Journal of Alloys and Compounds 271–273 (1998) 1–5

The future of nuclear energy in the world

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I have been asked today to address you on the future of nuclear energy in the world. As you know, prospective is a difficult exercise, and I hope my presentation will reflect a good balance between realism and optimism. Let me also emphasise that the real point of any prospective is not to *predict* the future, but to try to identify ways to make a given future possible. I shall attempt to tell you how to ensure that nuclear energy has, indeed, a future, and in which modest way your work, in this Actinides'97 symposium, can make this future possible.

You probably know the story of the poor driver lost in the countryside who asks a peasant for the way. And the peasant answers: " Well,... if you really want to go *there*, it would be better not to start from *here*! ". So, before we embark for the future, let us examine where we are now, let us assess the *present* state of nuclear energy in the world.

1. A few facts

Any assessment depends upon which yardstick you use, and it depends to some extent on one's state of mind: some people would say a glass is half-empty, while others will see the same glass half-full. Compared with the expectations of the early seventies, nuclear energy is in a sorry state indeed. We expected to have, by the turn of the century, i.e. three years from now, between 900 and 1600 GWe of nuclear capacity operating in OECD countries alone. We shall have less than 400 MWe in the whole world. In the United States, which pioneered this technology, no plant ordered after 1974 has been completed and their nuclear capacity, now at its peak, will now decline, even though new plants were to be ordered to-morrow (which is unlikely); in western Europe, only two French plants remain to be completed and no order is in view; countries from the former Soviet empire are just slowly recovering from the double shock of Chernobyl and the eruption of the marketplace economy; nuclear power is, at best, embryonic in Latin America and Africa.

But there is one other and brighter side to the nuclear coin! (Fig. 1).

Four hundred and thirty seven nuclear plant are now operating in the world; during 1996, these plants have generated 2300 billion kWh. To generate the same amount of electricity, you would have had to burn more than 500 million metric tons of oil or close to 800 million tons of high grade coal. Which yardstick should we use to assess this amount? Let me try two of them: in terms of oil, this is more than the annual production of Saudi Arabia. In terms of coal, that would be almost 3 billion tons of carbon dioxide sent to the atmosphere, not to mention sulphur dioxide, nitrogen oxides or radioactivity releases... 2300 TWh may be less than 20% of the world electricity generation today, it is however equal to the *total* world consumption in 1960. Nuclear plants supply reliably, safely and competitively 30% of the electricity in OECD countries, a proportion which exceeds 75% for France, since 1990, saving fossil fuels and preserving the environment. In some forty years, commercial nuclear power has come a long way indeed!

Furthermore, in contrast with the first half of my picture, nuclear power is flourishing in Southeast Asia: Japan, Korea, China and Taïwan. In China alone, which produces and burns 1300 million tons of coal per year and where coal transportation all by itself mobilises one third of all

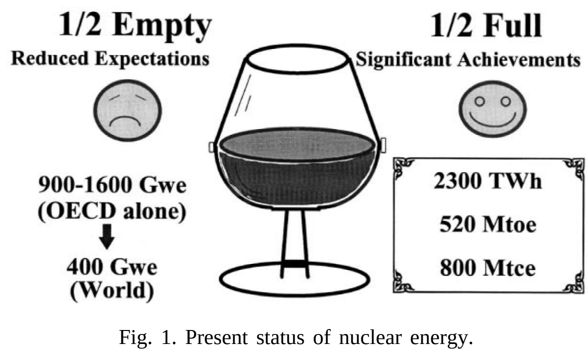

Fig. 1. Present status of nuclear energy.

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0925-8388/98/$19.00
PII S0925-8388(98)00013-9

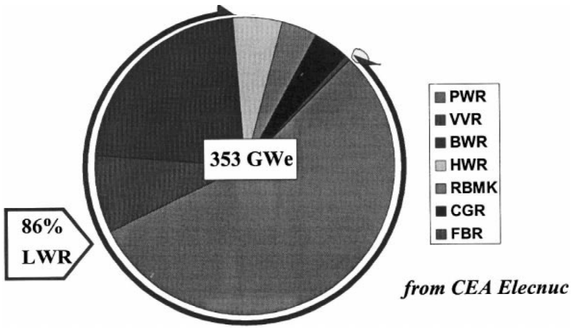

Fig. 2. Nuclear plants in the world, 1/1/97.

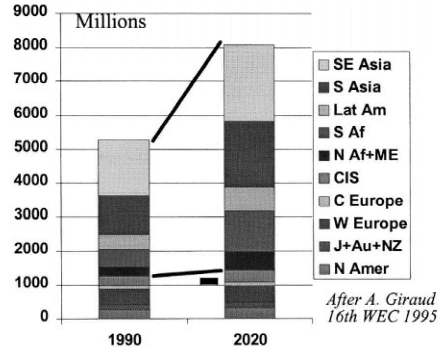

Fig. 3. Population transfer 1990–2020.

the railways and river barges, the prospects for nuclear power are tremendous.

One last fact is worth mentioning: the Light Water Reactor LWR, with its three subspecies PWR, VVR and BWR, seems to have won the race in the natural selection process. Together, LWRs constitute today 86.5% of the operating capacity in the world (Fig. 2). The most modern nuclear plants presently on the grid, the Japanese ABWR and the French N4 are LWRs, and most advanced projects on the drawing board belong to this family, including the European EPR.

It is a well documented fact in nature than when a given ''ecological niche'' is occupied by a very dominant species, there is no room left for another species to develop... until deep modifications of the environment alter the niche itself. The same can be said of ''technological niches'' – witness the way internal combustion engines have dominated the automobile market even though electric engines predated them. Recent concern about urban pollution may well reopen the niche to the electric car. Similarly, it is a safe bet that improved LWRs will remain for decades the nuclear workhorse, until depletion of uranium reserves, or specific needs for waste management, or some yet unexpected modification of the ''environment'' open the niche for more advanced machines: FBRs, HTRs, accelerator-driven systems? Assuming, of course, that the future of nuclear energy extends beyond decades – which brings me to the future.

2. Prospects

Today, on our planet Earth, about 6 billion people consume annually the equivalent of 9 billion tons of oil (9000 Mtoe, one third of which being actually oil, followed by coal and gas). Over the next decades, we have a certainty and we have a hope.

What is certain is that the world population will increase, to the point of possibly doubling our present number during the next century. A good order of magnitude of this increase to the year 2020 was given in a paper presented in October 1995 to the 16th Congress of the World Energy Conference by the late André Giraud (Fig. 3). Not only shall we experience a 35% increase within the span of only one generation, but almost all this population increase will happen outside of the affluent industrialised countries of today, USA, Europe, Japan, etc.

The hope we have is that those vast and often densely populated areas will develop, and raise their dramatically low standard of living. One should realise that if the average US citizen uses the equivalent of 8 tons of oil every year, versus 4 for a Frenchman and 3.7 for a Japanese, the huge populations of south and south-east Asia use only 0.6 ton per capita per annum. Differences in terms of electricity uses are even more striking: while a Suede needs 15 000 kWh per year, a citizen from Bangladesh or Tanzania has only access to less than 100 kWh! And energy and electric power are irreplaceable ingredients of development: witness South Korea whose annual per capita consumption rose from 70 kWh to 5000 kWh since 1960. If we believe that some development is possible, then the following evaluation (Fig. 4) lies in the lower bracket: more than 15 billion tons of oil-equivalent per year in 2020, and 65% of the increase in the world energy

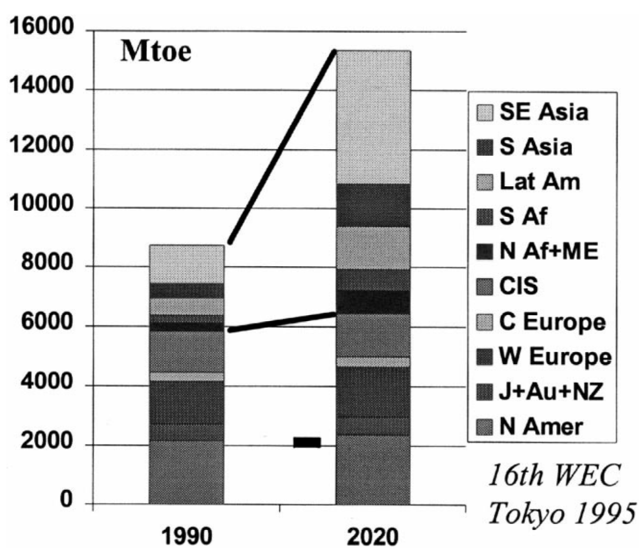

Fig. 4. Energy consumption shift.

Region	Oil + Gas reserves Gtep	1990-2020 Energy Consumption
N America	11.6	68
Jap+Aus+NZ	0.8	17
W Europe	7.0	47
C Europe	0.8	9
CIS	67.7	42
N Africa+M E	140.1	17
S Africa	6.9	14
Latin Amer.	24.5	30
S Asia	3.2	29
SE Asia	10.9	88
WORLD	264.5	361

Fig. 5. Reserves vs. consumption.

consumption, with respect to 1990, would come from Asia alone.

Furthermore, oil and gas, today cheap, plentiful and very easy to use, cannot measure to the task. The projected cumulative energy consumption from 1990 to 2020 already exceeds the known reserves of oil and gas (Fig. 5) and only Russia and the Middle East have comfortable margins. Of course, we shall discover new reserves, we shall improve the rate of recovery in known fields, and there is coal, and hydropower, and nuclear energy, and wood, and new energy sources will eventually increase their contribution: solar power, wind power, fusion, maybe... But this is precisely my point! We shall need *every* energy source we can master, and still make efforts to save energy in the most advanced economies. Do not expect me to describe all the advantages of nuclear energy over fossil fuels: this is futile because we shall need both, and more. And if – or when – we convince ourselves beyond any doubt that sending carbon dioxide to the atmosphere endangers the global climate, we shall have to find some way of trapping the CO_2, because we certainly cannot do without coal.

And remember: all these figures refer only to 2020. 2020 is tomorrow and will not be – I hope – the end of human history on Earth! I happen to have a baby granddaughter, and I fully expect her to be alive around 2080, and she may have children, and they would need energy as well...

3. The limits to nuclear growth

Let me summarise what I have just said: there shall be *no sustainable development* on this planet without a significant increase in the use of nuclear power. Therefore the question is not so much ''What will be the future of Nuclear Energy?'' as ''How to *ensure* the future of Nuclear energy in the world?''. This is this question I intend to address now, and especially in relation to the topics treated in this Conference.

What does limit the development of nuclear power today? Certainly not the availability of raw materials, but rather interrelated economic and public acceptance issues.

Resource availability need not be an issue, provided we can burn not only the existing fissile $_{235}U$, but $_{238}U$ as well, and, maybe $_{232}Th$. This well known figure, coming from the US National Academy of Sciences (Fig. 6), illustrates a fact which can be put this way: if we extract only from uranium ores only the amount of energy actually used today in Light Water Reactors, uranium resources are comparable to oil or gas resources and their exhaustion is a matter of mere decades – unless, of course, nuclear energy stays restricted to France, Japan, and a few others! If used in breeders, uranium resources can measure up to coal, and their depletion will require centuries.

But we can only make a significant use of $_{238}U$ through its transmutation into plutonium, and the recycling of this plutonium in nuclear reactors. Hence, of paramount importance, for the long term, is knowing the properties of ''major'' actinides and their chemical compounds, and a good reason for you to work on these topics.

What actually limits the development of nuclear energy varies, in fact from region to region. Let us set apart the case of France: with over 75% of our electricity provided

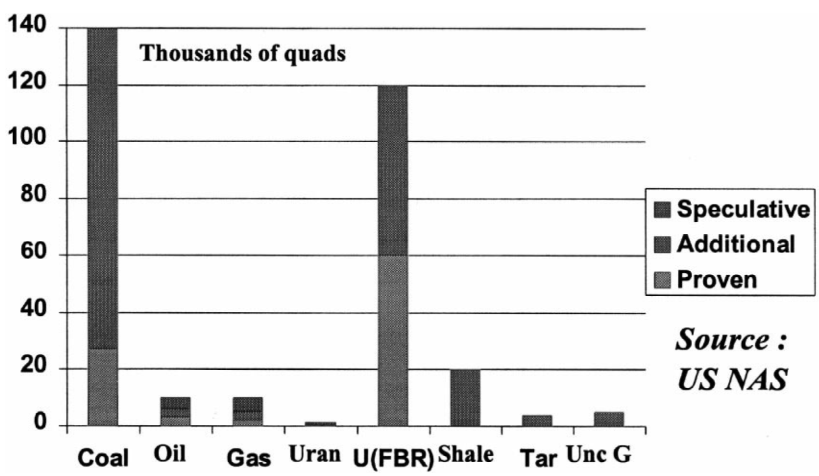

Fig. 6. Earth energy resources.

by nuclear plants and more than 15% coming from hydropower, with the domestic demand stagnating and exports already very significant, we need no new plant before the older ones begin to retire. For countries which have today no nuclear facility, the barriers to overcome are the general level of technological development, the capital costs of nuclear plants, the unit size of industrial units which can only fit a sizeable interconnected grid, etc. For a few countries where the need, the grid, and the capability exist, technology transfers are limited for non-proliferation concerns. The East must heal from its economic disruption before resuming its, once impressive, nuclear growth.

In Europe and North America, nuclear is at a standstill because of a mixture of economic and public acceptance issues (Fig. 7). And these issues are interrelated: opposition to nuclear facilities has led to delays in construction; those delays have accrued interest during construction; IDCs have sent capital costs soaring, and remember that nuclear and hydropower are very capital-intensive; nuclear power has lost its competitive edge, to the point that some utilities have cancelled almost completed plants to write off taxes rather than connect them to the grid and never recoup their investment; being non competitive, nuclear energy loses more public acceptance, and the vicious circle is initiated. Now, add Three Mile Island in 1979, where nobody was hurt but many millions of dollars were lost, and Chernobyl in 1986, a real catastrophe with world-wide repercussions, and you have a recipe for trouble!

Conversely, where public acceptance has been good, and construction times kept reasonably short, nuclear energy has proven its competitiveness for generating baseload power. This was easily true during the 70s and mid-80s, and this remains true today but less easily as shown in (Fig. 8) which summarises the latest report from the French Ministry of Industry even with today's low gas prices and very efficient combined cycle gas turbines.

This competitiveness can again be improved, so that we can keep up with the competition. I do not believe that stricter and stricter safety standards, of which I shall say a few words later, will allow us to decrease the investment costs of nuclear plants, but this investment can be amortised over a longer lifetime (most modern projects have a design target of up to sixty years!), and some of the devices or systems developed to increase plant safety can

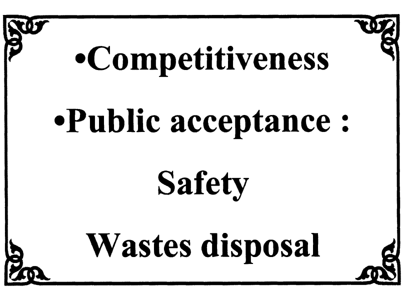

Fig. 7. Stumbling blocks.

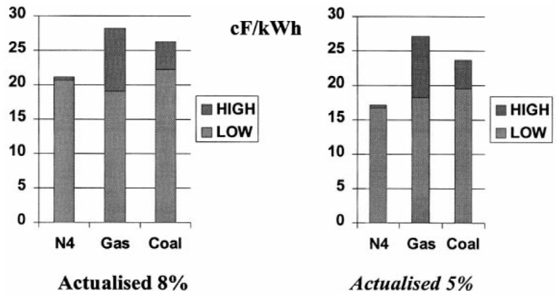

Fig. 8. ''Reference costs'' 97.

also increase its availability, with significant economic downfalls. Gains can also be realised on fuel and fuel cycle costs through MOX recycle, increased burn-up, etc. This is also a domain where actinide research can and should help.

This is why, without undue complacency, I am relatively optimistic as far as economics are concerned... be it only because I do not believe that oil and gas prices will stay low for very long: even the big ''gas bubble'' will collapse. To me, the real key problem is public acceptance, and public concerns seem to focus on two issues, Safety and Wastes Disposal.

Before April 1986, we could boast an impeccable safety record: commercial nuclear power had not harmed anybody. This is no longer true, and after Chernobyl we must patiently recover a public confidence severely eroded, and justly so. Eleven years later, confidence is not restored, but things have improved: Chernobyl *was* a tragedy, and still is for its unfortunate victims in Ukraine, Belarus and Russia, but we can begin to assess the actual magnitude of this tragedy: much more, alas!, than anticipated before but much less than feared immediately after. In terms of human casualties, immediate or delayed, it is comparable to Bhopal or the breakage of a large dam. Consequences on land use remain staggering. Furthermore, most people have now realised that Chernobyl was in no way representative of a modern western nuclear plant: some would say it is as much a *Soviet* accident as a *nuclear* accident.

Modern operating nuclear plants are very safe, and the probability of their core melting is extremely low. This is not enough, though: future plants will have to reduce even further the core meltdown probability, and nevertheless demonstrate that a core melt accident would have *tolerable* consequences, in terms of population doses and land agricultural use. Such is the philosophy behind the design of the French–German EPR (European Pressurised water Reactor), the Basic Design of which is presently completed.

Let us now say a last few words on radioactive waste management and disposal. One decade ago, speaking on the same topic and, I must admit that I did, I would have been confident and''relaxed'': waste management was one big advantage of nuclear power over its fossil competitors! Look: One 1 GWe coal plant, even equipped with scrubbers as big as an oil refinery, would send 5000 tons of

SO_2, 4000 tons of nitrogen oxides, and 500 000 tons of fly ashes containing many toxic heavy metals which never decay (Pb, Hg, Cd) into the atmosphere each year. At the time, I would probably have failed to mention the 6 or so million tons of CO_2, because global warming was not yet on the front pages.

In comparison, one 1GWe nuclear plant would produce less than 1000 cubic meters of low level radioactive wastes, which we know how to dispose of in subsurface storage until their radioactivity has decayed below background, and only 35 tons of spent fuel. Those spent fuel element will be reprocessed to recover valuable low enriched uranium and plutonium and we shall be left with 3 cubic meters of vitrified high level waste which, after a few decades of cooling will be buried deep underground in geological strata, completely isolated from the biosphere for millennia to come.

This was all very rational and Cartesian, and it is still technically sound, but it does not sell any longer. We have learned the hard way that acceptance is a matter of gut feeling rather than cold logic: people quite willing to accept – or let us say ‘‘to tolerate’’ – a nuclear plant in their backyard were very opposed to the idea of having deep under the same backyard a waste repository, even when they were convinced that any risk would only occur tens of thousands of years after their death. It is the very length of this period of time which appear to scare them. Furthermore, a number of scientists, mostly geologists, support the view that nothing on earth is predictable beyond a few centuries, and therefore take issue against the very idea of geological burial, even ‘‘reversible’’ disposal.

In France, the question was brought before Parliament in 1991, and the answer or the Representatives to us scientists was: you cannot pretend that there is only one solution to the waste disposal problem. Geological disposal is one solution, and you should study it further, but you must also explore other ways to deal with very long-lived radioactive species. And as you well know, those radioactive isotopes which remain active for a few thousand years are the actinides and a handful of fission products: $_{129}$I, $_{99}$Tc, $_{135}$Cs, etc.

If we do not want to bury those long-lived radioactive isotopes, and still retain the geological disposal option for the bulk of the high level wastes, we then have to separate them from the others, and this means developing quite novel chemical processes, based on a refined knowledge of actinides chemistry. Many a paper presented this week deals with this issue. Once separated, we need either to store these isotopes on the surface for a very long time, and properly conditioned, of course – this is another very active branch of actinides research – or to transmute them into shorter-lived or stable isotopes, and transmutation is also a very popular topic nowadays.

I have dwelled at some length on this waste disposal issue, because I think it is today nuclear power’s Achilles heel, and because your research may be of utmost importance to overcome this barrier.

4. Conclusion

The rules of a good speech is: tell them what you will tell them, then tell them, then tell them what you have told them. I now arrive at the last part of the exercise, and I will duly tell you what I have told you (Fig. 9), and in very few words.

The world population will increase; there will be no sustainable development without a substantial call to nuclear power. To make this desirable future possible, one will have to resolve a number of interrelated economic and public acceptance issues; and some of these issues will depend upon your work on actinides.

Thank You.

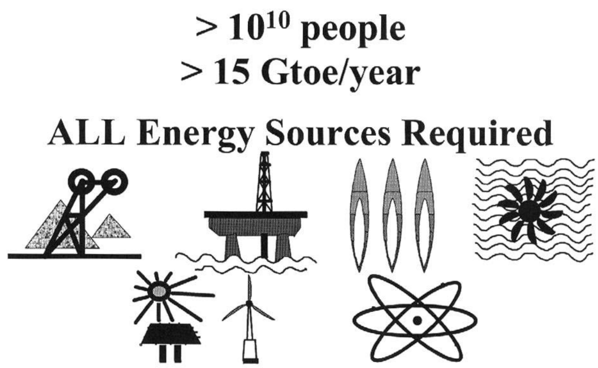

Fig. 9. In the first half of the 21st century...