

**NUCLEAR ENGINEERING**

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**The Role of Nuclear Energy in the  
Global Context of the 21st Century**

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## **1. Introduction**

The future of nuclear energy continues to be a hotly debated subject. Its present status is significant. About 5.3 % of the worlds primary energy production comes from nuclear sources, most of it for electricity generation which provides about 17% of the total generation. In Japan, South Korea, Taiwan and elsewhere the build up of nuclear power stations continues while in the US and now also in Europe there is a stand still. Indeed, while the existing capacity continues to be operated and, significantly enough, the share of nuclear power electricity generation is highest there, up to about 70 % in France and Belgium, 50 % in Sweden and Switzerland, no new orders are placed. But the end of the normal technical life time of the operating nuclear power stations comes closer and thereby the question of their replacement. Therefore the situation of the civil uses of nuclear power is opaque and the question on its future role arises.

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## 2. The global context of the 21<sup>st</sup> century

Today there seems to be no substantial energy supply problem for the moment [1] quite in some contrast to the situation and the understandings of the seventies. The most important primary energy source continues to be oil. Information on oil reserves are reported by the World Energy Council for the World Energy Congress in Madrid, 1992 [2].

Accordingly global proven oil reserves have risen by 10 % between 1987 and 1990 mostly by re-evaluations of already known reserves in the Middle East. In other parts of the world there is a certain decline of such proven reserves, mostly in the CIS states and Central Europe but to a lesser extent also in Canada and the US. The 1990 Reserve to Production ratio is reported as 43 years which indeed leads well into the year 2030. A different question is that of the down stream situation of the oil industry. Reduced surplus production capacity in the Middle East and an opaque situation in the CIS states pose problems and together with the current low oil price lead into problems of the financial markets.

The case of natural gas is somewhat similar to that of oil. Also there the proven reserves have increased by 17 % when comparing reported data of 1987 and 1990. Most of these increases come from the Middle East and the CIS states. The 1990 Reserve to production Ratio is 61 years, seemingly a most comforting figure. The extended uses of natural gas are accompanied by extensions and modernisations of infrastructures for transportation and distribution which are large problems by themselves. These problems are mainly the outcome of regional unbalances with the need to arrive at an international gas trade approximating that of oil. But here related time horizons equally lead into the first part of the next century.

The case of coal reserves appears as stable, only some new assessments appear as pertinent. For example China has made a reassessment leading to much smaller

reserves than reported earlier. The 1990 reserve to production ratio is reported as 260 years, significantly larger than those for oil and gas.

So the supply situation looks at first comforting when seen just from 1994 under more short range perspectives. Tab. 1 comprises these figures, it is taken from the World Energy Council's publication for its Madrid Conference of 1992 [1]. However, these are the reserve/production ratios for 1990. A growing demand will change that and increase at first the prices of oil and gas. Then, towards the middle of the next century, it will drive the exploration into more and more unconventional resources of decreasing quality. Athabaska and Orinoco are cases in point. The temptation to do so will be very large. And this induces at least potentially significant environmental damages or at best it leads into large investments for appropriate abatement measures. The case of coal reserves is somewhat different. Also in that case large scale abatement measures are required, indeed, but the reserves let alone the resources are vast. The problem there is transportation, either of coal as a raw material or of secondary energy such as electricity. The cases of Russia and India are cases in point.

The question of the evaluation of the fuel mix has been studied in great depth in the past. Table 2 and 3 give the results for the reference case of the recent WEC study for 1990 and 2020. The lions share there is oil and gas, in spite of the large coal reserves and resources. These numbers permit for the above made observation of a critical dwindling of conventional oil and gas and thus for the drive into the large unconventional resources of low quality or into the extend uses of coal.

An increase of the energy demand is a most direct consequence of the expected population increase. While, again, this is a big topic of its own only a few orientations are here in order.

Tab. 4 gives energy demands as reported by the World Energy Council [1]. Energy demand has risen from 3306 Mtoe in 1960 to 8807 Mtoe today. The expectation of a reference case (case B) scenario for 2020 is 13 359 Mtoe. Now, there is big

controversy about energy demand expectations, descriptive and normative attitudes are in conflict there. The WEC therefore has conceived four different scenarios. Besides the reference case B there is a modified reference case B<sub>1</sub> assuming "a weaker performance on improving energy intensity in the Central and Eastern Europe/CIS countries and a dramatically slower and delayed improvement within the developing countries". And there is a High Growth case A and an ecologically driven case C. Tab. 5 reports these scenario expectations for 2020.

It is now important to note that none of the scenario work (with one exception to be referred to later) has extended its time horizon beyond 2030.

This comes out more and more as a severe shortcoming as it will be the period after 2030 that will be dominated by the robust problem of population growth. It is therefore appropriate to have a somewhat closer look at that period. Presently the world population totals a 5.6 billion people. It is worthwhile to recall that after the end of World War II there were only slightly more than 2 billion people and - as we understand today more about global problems - it is fair to observe that with the 2 billion people of 1945 today's prevailing problems of energy and others appear as easily manageable.

The UN gives fairly disaggregated estimates for the years up to 2025. Its medium variant for 2025 is a total of 8.46 billion people as compared with the estimate for 1995 of 5.76 billion people [3]. But the population growth must be expected to continue. By the year 2060 as many as 10 billion people must be anticipated and this implies already a slow down of the present growth rate which today is a little less than 2 %. Most of it will take place in the Developing Countries, a fraction as much as 90 % must be anticipated. It is not the purpose of this paper here to elaborate on these population questions in greater detail. Instead it is the point to qualify the future population growth with its growing dichotomy between Developing and Industrialized Countries as the one dominating driving force for the global problems that are already here and much more so for the problems to come. A world population of 10 and more billion people is far away from an ecological

equilibrium of one sort or another, it is unnatural except when adapted by human rationality and that is technology as an extension of original nature.

The other big and robust development that must be expected is increasing Global Change. Again, it is not the point here to explain it in greater detail, much has been written about it [4]. Global change includes the general spread of contaminating chemical agents and radioactivity, the deterioration of soils, shortage of clean water supply, acid rain and the declining conditions of forests, the changes in the atmosphere with the damages to the ozon layer and the emission of CO<sub>2</sub> and other green house gases. As a matter of fact, a deeper understanding of Global Change must include the now almost total global communication, both public and private. Virtually every world citizen is already today in position to communicate with almost any other world citizen and information is available in an unlimited fashion. But at a closer look also epidemics, drugs and maybe other features should be included. In general, the link of such global change to energy demand is complex and not easy to analyse. But remediation and amelioration measures tend to increase energy demand. The case of clean water supply is just one case in point, there are others.

So, together with Population growth Global Change provides the context for a look into the middle of the next century.

Above it was stated that all the scenarios referred to go out only as far as 2030. However, there are the scenarios of Ch. Starr and Milton Searl [5] that reach out to 2060. For a world population of 9 686 billion people and a share of 82.7 % in the Developing Countries they expect for the trend scenario 33 182 Mtoe, for their case of full conservation 19 084 Mtoe. The case of the trend scenario implies a factor of 4.38 and the case of full conservation a factor of 2.52 when compared with 1986 (that year is chosen here for reasons of consistency with the quoted paper [5]). It is important to note that an increasing share of increasing energy demand will be that for electricity and especially so in the Developing Countries. Indeed, large scale uses of electricity will be one of the strongest components in the development of the Developing Countries. This is illustrated in Tab. 6 which

gives the primary energy share for electricity production for 1986 and two cases of Ch. Starr and M. Searl.

This brings the reasoning here to the role of nuclear energy in the global context of the 21<sup>st</sup> century as nuclear energy is mostly relevant for the generation of electricity.

### **3. Nuclear power at the end of the 20<sup>th</sup> century**

As of July 1993 there were 424 nuclear power reactors in operation world wide with a total capacity of 330 GWel. 72 more reactors are under construction with an additional capacity of 60 GWel. That totals in 496 reactors with 390 GWel. The nuclear electricity share was close to 17 % [6]. The present state of nuclear power in the CIS is somewhat opaque. The above given figures assume for Russia 28 reactors and 19 GWel, for the Ukraine 15 reactors with 13 GWel and Kasachstan with 1 reactor and 0.14 GWel. 18 respectively 6 reactors are under construction in Russia and in the Ukraine. Such impressive capacity and performance is mostly the result of the booming orders of the sixties and seventies. By contrast the general situation for new orders is now somehow depressed as observed already in the introduction. In the US there have been no new orders since the late seventies. The market for nuclear electricity in France is saturated. In Germany there have been no new orders since 1982 and in Sweden there is a moratorium explicitly requesting the shut down of all nuclear power stations by the year 2010. It is primarily in Japan, South Korea and Taiwan where nuclear power continues to be built up.

In the seventies and still in the eighties the prevailing nuclear fuel cycle strategy related to these reactor operations was reprocessing of the spent fuel, the use of the separated Plutonium (Pu) in Fast Breeder Reactors (FBR) or its recycling, primarily in Light Water Reactors (LWR). Such strategies were investigated in great detail [7]. The underlying assumption was a continued strong growth of nuclear

power. Now, in the midst of the nineties, it has become obvious that this did not materialize.

Instead, a saturation seems to take place. This can best be seen if the present growth is plotted in such a way that a logistic transition appears as a linear curve. Fig. 1 demonstrates indeed such a linear curve. Its mathematical implication is a saturation at 376 GWel, a figure not far away from the above reported actual 330 GWel. Until recently there was hope among the nuclear community that such stalling would be only a temporary phenomenon. But now it seems to become a tangible fact quite inconsistent with the expectations for contributions to world's electricity demand in the next century referred to above.

If a saturation of, say, 400 GWel is now to be taken serious the question arises what the strategic implications really are. There the first observation is that at such a rate the supply of fresh natural uranium is not really a problem. 1 GWel requires roughly 200 to/year of natural uranium for the supply of 30 tons of enriched uranium. Such figures vary slightly with the technical parameters in question but not very much. They are good enough here. 400 GWel therefore imply 80 000 tons of natural uranium per year. These amounts are indeed available. The NEA/IAEA regards [8] in 1992 3.7 million tons of "known" and 13 mill tons of so far "undiscovered" resources, a total of 17 million tons. For the 3.7 million tons the 1993 reserve/production ratio is therefore 46 years, that for the 1993 resource/production ratio years is 162 years. Such time horizons are large enough to engage in fuel supply strategies like in the case of oil and gas. But they are by far too small to reflect the real nature of nuclear power which permits for 10 000 years or more but indeed requires reprocessing and breeding [9].

The second observation is to expect a sound evolution in the design and operating characteristics of existing reactor types [10]. Development and testing of High Temperature Reactors and Fast Breeder Reactors was successfully demonstrated on the prototyp level but failed to be introduced as commercial power reactor units. LWR's of the forthcoming generation have somewhat simplified design

features, a power level of sometimes only 600 MWel instead of the early 1000 MWel and improved safety features [11]. Existing but modern LWR have a core melt down probability of  $10^{-5}$ /year. Earlier that was considered low enough to be content with containment designs that reduce the probability of large radioactivity releases by, say, a further factor of  $10^{-2}$ . The Harrisburg accident was of that kind. But it was possible to envisage core melt throughs or Hydrogen explosions that would damage these containments. The presently conceived German - French LWR designs imply a reduced melt down probability target of  $10^{-6}$ /year, a core catcher that prevents a core melt through and above all an improved double containment that prevents quasi deterministically the releases of significant amounts of radioactivity [11]. As an example Fig. 2, Fig. 3 and 4 give an overview of the safety features of the German - French 1500 MWel design that is foreseen to replace the present LWR after their regular retirement early in the next century. The reduction of reactor development to existing reactor types, mostly the LWR, and the lack of orders of new nuclear power plants implies a severe reduction of nuclear expertise, both in industry and in the National Laboratories in the US, Germany and elsewhere. This adds to the solidification not only of the present level of nuclear capacity but also of the present state of know how, a very serious implication.

The third observation is the growing problematique of appropriately handling the back end of the nuclear fuel cycle. Principally speaking there are three possibilities for that handling:

1. One follows the route of putting the irradiated fuel elements after some brief cooling period through reprocessing and uses the separated Pu for the first core inventories of Fast Breeder Reactors. The separated fission products are vitrified and put to final disposal.
2. One follows the route of direct disposal of irradiated fuel elements after a somewhat extended cooling period at the reactor site. This may include intermediate storage prior to the final disposal.

3. One follows the route of intermediate monitored retrievable surface or near surface storage for a considerable period, say four decades or so, and adjusts to the situation as it evolves.

The first possibility is the one that was traditionally followed by practically all countries with significant nuclear power programs. The underlying assumption is an aggressive build up of nuclear power far beyond the present level of 320 or 400 GWel. Only Japan and France are following that route still today. It must be borne in mind that this possibility indeed implies a truly large scale disposition of nuclear waste of all levels.

The second possibility follows the presently prevailing saturation of installed nuclear capacity. Nevertheless, one must bear in mind that this requires the opening of sites for the final disposal of irradiated fuel elements. If the second option is for situations of a reluctant acceptance of nuclear power this might be significant. 80 000 to of Heavy Metal (HM) content is somewhat of a typical figure for a final disposal site. At 8000 to of HM per year worldwide it means the opening of one such disposal site every ten years. By contrast, no such site exists today anywhere. A somewhat special case is Sweden. Due to the moratorium there only a finite and limited amount of the operation of the 12 Swedish nuclear power stations must be accepted amounting to roughly 10 000 to HM and so there is indeed a choice of a final disposal site imminent.

The third possibility follows the intent to buy time. Indeed, above it was explained that the present relatively calm period of secured primary energy supply is due to come to an end around 2030. It was explained further that in the midst of the next century a world population of ten billion people with a share of 90 % in the Developing Countries creates a demand for energy in general and electricity in particular that refers heavily to the large scale uses of civil nuclear power. It is therefore prudent and highly advisable not to foreclose a new and large scale engagement of nuclear power. And this might require all the Pu contained in the

irradiated fuel elements sitting in intermediate monitored retrievable surface or near surface storage. The important point is now this:

Such large scale intermediate storage, necessitated by global population growth, therefore implies an evolution from national to international global strategies for the uses of civil nuclear power.

Presently the respective national outlooks for such storages are not very promising except for the case of Sweden and also Finland. Therefore the author has made in 1993 the proposal, to establish an "International Monitored Retrievable Surface Storage (IMRSS)" primarily for the storage of irradiated fuel elements and preferably under the auspices of the IAEA [9]. Indeed, the fuel storages at the various reactor sites gradually run full and in the US there is word about the "98 syndrom" when these storages no longer can accept additional fuel elements, a precarious situation. In fact, the situation for instance in Germany is not much different: For example, the Mühlheim-Kärlich nuclear power station of Rheinland-Pfalz does not get the final operating license with the argument that the irradiated fuel elements have no way to go while the exploration and preparation for site at Gorleben, Niedersachsen, is impeded by the same political parties and groups. The present situation is at a deadlock. The proposal is to overcome that on a more international basis in view of the above stated necessity to arrive at strategies for the uses of civilian nuclear power that are international.

#### **4. The merging of the back ends of the civil and military nuclear fuel cycles**

More is to be said on the problematique of appropriately handling the back end of the nuclear fuel cycle though.

Since the end of the Cold War nuclear disarmament is taking place. The START I and START II treaties provide for a reduction down to 3500 strategic nuclear war heads in case of the US and 3000 in case of the former USSR within ten years if

not earlier. As the USSR does no longer exist there are severe institutional and political problems still to be overcome. But it is not the point here to elaborate on these. Instead it is the point to refer to the material implications of the dismantling of these weapons. Accordingly a total of about 120 tons of weapons grade Pu and 800 - 1000 tons of Highly Enriched Uranium (HEU) is to be taken care of in case of Russia, in case of the US it may be somewhat less. In addition there is weapon grade Pu in the various stages of fabrication, it may be up to 20 tons in case of Russia and up to 15 tons in case of the US. These amounts of Pu and HEU must go somewhere. The use of HEU for civil purposes is not so much of a problem, it can be deenriched to enrichment levels suited for use in civil nuclear reactors. In fact, that is already taking place. The US has agreed to buy 500 tons of Russia HEU for 11.9 billion \$ over a period of the next 20 years. The case of Pu is much more serious. It is a chemical element, distinct, and therefore chemical separation from whatever the admixture is always possible. Recently the Committee on International Security and Arms Control of the US National Academy of Sciences has published a comprehensive study on the Management and Disposition of Excess Weapons Plutonium [12], it has investigated that problem in depth. In that study the various options for the disposition of weapons Pu are identified:

- the spent fuel option,  
it envisages the use of weapons Pu as fuel in civil reactors in the form of the mixed oxides, the MOX fuel.
- the substitution of civil Pu,  
there is civil recycling of reactor grade Pu in civil reactors in some countries, not the US. If weapons grade Pu is substituting for reactor grade Pu it is more quickly down graded to reactor grade Pu than otherwise, that is by sitting idle in the weapons grade isotopic composition.
- the vitrification option,  
it envisages the mixing with fission products from High Level Wastes as a way of self defense and vitrification for final disposal.

- the deep - borehole option,  
it envisages the disposition route for Pu that is already explored for civil High Level waste.

None of these options offers a kings road. The spent fuel option and the substitution of civil Pu requires time. It is not likely to get away with the military Pu faster than in three or four decades. And it must be emphasized here: it does require reprocessing. By contrast, as referred to above, the present trend of the civil uses of nuclear power is getting away from such reprocessing, reprocessing was the first, the traditional, of the above given possibilities for the handling of the back end of the civil nuclear fuel cycle. The trend is presently towards the second possibility, the storage of irradiated fuel elements. And vitrification and deep bore hole disposition also takes time and it has significant uncertainties.

One should step back and reflect for a moment: Exept perhaps for the third option all the other options imply a merging of the military and the civil back end of the nuclear fuel cycle, the civil uses of nuclear energy facilitate nuclear disarmament. This is a major observation as the military and the civil back end of the fuel cycles were so far strictly separated. The end of the Cold War and Nuclear Disarmament now changes that situation. But this will not take place easily and quickly.

It is now very natural to consider also in the case of military Pu from nuclear disarmament long term intermediate storage. Such storage in it's various forms is now being considered quite often. Also the report of the US Academy of Sciencies considers that. Then safeguards is very necessary. In the early stages of the dismantling of nuclear weapons when the handling of pits must be accomplished a bilateral safeguarding between the US and Russia is necessary and practical. But at some point such safeguards must be internationalized. This is definitely in line with a forthcoming international Pu regime and much in line with the international nature of the Non Proliferation Treaty that now comes up for extension in April 1995. It is for sure that in view of Article VI of that Treaty international safeguards executed by the IAEA is the only way to go. And that leads us again to the scheme

of an IMRSS, an "International Monitored Retrievable Surface Storage". It is now very natural to merge these two types of IMRSS and to make it one. Indeed, also the reactor grade Pu content of irradiated fuel elements pose, to an extent, a proliferation risk. This has been clarified recently by the paper of J. C. Mark [13]: Even a nuclear explosion whose "yield is nominally 10 kT or more but has an associated fizzle yield of a few percent of its nominal yield - which is to say, some hundreds of tons" is sufficiently of a proliferation concern. This now makes the merging of both types of an IMRSS very natural. There should be two or three IMRSS under the auspices of the IAEA for both: Pu from disarmament and, not necessarily in the very same building or facility but under the same heading, irradiated fuel elements containing reactor grade Pu. Only one such facility would singularize that facility too much, for reasons of reciprocity two would be better and more than three might be too many. But this is subject to debate.

Indeed, as nuclear disarmament takes place the two back ends of the military and the civil fuel cycle are merging and both must go almost by necessity for intermediate storages. And for both it is necessary and natural to do that under international, global auspices, the military side of the IMRSS in view of the global necessity to have international safeguards in fulfillment of Article VI of the NPT and the civil side of the IMRSS in view of the global necessity to keep the nuclear option open by buying time awaiting the 10 billion people of 2060.

There is one more point to it. So far an IMRSS for the storage of irradiated fuel elements alone has almost unsurmountable difficulties of finding a site. If nuclear disarmament is to take place there will be sites for an IMRSS for the storage of military Pu. Now it should be recalled that the two fuel cycles are merging and civil nuclear Power is meant to consume the military Pu! Then it is impossible to leave the civil side alone with its siting problem: Accept the military Pu for the civil fuel cycle but solve your disposal problem by yourself? So strange is the outcome of the strict separation of both sides and that should be overcome on an international, global basis.

All this reasoning is for intermediate storage. Eventually the problem of final disposal of residues in whatever form and of whatever kind must be solved. That leads to the next topic of this reasoning, the final disposal of nuclear waste.

## **5. Final disposal of nuclear waste**

The final disposal of nuclear waste is probably the largest problem of all, de facto. Admitted, at a closer look one has to draw a number of distinctions, for instance between Low Level Waste and High Level Waste and between other lines. Many scientists, nuclear engineers and geologists agree that it is not that much of an unsolvable problem in technical terms but when taken together with its institutional, legal and societal aspects it has turned out to be presently the largest problem that nuclear power users are facing.

Candidate for host formations for deep geological repositories are given in Table 7. But also seabed and sub seabed as well as deep well and bore hole injection and rock melting disposal schemes have been considered.

In order to overcome the repelling complexity of the prevailing situation of the final disposal of nuclear waste international organisations, all on the governmental level, have instituted committees that studied the related problem in depth. Along such lines the IAEA has stated and published "Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes" [14]. The two overlying objectives of underground disposal of high level radioactive waste are:

- Responsibility to Future Generations
- Radiological Safety

The seven IAEA principles relate to the following topics:

- burden on future generations
- Independence of safety from institutional control

- effects in the future
- transboundary considerations
- dose upper bound
- risk upper bound
- additional radiological safety

Besides those seven principles the IAEA has formulated ten criteria.

On this level of abstraction there is a general broad consensus. Further, only recently the two relevant committees, the Radioactive Waste Management Committee (RWMC) of the OECD Nuclear Agency NEA and the International Radioactive Waste Management Advisory Committee (INWAC) of the IAEA have stated a collective opinion on the methodology and means for assessing the safety of radioactive waste disposal practices and concepts. It has been endorsed by the experts of the Community Plan of Action in the Field of Radioactive Waste Management of the Commission of the European Communities (CEC), (now the European Union) [15]. The two Committees

- confirm that safety assessment methods are available today to evaluate adequately the potential long-term radiological impacts of a carefully designed radioactive waste disposal system on humans and the environment, and
- consider that appropriate use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.

Other countries or group of countries have stated similar positions [16], [17].

In spite of such comforting statements and consensus there is no country that has already a final repository for nuclear waste or only a definite site for the later construction and operation for such repository. And there is no agreement on its

required timing. For the understanding of such contradiction it is helpful to consider the present situation in three exemplicative countries, Sweden, Germany and the US.

In Sweden for low and Intermediate Level Waste there is already a final repository near Forsmark, north of Stockholm. It is operational since 1988. It is positioned 50 m in granitic rock under the Baltic Sea roughly 1 km from the coast line with entrance tunnels from the shore. So far as spent fuel elements are concerned they are at first stored for about 40 years in the central interim storage facility at Oskarshamn. That operation started in 1985 and includes a sea transport for shipment of spent fuel as well as other radioactive waste. For the final disposal of spent nuclear fuel and high level waste a repository is planned to be situated in deep crystalline bedrock. The full scale operations are scheduled for 2020, the start of the construction for 2005. The selection of a specific site is progressing and will take place in the late nineties. The Swedish program gives a very sound impression. Also, there are no major controversies in the public, at least not at the moment. However, the basis for that sound situation is the official abundance of nuclear power, the referendum to phase out nuclear power by 2020. What is at stake therefore is the final disposal of the spent fuel and nuclear waste originating from the operation of 12 nuclear power stations til their end of life. No follow on nuclear projects are scheduled.

In Germany Low Level Waste is planned to go into the Konrad facility, a former mine for iron ores and now, after unification, also to the Morsleben facility that is situated in a salt dome. In the same general area there is the planned Gorleben facility primarily for High Level Waste and with the related legislation to come also for irradiated fuel elements. Exploratory work has started in 1979 but is now constantly impeded and not really progressing, at least not satisfactorily. In fact, in Germany there is hardly any progress in matters of the handling of the back end of the nuclear fuel cycle at all. The federal system permits the German Federation to be ruled by one party, presently the Christian and Free Democrats, while local state governments are frequently ruled by other, opposing parties, the Social

Democrats and the Greens. Social Democrats and the Greens are practically blocking any action with the idea to create thereby a state of total frustration. The implied goal is to abandon nuclear power totally and definitely. Only then it can be expected that the necessary handling of waste and its disposal will take place as it is presently the case in Sweden. The strong opposition to nuclear power in Germany is fundamental in nature and far beyond the level of arguments or international statements and consensus of principles and criterias referred to here.

In the US the progress for both, the HLW and the LLW disposals, is slow. Also in the case of the US there are opposite positions of federal institutions such as the DOE and local states such as Nevada, the case in point there is exploratory work for the Yucca Mountain site. The DOE follows the Standards of the Environmental Protection Agency (EPA) 40 CFR 191. That results in an attempt to follow a straight once through procedure whereby rules and criterias are predetermined with the idea to have in the end a depository whose safety can be predetermined for 10 000 years in a way that can be defended in court. This has been criticized lately [18]. So, the US Congress has asked the National Academy of Sciences to have a closer look at that document 40 CFR 191. Accordingly, in a report of the Board on Radioactive Waste Management, Commission on Geosciences, Environment, and Resources, National Research Council the observation is made that the strive for a statement on predetermined safety for 10 000 years on scientific grounds is by itself unscientific as this and related questions have broader implications beyond the scope of pure science. Therefore an impression must be avoided that such questions can be answered with pure science. In that report Sheila Jasanoff is quoted to make that point: the political need for accountability in the United States pressures regulators to seek a "scientifically correct" answer, even when there is none [19]. Instead, the report of the National Research Council asks for a learning, iterative approach. As one goes along it must be permitted to learn and to correct the course.

As a matter of fact such an adaptive approach is now followed in Sweden. It was concluded that it is now time to complete research and development for a final

repository and one of the two contemplated site candidates would now be chosen. But the idea is indeed to progress in stages. Initially only 5 - 10 % of the total amount of spent fuel in question shall be deposited and at first in the mode of retrievability thus permitting for a stepwise investigation and characterisation of the repository site. The long term safety must be demonstrated by a technical-scientific assessment of the repository performance [20]. Quite in harmony with that approach underground laboratory investigations are progressing.

The reason for the difficulties primarily around final High Level Waste disposal is the long range time horizon and the associated uncertainties. Conscious human history so far has basically covered 10 000 years and the human situation on that time was hardly comparable with our present situation. A set of fundamental questions must be dealt with [21]:

- which is the time span for which a Performance Assessment can reasonably be performed?
- is it possible to perform a Risk Analysis in its proper sense for a geological repository?
- how can we account for possible living conditions of future human generations?
- how can we deal with possible future human impacts on the repository?
- how can we deal with uncertainties (in models, in scenarios, in data, in parameters, in expert judgement)?

Above all, these questions must be handled not only in an arcane style but with a real understanding and trust of a wider public. This requires confidence and trust in persons, in institutions and a scientific-societal culture. It thereby does imply reference to the feature that nuclear energy and its associated problems is global in nature. Trust and confidence must therefore be established in just that frame and format. Indeed, the military side of nuclear power is a global matter since it's inception, the Non Proliferation Treaty is a global Treaty, the accident of Chernobyl has been a continent wide and ultimately a global affair, the Pu regime as it is now

forthcoming is meant to be global in nature. So also nuclear waste disposal must be approached as a global issue quite in contrast to the present separated strictly national approaches. But, significantly enough, none of the nations except for Sweden and Finland has succeeded so far. And this is not for technical reasons. It is suggested here that this lack of success has a deep seated reason: nuclear waste disposal must be seen as part of a more general pattern now evolving, addressed as Global Change.

Indeed, the uncertainties, risks and resulting issues and problems cannot be evaluated in the absolute, and this is a typical feature of Global Change. Strives for the absolute lead to the pitfalls of our presently prevailing situations. Instead, it is the comparison with the alternatives that is the responsible way to address these issues and problems. Above we have seen that large scale uses of coal is one alternative. Such large scale uses of coal are indeed accompanied by uncertainties and risks. The concern about the global climate is in the forefront there. If unabated, continent wide impacts on the ecosphere must be expected and especially so if the transition to low grade fuels as explained above take place. Also the impacts of truly large scale hard technology of solar power covering hundred thousands if not millions km<sup>2</sup> of arid areas is obviously accompanied by uncertainties and risks. Presently we do not even can estimate the nature and size of these problems. One may expect them to be comparable to the geopolitical problems of oil supply from the Middle East.

One particular area of uncertainty, like in the case of waste disposal mostly as perceived uncertainty though, is the area of health damages from radiation. Accordingly radiological protection is of great importance and certainly a matter of confidence and trust in persons, in institutions and a wider scientific-societal culture. And so there is a prominent example for such an institution: The International Committee on Radiological Protection (ICRP). It functions on a non governmental basis, has a long standing high reputation and scientific as well as public credibility and perpetuates its membership not by appointment of governments but by peer election from within the ICRP. Obviously this has much

to do with its early foundation back in 1925 on the occasion of the First International Congress of Radiology. As a result, in 1928, the International Commission on X-ray and Radium protection was established. In 1950, in line with the more general application of ionizing radiation and radioactive materials, the Commission was renamed as the International Commission on Radiological Protection [22]. The ICRP's recommendations have since served as a basis for national as well as international legislation and standard setting. Thereby ICRP has contributed to bridge the gap between governmental actions and a strive for confidence and trust in persons, in institutions and a scientific culture.

It was along such lines that the author has proposed the foundation of an "International Commission on [Nuclear] Waste Disposal" (ICND) [9]. Indeed, such ICND is not meant to substitute the successful committees of the IAEA and OECD/NEA. As a non governmental body of high scientific credibility it is meant to contribute to public confidence in nuclear waste disposal. L. W. Shemilt and W. Häfele have explained that ICND idea in some greater detail [23]: "For credibility and independence, such a new commission, international in scope and composition be composed of recognized experts from disciplines deemed relevant whose selection should arise through the most prestigious national and international bodies. Specifically, national academies of science and national academies of engineering should be the nominators, and possibly, selectors for commission membership. Internationally, the International Council of Scientific Unions (ICSU) and the Council of Academies of Engineering and Technical Sciences (CATS) should be involved".

This proposal is presently under active consideration and evaluation.

## 6. A Second Nuclear Era

After this comprehensive review of nuclear energy as it is understood today it is indeed important to realize that there are advanced schemes for nuclear power beyond present nuclear technological means.

One advanced scheme is that of a spallation source driven nuclear reactor configuration. During the eighties there have been technical breakthroughs that permit for new approaches, in particular it is the break through in the field of high current low energy linear accelerators that is of relevance here. It permits the old idea to drive a subcritical reactor configuration by additional spallation neutrons. As such this idea is old. Reference must be made to the early work of B. W. Lewis at Chalk River [24] as well as the work of M. Steinberg and coworkers at Brookhaven [25] and others. Now C. D. Bowman and coworkers have reconsidered that scheme in light of the new accelerator opportunities [26]:

A linear accelerator of 1.6 GeV projects protons into a lead target and produces about 55 neutrons per spallation event. These neutrons are given to a nuclear fission configuration which is well below criticality, say at 0.8. The resulting richness in neutrons is then used to maintain the energy liberation through fission and spallation, breeding and above all the transmutation of nuclear waste. In the report of C. D. Bowman it is explained in fair detail that one such Spallation Reactor of a given power level could transmute the long lived fission products of ten normal LWR's of the same power level as the Spallation Reactor. This would reduce the period of concern for the disposal of nuclear waste down to 300 years. Thus it would fundamentally alter the profile of nuclear power uses. C. D. Bowman suggests a reactor design using molten salts as fuel, D<sub>2</sub>O as a moderator and very high thermal fluxes,  $10^{16}$  n/cm<sup>2</sup>sec. Of course this implies among many others, problems of material corrosion resistance. These can be overcome probably by a R + D program of sufficient size. By far the greatest obstacle might be the implied chemical reprocessing which is meant to separate not only Thorium and Uranium, respectively Uranium and Plutonium from the fission products but also a

partitioning the various fission product isotopes, in fact a reprocessing of a higher degree. The relevant technologies for such a Spallation Reactor lead clearly into the next century and thereby into a Second Nuclear Era.

Of course, a Fusion Reactor belongs also to a Second Nuclear Era. The recent advances in the Physics of Tokamak Fusion Reactor configurations have been impressive and are well reported and known. It is only a factor of three or so that separates the JET reactor from ignition conditions where the  $\alpha$  particles provide for the self heating of the D-T plasma. The next step, the international global fusion project ITER, should reach the required targets of plasma physics. It is widely known that after such an accomplishment the engineering problems must be solved. This leads again mostly into materials development and testing and requires in particular a strong 14 MeV neutron source. This does not exist yet, but it can be done. And it is not clear that the engineering problems are all understood but there is confidence that these can be overcome once the physics is fully in hand. If a future Fusion Reactor can be made safe in handling the implied amounts of Tritium and can be made not to produce long lived nuclear waste for example from the structural materials involved and if the diversion of neutrons can be avoided by design or operating schemes then also Fusion could alter the profile of nuclear energy uses and thereby lead into a Second Nuclear Era.

Reaching the next century with advanced nuclear engineering and entering a Second Nuclear Era requires steadiness, high level expertise from devoted individuals and funding. It is presently not clear that these requirements can indeed be met. But in taking relevant decisions in both, the public and the private sector, the full picture of the energy situation in the 21<sup>st</sup> century should be looked upon. Much is at stake.

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	Estimate of Cumulative Production to 1990 (Gtoe)	Estimate of Proven Reserves in 1990 (Gtoe)	Estimate of 1990 Reserves to Production Ratio (Years)
Coal (Excluding Lignite)	n/a	496	197
Lignite	n/a	110	293
Oil	86	137	40
Natural Gas	40	108	56

Source: WEC Survey of Energy Resources

Table 3.1 Proved Fossil Fuel Reserves and Reserves/Production Ratios

	Gtoe	%
Coal and Lignite	3 400	76
Conventional Oil	200	5
Unconventional Oils:		
Heavy Crude	75	2
Natural Bitumen	70	2
Oil Shale	450	10
Natural Gas	220	5
<b>Total (approx.)</b>	<b>4 400</b>	<b>100</b>

Source: WEC, 1992 Survey of Energy Resources; WEC 1989 World Energy Horizons 2000-2020; Masters C.D. et al, World Resources of Crude Oil and Natural Gas, 13th World Petroleum Congress, 1991; Masters C.D. et al, World Reserves of Crude Oil, Natural Gas, Natural Bitumen and Shale Oils, 12th World Petroleum Congress, 1987

Table 3.2 Ultimately Recoverable Fossil Fuel Resources

Source: Energy for Tomorrow's World  
World Energy Council 1993

	Fossil fuels:			Nuclear Energy	Renewables:			Total
	Coal	Oil	Natural Gas		Hydro.	Traditional	"New"	
North America	508	809	497	145	127	38	34	2 158
Latin America	22	218	80	3	80	125	50	578
Western Europe	333	568	254	169	99	20	19	1 462
Central and Eastern Europe	156	49	64	11	5	4	4	293
CIS	365	378	569	47	50	26	11	1 446
Middle East and North Africa	7	167	117	0	5	21	1	318
Sub-Saharan Africa	68	38	4	1	9	141	6	267
Pacific <sup>1</sup>	734	486	108	64	69	351	31	1 843
(includes CPA) <sup>1</sup>	(575)	(100)	(14)	(0)	(30)	(218)	(13)	(949)
South Asia	126	60	25	1	20	204	10	446
World	2 319	2 773	1 718	441	464	930	166	8 811

<sup>1</sup> Data for the Pacific Region include Centrally Planned Asia (CPA), which are also shown separately.  
Source: UN Energy Statistics Yearbook: WEC

Table C8 Fuel Mix in 1990, Mtoe

Source: Energy for Tomorrow's World  
World Energy Council 1993

Tab. 2

	Fossil fuels:			Nuclear Energy	Renewables:			Total
	Coal	Oil	Natural Gas		Hydro.	Traditional	"New"	
North America	400	793	601	188	162	46	147	2 337
Latin America	79	483	296	26	235	179	99	1 397
Western Europe	352	534	354	244	149	20	73	1 726
Central and Eastern Europe	98	67	105	27	6	5	11	319
CIS	236	355	744	69	58	31	36	1 529
Middle East and North Africa	17	368	412	0	18	38	11	864
Sub-Saharan Africa	141	165	29	6	31	299	19	690
Pacific <sup>1</sup>	1 423	797	342	203	191	414	112	3 482
(includes CPA) <sup>1</sup>	(1 154)	(273)	(126)	(40)	(105)	(257)	(54)	(2 009)
South Asia	289	207	94	30	70	291	34	1 015
World	3 035	3 769	2 977	793	920	1 323	542	13 359

<sup>1</sup> Data for the Pacific Region include Centrally Planned Asia (CPA), which are also shown separately.  
Projection by WEC - Case B

Table C9 Fuel Mix in 2020 for Case B, Mtoe

Source: Energy for Tomorrow's World  
World Energy Council 1993

Tab. 3

	1960	1970	1980	1990	2020*
North America	1 143	1 762	1 991	2 157	2 337
Latin America	162	259	431	577	1 397
Western Europe	662	1 072	1 306	1 462	1 726
Central and Eastern Europe	135	229	336	292	319
CIS	441	732	1 085	1 447	1 529
Middle East & North Africa	35	70	162	317	864
Sub-Saharan Africa	92	142	208	266	690
Pacific <sup>1</sup>	510	806	1 258	1 843	3 482
(includes CPA) <sup>1</sup>	(321)	(374)	(621)	(950)	(2 009)
South Asia	126	193	268	446	1 015
World	3 306	5 265	7 045	8 807	13 359
<sup>1</sup> Data for the Pacific Region include Centrally Planned Asia, which is also shown separately * Projection by WEC - Case B Sources: UN Energy Statistics Yearbook, WEC					

Table C4a Primary Energy Requirement, Mtoe

Source: Energy for Tomorrow's World  
World Energy Council 1993

Tab. 4

Case	A	B <sub>1</sub>	B	C
Name	High Growth	Modified Reference	Reference	Ecologically Driven
<b>World General Data</b>				
Population (millions)	8 092	8 092	8 092	8 092
Economic Growth Rate (% per Annum)	3.8	3.3	3.3	3.3
GDP (trillion US\$)*	64.7	55.7	55.7	55.7
GDP per Capita (US\$)	8 001	6 884	6 884	6 884
<b>World Primary Energy</b>				
Total Energy Demand (Mtoe)	17 208	16 008	13 359	11 273
Energy Demand per Capita (toe/Capita)	2.13	1.98	1.65	1.39
Energy Intensity (toe/1000US\$)	0.27	0.29	0.24	0.20
<b>Primary Energy Mix (Mtoe)</b>				
Coal	4 852	3 814	3 035	2 128
Oil	4 594	4 532	3 769	2 898
Natural Gas	3 648	3 561	2 977	2 486
Nuclear	982	981	793	693
Hydro	999	987	920	661
Traditional	1 323	1 323	1 323	1 060
New Renewables	810	810	542	1 347

Table C17 Basic Data for the four WEC Cases

Source: Energy for Tomorrow's World  
World Energy Council 1993

**Share of primary energy inputs for electricity generation \*  
and total energy demand**

<b>%</b>	<b>1986</b>	<b>Trend</b>	<b>full conservation</b>
<b>World</b>	<b>32</b>	<b>45</b>	<b>52</b>
<b>Less Developed Countries</b>	<b>26</b>	<b>41</b>	<b>49</b>
<b>Developed Countries</b>	<b>34</b>	<b>48</b>	<b>55</b>

<b>World, Mtoe</b>	<b>7573</b>	<b>33 182</b>	<b>19 084</b>
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Tab. 6

\* data and notions based on Ch. Starr and M. Searl [5]

## CANDIDATE HOST FORMATIONS FOR DEEP GEOLOGICAL REPOSITORIES

FORMATION	COUNTRY
Clay	Belgium, France, Italy, Switzerland (marl)
Crystalline	Canada, Finland, France, Japan, Sweden, Switzerland
Salt	Federal Republic of Germany, Netherlands, United States (Carlsbad)
Tuff	United States (Jucca Mountain)

Tab. 7

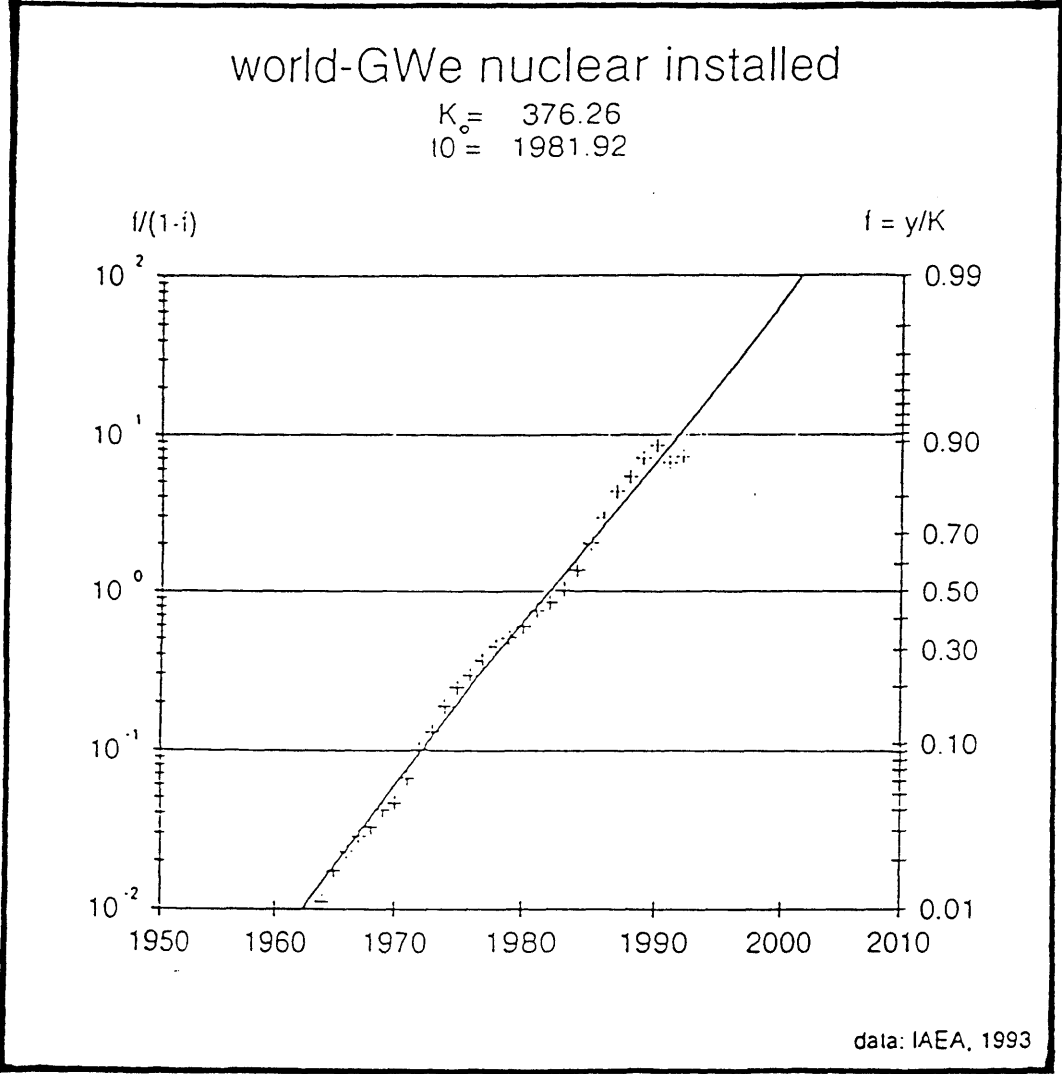


Figure 1 - WORLD-GWe NUCLEAR INSTALLED

## PWR Concepts: Status and Further Development

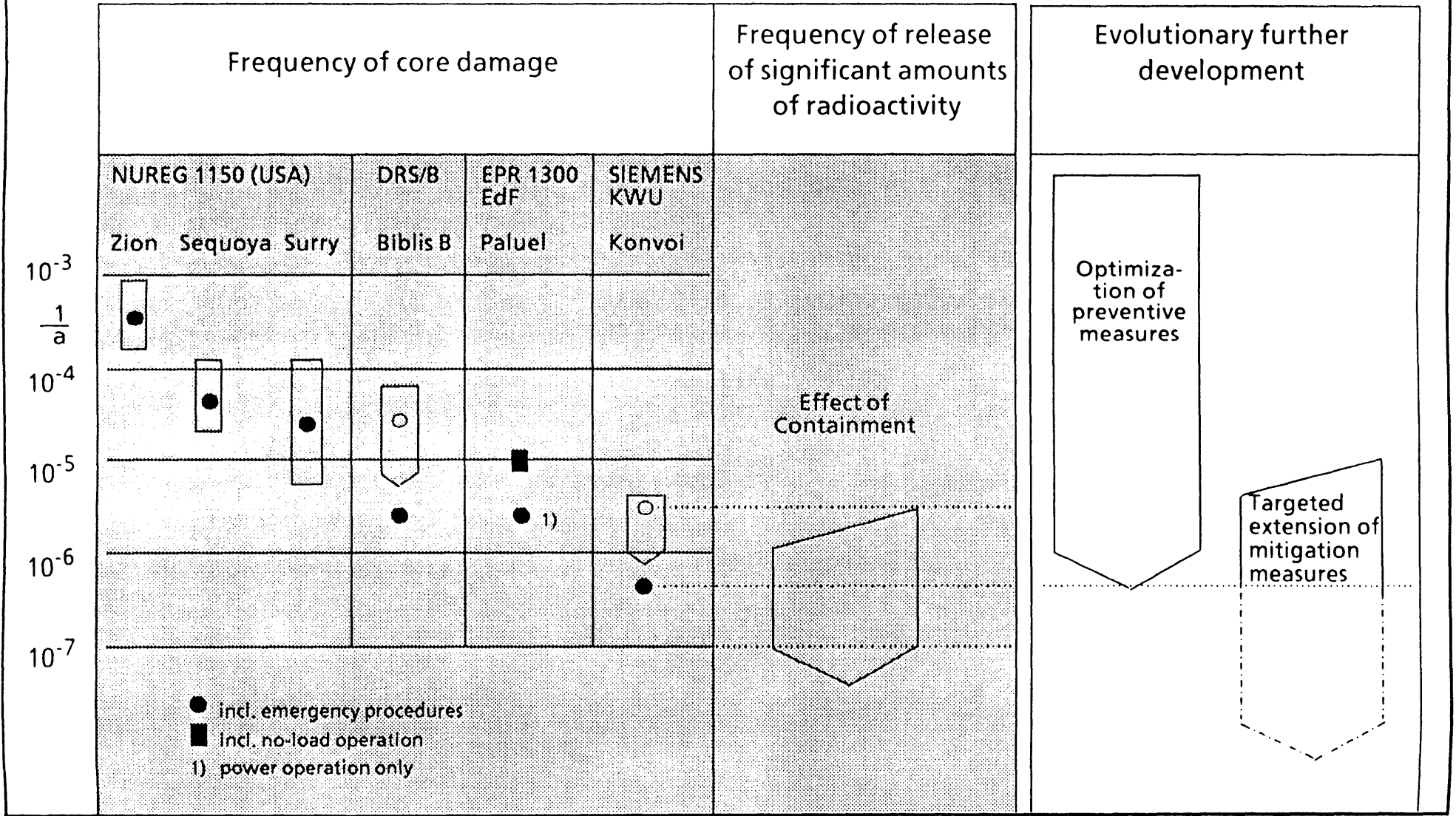


Fig. 2

# Safety Concept: Further Development in the Field of "Beyond Design Basis Events"

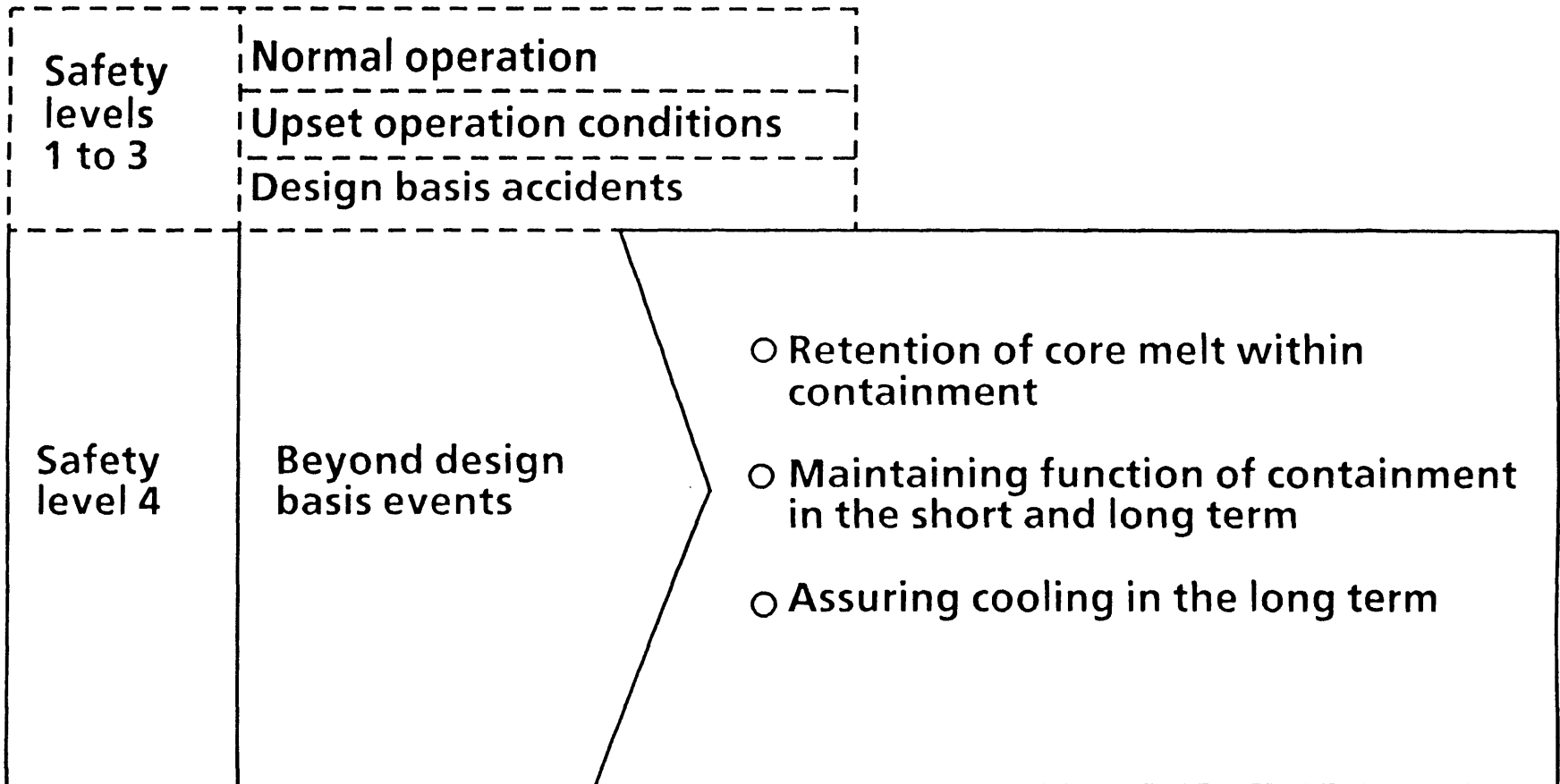


Fig. 3

## Mitigating the Consequences of Core Melt Accidents (Phenomena, Strategy and Actions)

Phenomenon	Strategy and actions to be taken
Core melt at high pressure	Extention of reactor coolant system overpressure protection, i.e. safe transfer from HP to LP core melt path by means of pressure relief (bleeding)
Direct heating	Prevention of HP path
Steam explosion	Energy release does not lead to consequential damage
Hydrogen deflagration/ detonation	Implementation of structural measures to minimize amount of H <sub>2</sub> produced (prevention of core melt/ concrete interaction) Implementation of reduction system to ensure H <sub>2</sub> concentration does not reach dangerous level (ignition; catalytic recombination)
Stabilization of core melt in containment	Retention and stabilization in clearly defined geometry. Installation of a special dispersion surface of retention facility.
Containment failure due to high internal pressure	Prevention of unacceptably high pressure by means of active cooling measures after an operator response time (> 1 day)

Fig. 4