) n/cm$^2$/pulse.

The facility allows to study systematically and with excellent resolution neutron cross sections of almost any element using targets of very modest mass (even few milligrams), as needed for unstable or otherwise expensive materials, like for instance transuranics, in the interval from 1 eV to 250 MeV.


\textsuperscript{1}On leave from CEN-Bordeaux
\textsuperscript{2}CRS4 Cagliari
\textsuperscript{3}University of Basel
\textsuperscript{4}University of Thessaloniki
<table>
<thead>
<tr>
<th>Country</th>
<th>Institution/University</th>
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<tbody>
<tr>
<td>Austria</td>
<td>Institut für Kernphysik, Technische Universität Wien, Wien</td>
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<td>Belgium</td>
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<td>France</td>
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<td>ILL, Grenoble</td>
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<td>ISN, IN2P3/CRNS &amp; University J. Fourier, Grenoble</td>
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<tr>
<td></td>
<td>SUBATECH UMR 6547, Nantes (Ecole des Mines &amp; University)</td>
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<td>Ecole Supérieure de Physique et Chimie Industrielle (ESPCI), Paris</td>
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<td>Greece</td>
<td>NRCPs &quot;Demokritos&quot;, Institute of Nuclear Physics, Athens</td>
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<td>University of Athens, Division of Nuclear Physics, Athens</td>
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<tr>
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<td>Technical University of Athens, Division of Physics, Athens</td>
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<td>University of Ioannina, Nuclear Physics Laboratory, Ioannina</td>
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<td></td>
<td>Aristide University of Thessaloniki, Dept. of Physics, Thessaloniki</td>
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<tr>
<td>Russia</td>
<td>JINR, Frank Laboratory of Neutron Physics, Dubna, Moscow</td>
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<td>P. N. Lebedev Institute of Physics (FIAN), RAS, Moscow</td>
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<td>A-RSRIEP, Sarov, Nizhni Novgorod region</td>
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<td>Universidad de Santiago de Compostela</td>
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<td>Instituto de Fisica Corpuscular, Universidad de Valencia, Valencia</td>
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<tr>
<td>Switzerland</td>
<td>Dep. of Physics and Astronomy, University of Basel, Basel</td>
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<td>Institute of Physics, University of Basel, Basel</td>
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<td></td>
<td>SL Division, CERN, Geneva</td>
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<tr>
<td>USA</td>
<td>LLNL, Analytical and Nuclear Chemistry Division, Livermore</td>
</tr>
<tr>
<td></td>
<td>University of Notre Dame, Notre Dame</td>
</tr>
<tr>
<td></td>
<td>Oak Ridge National Laboratory, Oak Ridge</td>
</tr>
</tbody>
</table>

Interested International Organisations:
- EC, DG XII, Brussels
- IAEA, Vienna
- NEA/OECD, Paris
The CERN Time of Flight Facility

~ 600 neutrons / 20GeV proton
4 x 0.7x10^{13} p >>> 1.7x10^{16} n
every 2.4 s
(0.7x10^{16} n/s)
A nuclear engine for deep space travel

The new idea proposed by Carlo Rubbia is to use the high kinetic energy of fission fragments to directly heat up hydrogen gas into a plasma, to obtain high exhaust velocities ($v_{ex}$), hence high specific impulses ($v_{ex}/g$).

| Energy (MeV) | Kinetic energy of Fission Fragments | 168 ± 5 |
| Instantaneous $\gamma$ rays | 5 ± 1 |
| Neutron Kinetic Energy | 5 ± 0.5 |
| Decay products $\beta$ particles | 7 ± 1 |
| Decay products $\gamma$ particles | 6 ± 1 |
| Neutrinos | ∼ 10 |
| Total | 201 ± 6 |

A small critical mass of a thin layer of $^{242}_{\text{Am}}$ can be obtained, by using the strong neutron flux enhancement method tested at CERN with TARC, in a configuration called neutron-Hohlraum.
\[ \sigma(\text{fission}) \sim 5300 \text{ barns; } P(\text{fission}) \sim 0.13 \text{ for a } 1 \mu\text{m } 242\text{mAm layer} \]
Figure 3.3: *Orbital scenario with Hohmann trajectories for slow, unmanned TUG missions. Circular orbits only have been considered, thus only approximate LEO departure dates are shown.*

**Table 3.1:**

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outbound</td>
<td>259 days</td>
</tr>
<tr>
<td>Mars Entry, Stay, Escape</td>
<td>480 days</td>
</tr>
<tr>
<td>Return</td>
<td>259 days</td>
</tr>
<tr>
<td>Total mission</td>
<td>998 days</td>
</tr>
</tbody>
</table>

Leaving LEO dates:
- Summer 2007
- Summer 2009
- Autumn 2011
- Winter 2014

---

Figure 3.4: *As for Figure 3.3, orbital scenario for typical fast, CLIPPER manned missions.*

**Table 3.2:**

<table>
<thead>
<tr>
<th>Mission Phase</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outbound</td>
<td>150 days</td>
</tr>
<tr>
<td>Mars Entry, Stay, Escape</td>
<td>41 days (typical)</td>
</tr>
<tr>
<td>Return</td>
<td>176 days</td>
</tr>
<tr>
<td>Total mission</td>
<td>369 days</td>
</tr>
</tbody>
</table>

Leaving LEO dates:
- Summer 2007
- Autumn 2009
- Autumn 2011
- Winter 2014
☐ Specific impulses (time duration over which a given propellant mass can produce a thrust force equal to its weight) of 2000 to 4000 s could be obtained as compared to 450 s for chemical fuel and 950 s for NERVA.

☐ The Tsioikowskii rocket equation can be used to show that with such a system one can avoid Hohmann trajectories and reduce in a considerable way the duration of a trip to Mars for instance (one year round trip with 41 days on Mars):

\[
M_f = M_0 e^{-\frac{u_0}{v_{ex}}}
\]

☐ The preferred nuclear fuel is \(^{242}\text{mAm}\). A round trip to Mars would require only a few kg of \(^{242}\text{mAm}\).

☐ Conceptual studies of such a device have started in Italy.

REPORT OF THE WORKING GROUP ON
A PRELIMINARY ASSESSMENT OF A NEW FISSION FRAGMENT HEATED PROPULSION CONCEPT AND ITS APPLICABILITY TO MANNED MISSIONS TO THE PLANET MARS (PROJECT 242)

\/

MEMBERS

Mauro Augelli
Giovanni F. Bignami (chair)
Claudio Bruno
Elio Calligarich
Giovanni De Maria
Marco Mulas
Carlo Musso
Alberto Pellizzoni
Walter O. Piperno
Renzo Piva
Benedetto Procacci
Marco Rosa-Clot
Carlo Rubbia

ASI
ASI and University of Pavia
University of Rome “La Sapienza”
INFN (Section of Pavia)
University of Rome “La Sapienza”
CRS4, Cagliari
ASI
ASI
University of Rome “La Sapienza” and ASI
ASI
CRS4 Cagliari
CERN and University of Pavia

Roma, 15 March 1999
Concerning the accelerator, the following main objectives have been defined by the TWG:

- achieving the required beam power while keeping beam losses at an extremely low level;
- achieving the reliability/availability required, in particular, to keep the number of beam trips to an extremely low rate;
- combining the first two objectives in a rather conservative design with particular effort towards cost effectiveness.

The TWG interim report has considered two basic options for an accelerator: a facility based on a super conducting Linac and a facility based on coupled isochronous multi-sector cyclotrons.
The Energy Amplifier Project in Europe

- Basis physics principles checked at CERN with FEAT and TARC experiments

- Development of an appropriate simulation and of computing tools used in optimization of parameters for conceptual design (CERN)

- Setting up of an advisory panel for research ministers of 11 European countries (CERN as observer)

- Setting up of a Technical Working Group (C. Rubbia Chairman) to prepare white book on strategy for prototype

- Industrial study of prototype designs (CERN, Ansaldo, Framatome, ENEA, CRS4, INFN, CEA, GEDEON, etc.)

- European Parliament study (Scientific and Technological Option Assessment) indicates strong support for construction of a prototype in view of eliminating nuclear waste

- TOF facility approved at CERN to make systematic measurements of neutron cross-sections
**Preliminary Parameters of the EAP80 Demo**

*Conditions at BOL*

Main parameters of the EAP80 reference configuration

<table>
<thead>
<tr>
<th>Global Parameters</th>
<th>Symbol</th>
<th>EAP80</th>
<th>Units</th>
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<tbody>
<tr>
<td>Initial fuel mixture</td>
<td>MOX</td>
<td>(U-Pu)O₂</td>
<td>ton</td>
</tr>
<tr>
<td>Initial fuel mass</td>
<td>( m_{\text{fuel}} )</td>
<td>3.804</td>
<td></td>
</tr>
<tr>
<td>Initial Pu concentration</td>
<td>( m_{\text{Pu}}/m_{\text{fuel}} )</td>
<td>18.1</td>
<td>wt.%</td>
</tr>
<tr>
<td>Initial Fissile enrichment (^1)</td>
<td>( \text{Pu}^{39,41}/\text{U}^{38} )</td>
<td>18.6</td>
<td>wt.%</td>
</tr>
<tr>
<td>Thermal Power Output</td>
<td>( P_{\text{th}} )</td>
<td>80</td>
<td>MWatt</td>
</tr>
<tr>
<td>Proton Beam Energy</td>
<td>( E_{\text{p}} )</td>
<td>600</td>
<td>MeV</td>
</tr>
<tr>
<td>Spallation Neutron Yield</td>
<td>( N(n/p) )</td>
<td>13.6 ± 0.1</td>
<td></td>
</tr>
<tr>
<td>Neutron multiplication</td>
<td>( M )</td>
<td>24.12 ± 0.66</td>
<td></td>
</tr>
<tr>
<td>Multiplication Coefficient</td>
<td>( k=(M-1)/M )</td>
<td>0.9585 ± 0.0011</td>
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</tr>
<tr>
<td>Energetic Gain</td>
<td>( G )</td>
<td>34.6 ± 1.0</td>
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<tr>
<td>Gain coefficient</td>
<td>( G_0 )</td>
<td>1.4</td>
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</tr>
<tr>
<td>Accelerator Current</td>
<td>( L_p )</td>
<td>3.97 ± 0.11</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)namely \(^{239}\)Pu and \(^{241}\)Pu isotopic concentrations
Evolution with Fuel Burnup

Reactivity Swing and Proton Current Variation
 Evolution with Fuel Burnup

EAP80 reference configuration: Transmutation Rates at EOL

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>TR (kg/TWhe)</th>
<th>ΔM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>− 111</td>
<td>− 53.2</td>
</tr>
<tr>
<td>Neptunium</td>
<td>+ 0.73</td>
<td>+ 0.35</td>
</tr>
<tr>
<td>Plutonium</td>
<td>− 22.4</td>
<td>− 10.7</td>
</tr>
<tr>
<td>Americium</td>
<td>+ 0.52</td>
<td>+ 0.25</td>
</tr>
<tr>
<td>Curium</td>
<td>+ 0.81</td>
<td>+ 0.39</td>
</tr>
</tbody>
</table>