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SOME PRELIMINARY CONSIDERATIONS ON THE ECONOMICAL ISSUES OF THE ENERGY AMPLIFIER

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Abstract

This report complements the document Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier, CERN/AT/95-44 (ET), by C. Rubbia et al., September 1995, and surveys the economical aspects of the Energy Amplifier in the context of the two main topics related to energy production:

a) direct costs of construction and of operation of a plant based on the Energy Amplifier and of the electrical KWh produced;

b) social and political benefits to be expected from the development of the Energy Amplifier.

Assumptions made are based on the present state of the art of the conceptual design of the fast neutron operated High Power Energy Amplifier. Obviously, more elaborated economic studies are required when the detailed design study of the Energy Amplifier is completed and subsequently when prototypes are developed.

However, on the basis of our present knowledge and of the auditing of our assumptions and calculations by the IEPE (Institut d'Economie et de Politique de l'Energie de Grenoble) and by several independent experts we can conclude that when comparing direct costs, within the range of the usual industrial uncertainties translated into severe contingencies in our calculations, the higher limit of the electrical KWh produced by the Energy Amplifier is smaller or comparable to that of the other sources of energy. When taking into account the other elements of the overall real cost of a source of energy, the Energy Amplifier provides a significantly positive case.

Geneva, 29th October, 1995

The economical issues related to energy production can be divided into two main topics:

1. The prospects of competitiveness of the Energy Amplifier: analysis of the direct costs of construction and of the electrical KWh produced.

   These elements of costs can be technically quantified. The initial global approach is refined in parallel with the detailed design study of the characteristics and performances of the equipment used. Cost analysis requires hypotheses on unit cost of manpower, on interest rates, and depends upon accounting procedures. Once these assumptions have been set, estimates and actual costs can be technically determined.

2. The social and political benefits of the development of the Energy Amplifier.

   In particular the advantages for the environment, as resulting from the considerations made in the previous chapters.

   Another topic is the contribution to the global balance of energy production in future years. This topic can be considered in the light of studies elaborated by specialized institutions. Organizations, established at the European or World level, have examined several scenarios for the forthcoming century which may lead to contrasted strategies.

Since these topics call for objective but also for rather subjective approaches, there are different ways of estimating consequences and costs.

1 - Analysis of the Costs

1.1 - Direct Construction Costs of Prototypes and Series

We have based our estimates of the direct costs of prototypes and series on the technical descriptions and parameter values of the Energy Amplifier worked out by C. Rubbia et al. in the document CERN/AT/95-44 (ET) "Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier" of September 1995. The estimates of the cost of the Amplifier System have also taken into account the calculations made in note CERN/AT/ET/INTERNAL NOTE 94-011-ADD on cost analysis, complementing in 1994 the document CERN/AT/93-47 (ET) "An Energy

Amplifier for Cleaner and Inexhaustive Nuclear Energy Production driven by a Particle Beam Accelerator" of November 1993.

These estimates can be further refined only at later stages of the Energy Amplifier programme, when detailed specifications are made available by each professional group involved.

Our experience in building accelerators makes us confident that the final cost of this part will be close to our estimates.

Additional technical development is needed before freezing the costs of the energy producing unit; therefore direct and indirect contingencies are included in the present estimates.

For the conventional systems, we made cross-checks with the reference documents of the Department of Energy of the United States and of the Electricité de France.

The cost of a prototype producing 1500 MWth or 675 MWe, as described in document CERN/AT/95-45 (ET), would be of the order of 500 Million US$. The costs of the prototype do not include land and premises. It is assumed that the region hosting the project (or another partner) will provide for them. It could be envisaged to build the prototype close to an existing plant in order to take advantage of the "conventional" part of an existing plant.

We used as an hypothesis that, when produced by industry for at least 10 units, the cost of a unit represents 45% of the cost of the prototype ("The Series Effect: Impact on Capital Cost of the Standardization of PWR Plants", from: EDF, Engineering and Construction Division, presented at the AEE/IAEE Conference, May 1992).

The cost of an industrially-made Energy Amplifier system (excluding the conventional systems) producing 1500 MWth would then be of 225 MUS$. Further approximations will be developed during the prototyping phase.

Tables 1 and 2 summarize our estimates for construction costs.

1.2 - Economic Costs of the kWh

The cost of the kWh of electricity is the current yardstick used to compare different sources of energy. It is composed of the economic cost of the kWh (financial costs of capital, operating and maintenance costs, fuel costs) and of external costs.

These external costs (which may become controversial) require the consideration of external, sometimes subjective, elements to be developed under the next section.

We will limit, in this section, our comparisons to direct costs, for a plant producing about 2 GW of primary electrical power, made with a cluster of three modular units of 1500 MWth each and a fourth, spare, accelerator to ensure back-up reliability.

The IEPE (Institut d'Economie et de Politique de l'Energie de Grenoble) made an independent study (Evaluation Economique de l'Amplificateur d'Energie dans ses Configurations à Neutrons Thermiques et à Neutrons Rapides: une Analyse Critique, D. Finon et P. Ménanteau, décembre 1994). It confirms, taking into account the industrial uncertainties, that the calculations made are within reasonable limits of confidence.

The costs of operation and the hypotheses used are detailed in Tables 3 and 4. We have considered limits of uncertainty suggested by IEPE, on top of our own reserves for contingencies.

For comparison purposes, as done in the IEPE study and in the OECD reports, we have normalized the costs of capital, O&M and fuel to the kWh produced by a plant of about 1100 MWe and included the margin of uncertainty resulting from the above mentioned study. The results are shown in Table 5 and Graph 1. Graph 1 includes political parameters (differences in national regulations or accounting) on top of a purely objective analysis of costs. It gives however a good indication of the positioning of the costs of the Energy Amplifier (not located in a precise country at this stage).

By comparing the costs of the Energy Amplifier to the other sources of energy we may conclude, from our first estimates, that the costs of the Fast Energy Amplifier could be significantly lower. There are still technological uncertainties at this stage, in particular due to the need of knowing better the behaviour of Lead. Nevertheless, even when taking the high value of the limits of uncertainty, costs would still remain below those of the cheapest PWRs.

1.3 - Further Considerations

The research under way shows that the energy amplifier is capable of incinerating not only its own wastes but also those produced by other plants. It could transform the unwanted Plutonium into Uranium 233 which, once chemically separated, could be used to enrich the fuel for the plant (or for other plants, even classical ones).

As a consequence it could be envisaged to build an energy amplifier coupled to an existing "classical" plant in view of incinerating its wastes: by doing so the incinerating function of the energy amplifier would amortize its investment cost while the complementary power produced would be almost free of charge.

Furthermore, the Uranium 233 produced by the amplifier and chemically separated could replace the Uranium 235 whose preparation is more expensive and therefore bring an extra financial bonus to the operation.

Obviously, economic studies should be undertaken when the technical design study is completed, the industrial processes defined and regulatory aspects clarified, in view of a more precise evaluation of the financial consequences of this new option. It still remains that an approach which would allow both the transmutation of waste into fuel and the production of energy complementing the needs for peak or maintenance periods on an existing nuclear site could only increase the return on investment.

2 - Social and Political Benefits

The evolution of the demand of energy in the world and the matching of these requirements to the possible supply are key elements to include in an economic analysis on energy.

On the demand side, the scenarios elaborated by several specialized institutions (World Energy Council, WEO-OECD, IIASA, Ecotech-CNRS), anticipate that the world energy consumption will increase from about 9 Gtep to 11 Gtep by the year 2020, in the optimistic approach, and to 16 Gtep in the pessimistic approach.

As illustrated by Graphs 2 and 3, most of the increase is expected to take place in the developing countries, which would represent more than half the world primary energy consumption by the year 2020.

To meet these anticipated needs, which are supposed to grow between 20% to 80% at the 2020 horizon, the "classical" solutions will give only a partial answer:

- The contribution from non-renewable energies would remain important but, by nature, its supply is potentially limited.

- Furthermore, increase in consumption of fossil fuels will induce a rising emission of CO_2, alleged primary cause of climatic change. The level of damages to the environment created by CO_2 is still scientifically disputable. However Graph 4 raises serious questions about the extensive use of fuels.

- The present designs of nuclear plants encounter considerable social intake difficulties: safety of reactors, waste management, risks from proliferation are well known issues. Furthermore, the technological level of the developing countries and the limitations in the funding capability are limiting factors to a possible extension of fission-based reactors.

- Fusion is the third category of potential source of energy supply. However, the present and anticipated technological difficulties will still require a long and persistent effort of R&D to allow, optimistically, for some tangible results around year 2050.

- Excluding fusion, which can be considered a too-far away answer to the present pressing demand of energy, and the renewable-type of energy which can only provide limited supply, the two other sources both entail acute environmental problems: the non-renewable energies increase dramatically the level of CO_2 while the nuclear plants bring with them a series of outstanding threats to the environment and the populations. These options are compared in Table 6.

Hence clearly appears the interest attached to a source of energy which would provide the major advantages of non-renewable or nuclear systems while avoiding their inherent risks. This calls for one of the most fundamental roles of the scientific community to propose new concepts to society which can sustain its development while giving reasonable answers to issues and concerns induced by the present technologies.

It is our belief that the Energy Amplifier is a genuine solution to energy-related problems and that it could also contribute to the economic development both in the Industrial world and in the Developing countries. In that respect it should be noted that:

- Most classical nuclear plants will come to the end of their life-time in the coming decades. Almost no new construction or replacement of reactors are underway or scheduled in a near future. As shown by Graph 5 the booming time of nuclear plants construction is over.

- The design of the Energy Amplifier allows for: massive manufacturing by industry; flexibility in size of plants and flexibility in production level of energy (to cope with peaks in the demand). The construction and operation of particle accelerators are based on reliable and well-mastered techniques; in contrast with nuclear plants the implementation process is fast, the risks on the investment are widely lessened and the operation and maintenance may require a less sophisticated technological level.

- The possibility to use Energy Amplifier output for purposes other than production of electricity (heating, water desalination, production of hydrogen) as well as the opportunity for rehabilitating less favoured or isolated (Island) areas, opens the door to new markets in an energy-hungry world.

- Finally the Energy Amplifier offers a low dependency on source of "fuel" since very long-term availability of fuel is ensured, which means no crisis in supply (this may look disputable today but critical changes in future cannot be excluded).

The public opinion, in many countries, demands that the economical and technical development are not conducted at the expense of the environment.

Beyond direct and indirect economical aspects it is therefore necessary to take into consideration the "other" factors which gather the public's attention. Among these factors, the following seems fully representative of today's concerns:

- Greenhouse effects are increased by conventional plants (gas, fuel, coal). This is still a scientifically controversial issue.

- The present civilian nuclear system creates radioactive wastes of variable life-time and potential danger. It also opens the possibility of highly dangerous proliferation of fissile materials such as Plutonium.

- Geologic repository after vitrification is, at present, the most favoured and practical option (but illegal in some countries). However, very long-term predictions on geological and political stability are not without risk. Therefore, scientific and technical solutions to neutralize nuclear waste remain to be found beyond the present state of the art.

- Other well-known issues are the disposal and the re-processing of Plutonium. Its world-wide stock (see Graph No 6) is accumulating over the years and there are serious doubts on the extent of its control.

The Energy Amplifier brings, again, a reassuring answer to these types of worries:

- As for nuclear plants it generates a low level of CO_2.

- Long-lived nuclear waste (Plutonium and other heavy elements) is practically not produced by the system.

- The remaining waste, mostly fission products, would be neutralized by re-processing within our system.

- It contributes to the reduction of the risk of proliferation of weapon-grade material, by its minimal production but also by its ability to convert the Plutonium produced by classical nuclear plants into Uranium 233.

3 - Concluding remarks

Under the assumption that the demand of energy will increase from today 9 GTOE to tomorrow 11 to 16 GTOE, it is anticipated that the present supply canvassing can hardly cover the needs: either because the offer will come from sources which, by nature, are going to phase out or because the means of production does not get public consensus.

When accounting and comparing direct costs, the Energy Amplifier, within the range of usual industrial uncertainties, is about comparable to other sources of energy. When taking into consideration the other elements of the overall real cost of a source of energy, the Energy Amplifier provides a significantly positive case.

Although we must admit that it is difficult to put today a price tag on each of the items developed above, such an exercise should be undertaken rather soon and economists should innovate in parallel to scientists. Further developments of this study are also required to integrate in future the lessons of the prototyping stage.

Assuming that, in the first half of the next century, the nuclear energy would supply 3.2 TOE (0.4 in 1990), corresponding to 2600 GW and assuming that the present classical nuclear plants remain at a constant level, the potential share of the Energy Amplifier would be of about 2000 GW (IEPE study). Such a potential market represents 4000 Billion US Dollars.

4 - *Acknowledgments*

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Table 1 - Construction Cost of Prototypes [1]

Cost of Prototypes (675 MWe)	MUS$	
Booster Ring		60
Intermediate Injector		25
Ion Source Injector		10
Beam Transport		5
Control Room, equipment for measurements		5
Installation		20
Total Accelerator	**125**	
Energy Producing Unit (hardware)		120
Installation		30
Waste Transformation		50
Connections between Systems		30
Total for Energy Producing Unit	**230**	
Personnel	**60**	
Contingency (20%)	**85**	
Total Energy Amplifier	**500**	

Table 2 - Capital Cost of Industrial series [1]

Cost of Industrial Series if series production (at least 10 units)	MUS$
One unit of **675** MWe	**225**
A group of **three** units (+ 1 spare accelerator system)	**750**

(1) Excluding land and conventional facilities

Table 3 - Yearly Operating Cost of a Plant based on a Fast Energy Amplifier and providing about 2 GWe (in 1993 MUS$)

~ 2000 MWe	Heads	MUS$
Staff numbers:		
Accelerators (3 + 1 spare)	60	
Energy Producing Unit	40	
Conventional Systems	180	
Management and Administration	20	
Total	**300**	
Total Staff Costs		**20**
Annual Material Costs:		
Fuel Costs (including reprocessing)		20
Other Consumable Costs		15
Other Maintenance Costs		30
Total Material Costs		**65**
Contingency + Unforeseen Recurrent Costs		**15**
TOTAL ANNUAL OPERATING COSTS		**100**

Table 4 - Costs of a Plant based on a Fast Energy Amplifier and providing about 2 GWe (in 1993 MUS$)

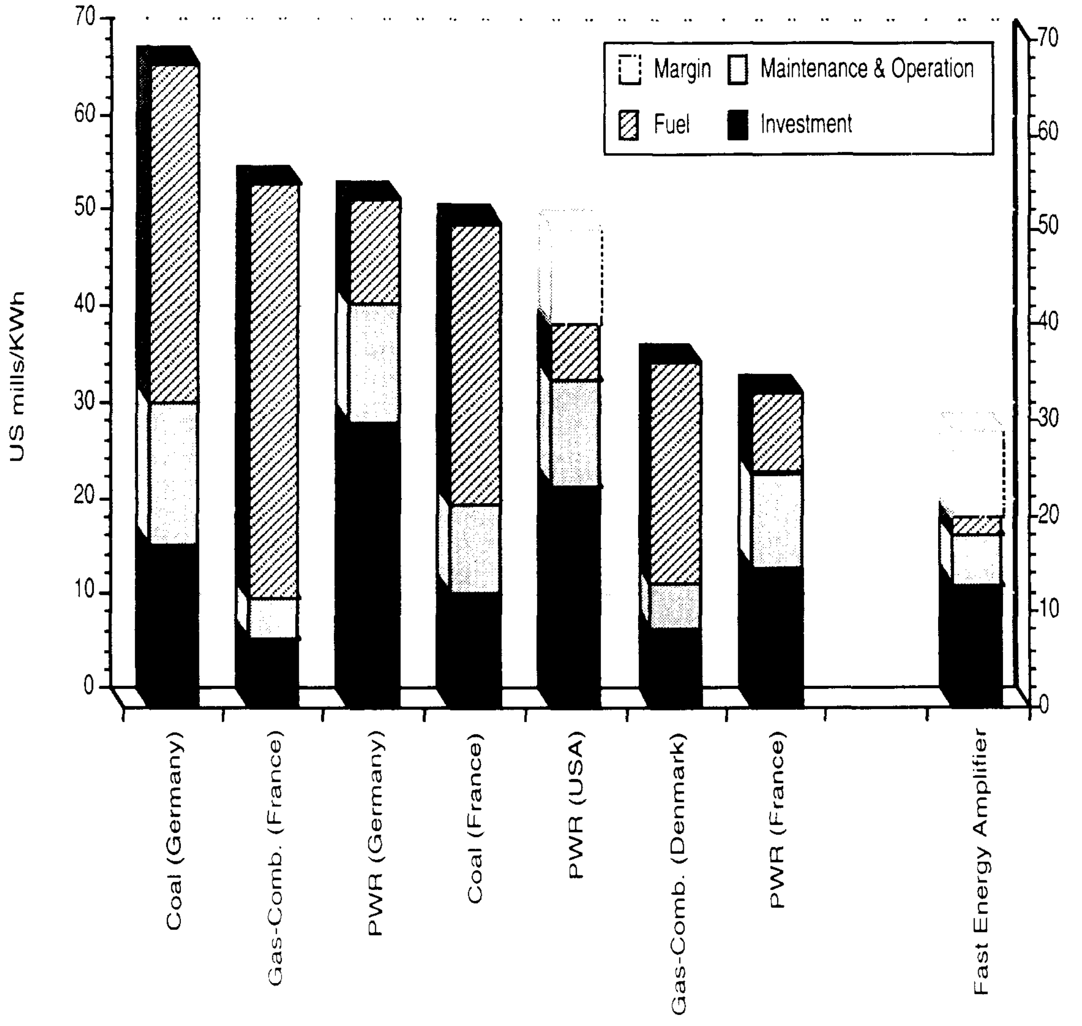
~ 2000 MWe	MUS$
Land preparation, Buildings, Safety, rad. protection, etc.	600
Mechanical systems (Turbines, cooling, heat exch., etc.)	700
Electrical systems (cabling, transformers, etc.)	300
General expenses	300
Total Conventional systems	**1900**
Total Amplifier (3 accelerators + 1 spare)	**750**
TOTAL CAPITAL COSTS	**2650**
Annual Financial costs (50 years life, 6% interest rate)	170
Annual Operating costs (including Fuel & Contingency)	100
TOTAL ANNUAL COSTS	**270**
GWh/year (about 90% operation - 5% of power used for accelerators)	***~ 15000***
US$ ct/KWh	**1.8**

Table 5 - "Normalized" KWh Cost of Plants based on Energy Amplifiers

Item	US$ mills of 1993/kWh
Capital	12.5
O&M	5.5
Fuel	2.0
Total	**20**
Limits of uncertainty	*18-29*

Table 6 - Comparison between Sources of Nuclear Energy

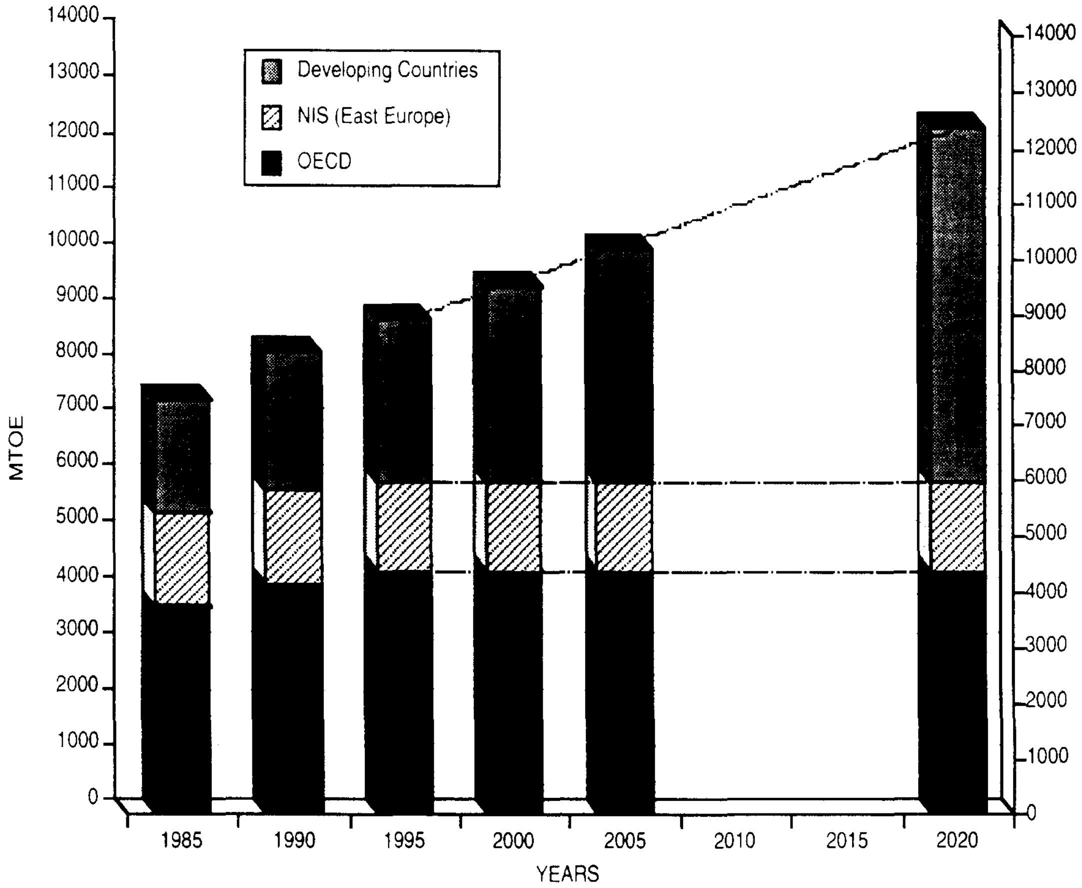
	Classical Fission	Energy Amplifier	Fusion
Fuel Availability	Limited	Almost Unlimited	Almost Unlimited
Criticality	Yes	No	No
Toxicity	Important	Negligible	Weak
Proliferation	Important	Negligible	Negligible
Technology	Highly Mastered	To be developed but exists	Non-existent
Time Scale	Already Existing	5 to 10 years	More than 30 years



* From "Projected Costs of Generating Electricity from Power Stations for Commissioning in the Period 1995-2000" (OECD Nuclear Energy Agency, 1989) and from IEPE- Grenoble

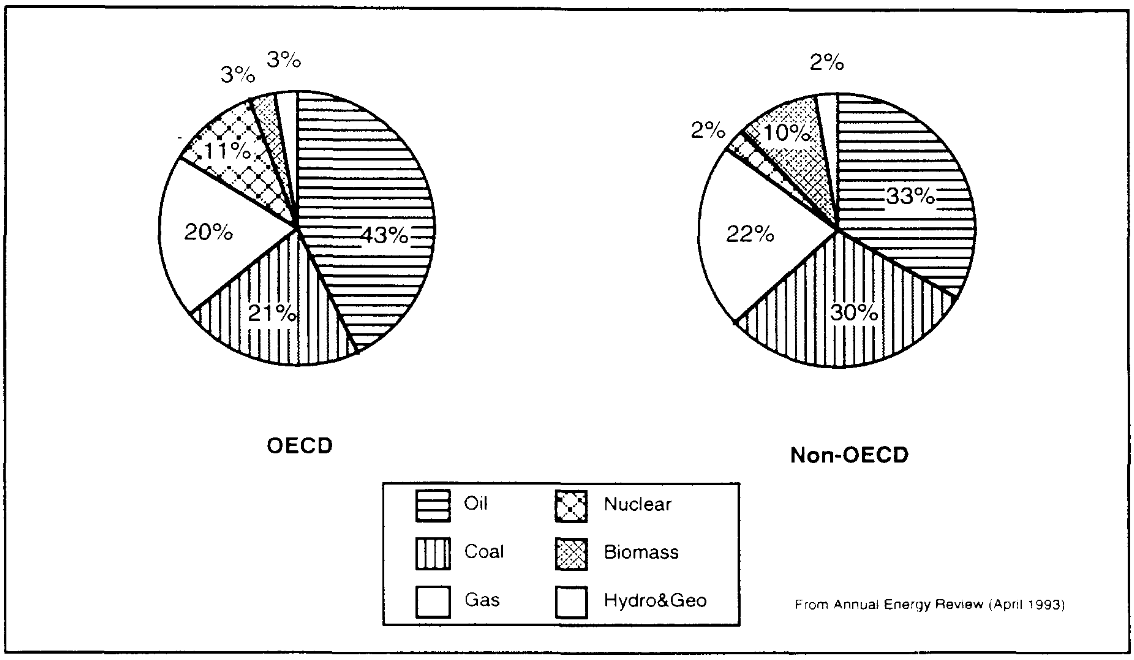
Christian Roche, September 1995

Graph 1 - Cost of electricity generation in different locations* and different sources. Comparison with the Energy Amplifiers

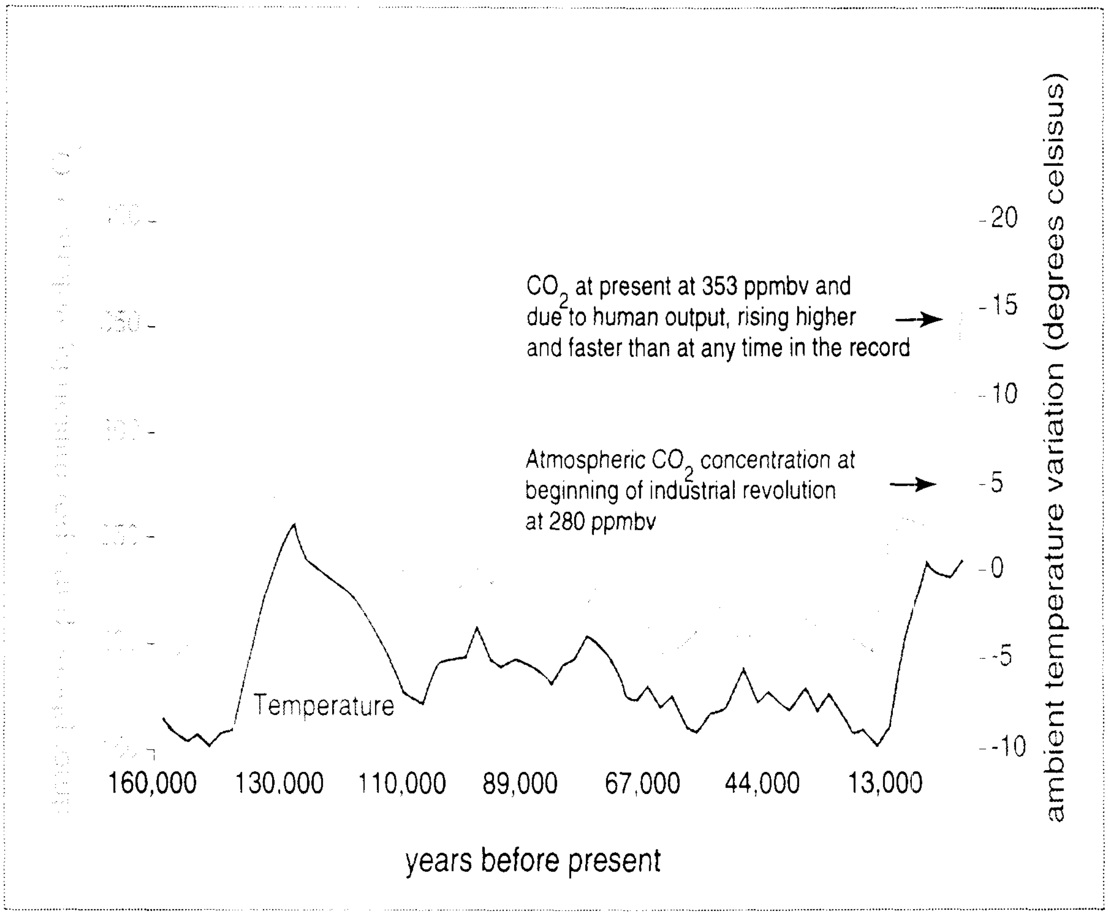


* *Based on data from "Energy in Europe, A View to the Future, CEC, DG XVII, 9/1992": for years 1985 to 2005 and from "Energy for Tomorrow's World, WEC, 9/1992, Reference Case": for year 2020 but assuming that there is no increase for NIS & OECD countries from 1995 onwards.*

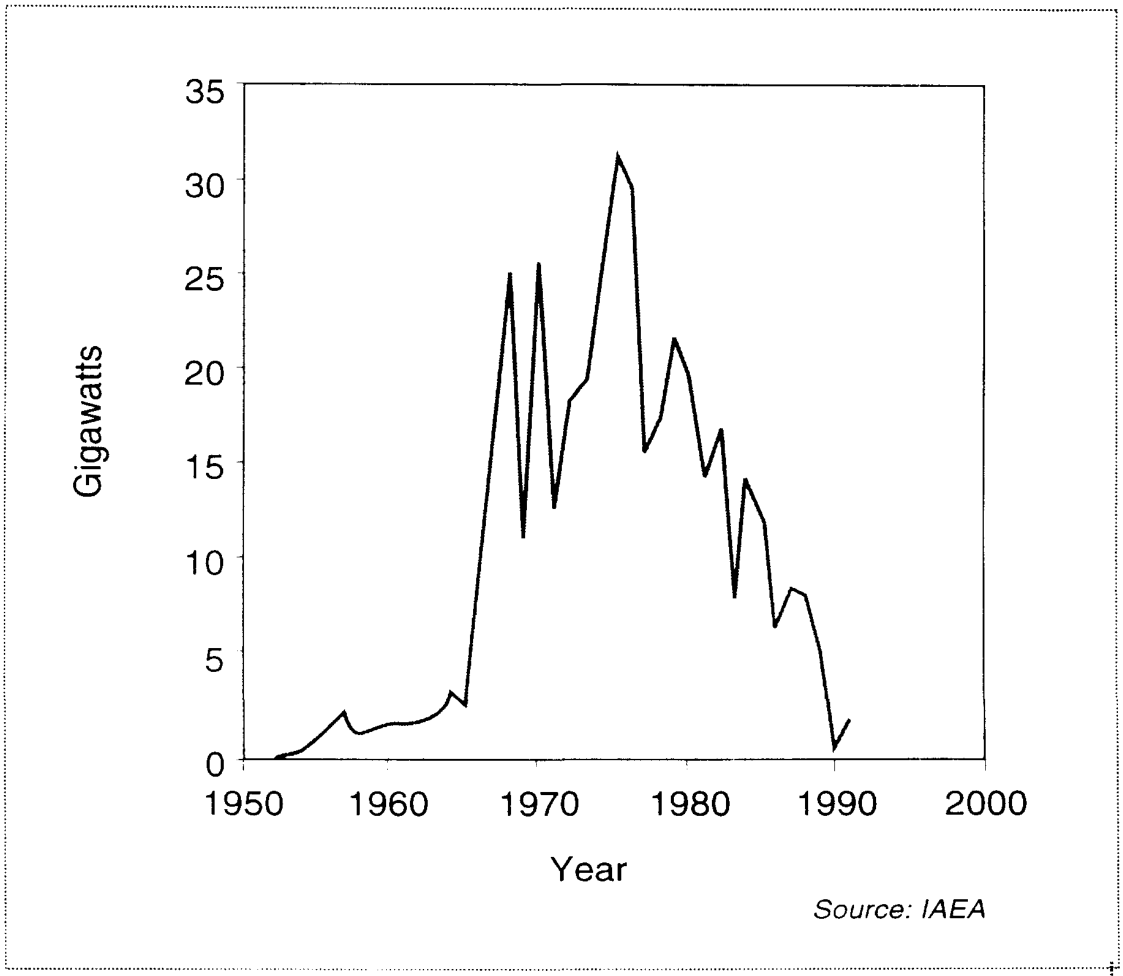
Graph 2 - World Primary Energy Consumption (Assuming no increase in NIS & OECD countries after 1995)*



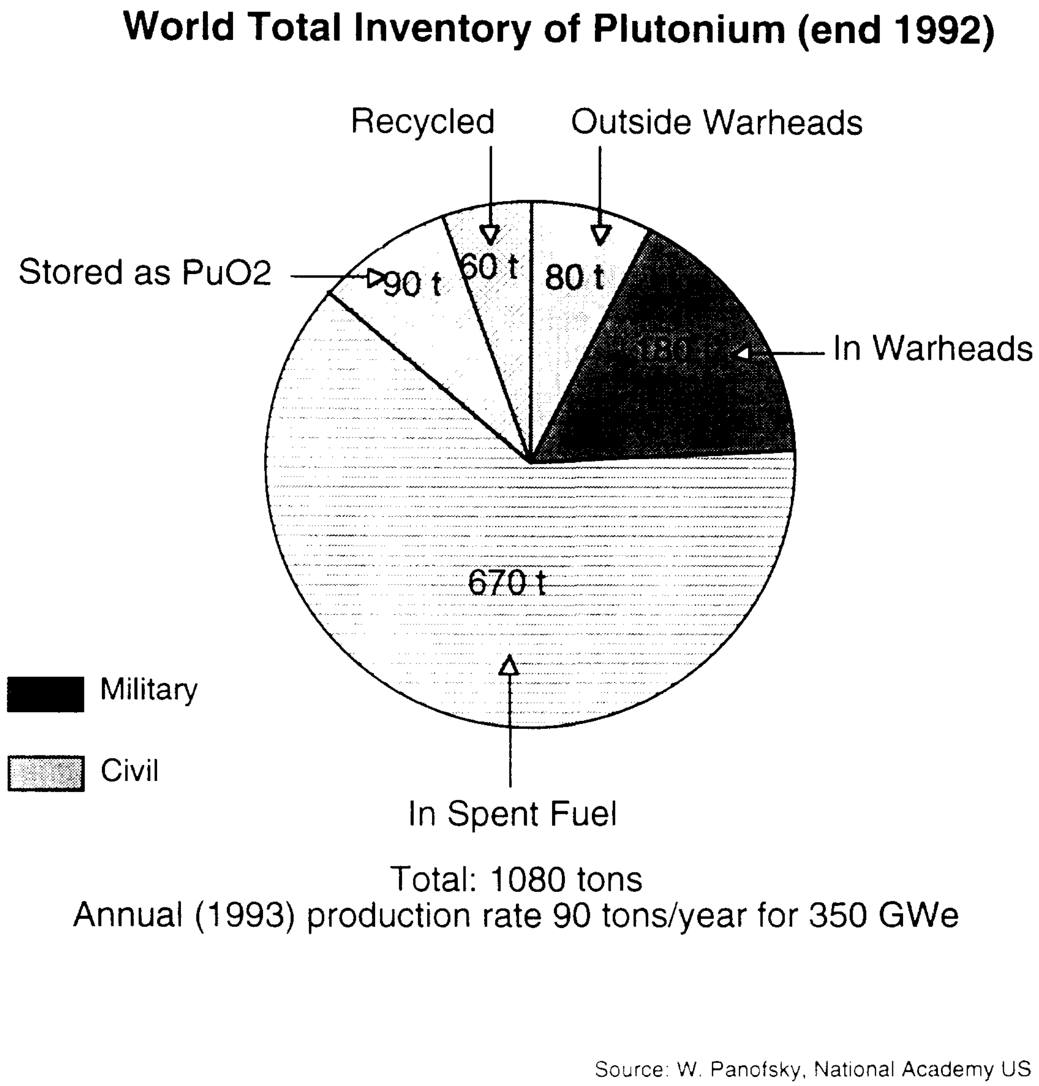
Graph 3 - World Primary Energy Consumption (1991)



Graph 4 - Correlation of CO_2 and Temperature Variation from 160,000 years before present to 2100 (Source: H. Lehmann, Wüppertal Institut für Klima, Umwelt, Energie)



Graph 5 - World Nuclear Reactor Construction Starts, 1951-91



Graph 6 - World Total Inventory of Plutonium (end 1992)