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# ENERGY STRATEGIES AND THE CASE OF NUCLEAR POWER*

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## PREFACE

Within the Energy Program, this paper contributes to the identification of systems aspects of the nuclear option. It is to some extent a follow-up to the paper *Considerations on the Large Scale Deployment of the Nuclear Fuel Cycle* (RR-75-36) by R. Avenhaus, W. Häfele and P.E. McGrath, which it amplifies by identifying for the first time a decision/action tree for regulations. It reiterates considerations on the special deployment of nuclear fuel cycle facilities.

## SUMMARY

In the past, almost all the attention of the nuclear engineering community has been concentrated on the nuclear reactor. Reference is made to the recent OECD survey on the anticipated growth of nuclear power in the OECD countries. That growth is accompanied by a buildup of nuclear fuel cycle facilities, and related OECD data are reported. Ecological and environmental considerations raise the problem of the necessary tightness of the fuel cycle; this is quantitatively evaluated, in particular for a reprocessing facility. Related considerations for regulatory requirements are discussed.

Nuclear fuel cycle parks and energy centers are treated, as are features of secondary energy systems, leading to more global considerations on nuclear fuel cycle deployments. The paper concludes with conjectures on features of the terawatt domain.

# Energy Strategies and the Case of Nuclear Power*

## INTRODUCTION

In the second half of the 60s electricity generation by nuclear power stations became competitive with conventional power stations. An order boom followed. In Japan, the U.S.A., the F.R.G. and other countries this led to a commercially significant production of nuclear electricity, which was in line with a more general striving for technological innovation.

Yet this commercial competitiveness was not necessarily identical with the need to provide an energy production capability in view of the limited and vulnerable supply of cheap oil and gas. While this need was recognizable as an ever-increasing problem already in the early 60s, it became fully apparent to a wider public only in 1973. Today it is clearly the adequate supply of energy which establishes the scope for energy strategies. For the consideration of energy strategies it is fundamental to identify their time horizon; here it must be observed that there appear to be three time phases of the energy problem (Figure 1).

| TIME PERIOD | CHARACTERISTICS | OPTIONS |
|---|---|---|
| 1960 – 1973<br>(YESTERDAY) | – CHEAP OIL, GAS<br>– LOW CAPITAL COSTS<br>– WIDE TRANSPORTATION OF OIL | – OIL, GAS<br>– (OLD) COAL |
| 1973 – 1990?<br>(TODAY) | – EXPENSIVE FUEL<br>– ENERGY CONSERVATION | – OIL, GAS<br>– NUCLEAR ELECTRICITY<br>– ENHANCED (OLD) COAL |
| 1990 – ?<br>(TOMORROW) | – CHEAP FUEL<br>– SIGNIFICANT CAPITAL COSTS<br>– TRANSPORTATION AND STORAGE OF SECONDARY ENERGY | – NUCLEAR<br>– (NEW) COAL<br>– (SOLAR?) |

Figure 1. Three time phases for energy.

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Since the early 60s we have been in the phase of cheap and at the same time versatile fossil fuels. Remarkably enough, these also allowed for low capital costs. Advancements in tanker ship technology as well as the installation of oil pipelines made worldwide transportation of cheap oil possible without adding significantly to the fuel costs. In the industrialized countries this led to cheap energy and in turn to an energy-intensive economic infrastructure that freed capital and labor for additional and expensive purposes: we all experienced high economic growth rates, the most striking example being Japan.

Now fossil fuels have become expensive, one reason being the physical limitation of a miracle of nature: the oil sources of the Middle East. The other reason is the worldwide political confrontation of the developing countries with the industrialized world. Any technological strategy to meet these challenges takes time, however. The second phase of the energy problem is therefore characterized by expensive fuel and the necessity for energy conservation. Traditional coal production will be enhanced and nuclear electricity will be given the largest possible share, as these technologies are available today. If the industrialized nations are sufficiently encouraged to prepare and launch long range technological programs, this will have to be done in the second phase.

In the medium and long range future there are several options for a practically unlimited supply of energy: the fast breeder, solar power, coal within certain limits, possibly fusion, and geothermal energy. They all are capital intensive. One of these options, or more probably a combination thereof, will characterize the third time phase. In view of the then fundamentally and radically different natures of primary and secondary energy, energy storage will become an integral part of modern energy systems, probably along with the associated energy transportation. The fundamental constraint for related energy strategies will probably be the availability of capital.

## GROWTH OF NUCLEAR POWER

The latest figures for electricity generating costs are given in Table 1. Referring to the F.R.G. in January 1976, they are typical of the beginning of the second phase of the energy problem. Electricity from lignite is unbeatable but nuclear electricity is close. The capital cost component is shown to be high, and the fuel costs are low in spite of the fuel cycle services that have lately become so expensive. At the same time one may note the high fuel costs of coal, as well as its capital costs which reflect environmental abatement measures.

Table 1. Electricity production, cost components in U.S. mills*/kWh (1 mill = $10^{-3}$) for new plants (load factor 7000 h/a).

| | Lignite | Hard Coal | Oil/Gas | Nuclear (LWR) |
|---|---|---|---|---|
| Fuel Including Fuel Cycle | 6.8 | 23.2 | 19.2 | 7.2 |
| Operation and Maintenance | 2 | 2.8 | 1.2 | 2.4 |
| Capital Cost | 9.6 | 6.4 | 6.4 | 14.4 |
| Total | 18.4 | 32.4 | 26.8 | 24.0 |

*$1 ∧ DM 2.5.

Source: Rheinische-Westfälisches Elektrizitätswerk (RWE), 1976.

Table 2 shows figures of a recent OECD nuclear power growth estimate [1]. Accordingly, in the early 90s Japan can expect roughly 100 GW(e) and the U.S. 500 GW(e) of nuclear power, while a low OECD total would be at 1 TW(e). For comparison one should remember that the world total of electric power today is only at roughly 2 TW(e). This therefore indeed reflects an expected worldwide technological development.

The nuclear community is only gradually learning to envisage not merely nuclear power stations but also the related fuel cycle, and in particular its hot tail end. Table 3 gives data from OECD nuclear fuel cycle estimates that are consistent with the low OECD estimate of Table 2 and with the case of no Pu recycle. Cumulated LWR fuel reprocessing requirements build up from about 2000 t in 1976 to about 300,000 t in the late 90s. A comparison with the figures for fresh uranium demand indicates a delay of about 15 years, the time taken to build a nuclear power station, burn up the first core and wait for reprocessing. This delay to some extent explains why the nuclear community is just beginning to envisage fully the problems of the hot tail of the fuel cycle. What it must also envisage is the fact that these amounts of irradiated fuel frighten the scientific and the general public. Such concerns are further highlighted by the amounts of plutonium that thus

become available. Table 2 indicates an OECD cumulative total of 1000 t of fissile plutonium in the mid-90s. Fears are extreme enough for reasonable people to maintain that plutonium makes the difference between good and evil.

Table 2. OECD nuclear power growth estimate [GW(e)].

| | 1976 | 1980 | 1990 | 2000 |
|---|---|---|---|---|
| Japan | 9 | 17 | 84 | 157 |
| F.R.G. | 7 | 19 | 77 | 134 |
| U.S.A. | 48 | 82 | 385 | 1000 |
| OECD (High) | 87 | 183 | 889 | 2089 |
| OECD (Low) | 86 | 171 | 773 | 1685 |
| World (High) | 88 | 192 | 1003 | 2489 |
| World (Low) | 87 | 179 | 874 | 2005 |

Source: R.E. Crawford and W. Häussermann, OECD/NEA, November 1975.

## TIGHTNESS OF A LARGE COMMERCIAL FUEL CYCLE

The most pressing issues of the hot end of the fuel cycle concern the reprocessing facilities. Here we leave aside the chemical engineering problems of radiation damage to the TBP leading to DBP and MBP, as well as similar problems. Significant as they are, they can be solved if chemical engineering tests and related developments are pursued on a large enough scale. It should be realized that this requires adequate amounts of highly irradiated LWR fuel elements, and that these have become available only recently. What is needed is a few prototype facilities to develop and test dissolving and processing engineering schemes that deal with technologically significant amounts of highly irradiated LWR fuel elements, perhaps above 30,000 MWd/t. One should recall that there were--and still are--several such facilities that tested the dissolution and processing of fuel elements with low and medium burnups of up to 12,000 MWd/t (e.g. Hanford, NFS, Winfrith, The Hague, Mol). The chemical engineering problems cited above turned up unexpectedly when burnups from 12,000 MWd/t up to 35,000 MWd/t had to be reprocessed. A few such reprocessing facilities for the development and testing of modern chemical engineering schemes would assume a function related to that of Dresden, Yankee and Indianpoint in the development of LWR's in the U.S.A., and Gundremmingen and Obrigheim in the F.R.G. To

Table 3. OECD nuclear fuel cycle estimates (low estimate, without Pu recycling).

| | 1976 | 1980 | 1990 | 2000 |
|---|---|---|---|---|
| Power Capacity [GW(e)] | 86 | 171 | 773 | 1685 |
| Ore Requirement | | | | |
| Annual [$10^3$t/yr U] | 19 | 45 | 124 | 202 |
| Cumulative [$10^3$t U] | 36 | 171 | 1023 | 2748 |
| Separative Work | | | | |
| Annual [$10^3$t/yr S.W.U.] | 12 | 27 | 85 | 148 |
| LWR Fuel Fabrication | | | | |
| Annual [$10^3$t/yr H.M.] | 2.6 | 5.9 | 20 | 35 |
| LWR Fuel Reprocessing | | | | |
| Annual [$10^3$t/yr H.M.] | 1.2 | 3.3 | 14 | 31 |
| Cumulative [$10^3$t H.M.] | 2.1 | 10.7 | 102.3 | 377.3 |
| Fissile Pu Availability | | | | |
| Annual [t/yr Pu] | 8 | 18 | 84 | 190 |
| Cumulative [t Pu] | 14 | 79 | 614 | 2374 |

Source: R.E. Crawford and W. Häussermann, OECD/NEA, November 1975.

some extent the WAK facility of Karlsruhe fulfills this function in the F.R.G., and the PNC[1] fuel reprocessing plant in Tokai Mura is expected to play that role in Japan.

As mentioned above, it is assumed in the reasoning of this paper that this problem can be taken care of. But there are others. On the technological side there are problems of tightness: what retention factors have to be installed under normal operating conditions? What is the required tightness in design basis accidents for forthcoming reprocessing facilities?

Let us look at a few figures. The reprocessing plant of Mol (Belgium) was permitted to release $4 \cdot 10^{-8}$ Ci/sec of Pu or 1.2 Ci/year [2]. The fuel throughput was at 100 t/year. In the case of the WAK at Karlsruhe only a few mCi/year were released, but the throughput was smaller than that of Mol by at least one order of magnitude. At Hanford (U.S.A.), a total of 5.3 mCi of α-emitters were released in 1972, together with the effluents of the "200 areas" where the reprocessing and waste treatment facilities are located [3].

The important point here is the fact that such releases are streams of α-emitters per time. If the streams become limited by regulation one has to anticipate a possibly small but steady buildup of α-emitters in the environment. In view of their very long halflife this can, in principle, become a significant buildup. This raises two questions:

a) What are the pathways for the various isotopes in a given environment, and are there accumulating mechanisms?

b) What are to be the reference time periods for the continuous buildup of radioisotopes in the environment when regulations for the facilities' effluents of α-emitters are conceived?

The first question is of a strictly technological nature. Much work needs to be done in this area. But it can be done: cumbersome as it might be, it is ultimately a straightforward task. This is not so with the second question. Is a period of 50 years sufficient, or will only 100 years do? What happens after such a reference time period if nuclear power is then still a necessity? Needless to say this question refers not only to α-emitters. A perhaps yet more striking case is that of $I^{129}$, having a halflife of 17 million years. Iodine does enter the biosphere. Estimates show that within a 10 km radius around a 1500 t/year reprocessing plant, a relative $I^{129}$ buildup of $1.6 \cdot 10^{-4}$ per year takes place [4], assuming a

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[1] Power Reactor and Nuclear Fuel Developing Corporation.

retention factor of $10^3$ which is consistent with today's technology. König belives that not more than a fraction of $1.6 \cdot 10^{-3}$ of $I^{129}$ should be in the thyroid [5]. Arithmetically this would lead to a permissible time period of only 10 years, assuming, however, that a given individual lives in the neighborhood of the reprocessing plant throughout that period.

It is hard to give a conclusive and straightforward answer on these issues. Let us therefore put the question of permissible effluents of α-emitters differently: what retention factors are technologically feasible? Here it is important to reflect on the transuranium activity of spent LWR fuel one to three years after shutdown. Table 4 gives values for these activities per $10^3$ t of spent LWR fuel. Practical experience at Oak Ridge [6] has shown that air waste streams contain about 10 mg of aerosols per $m^3$ of air. Such aerosols also come from chemical dissolution processes of the spent fuel. Assuming air ventilations of $10^3$ $m^3$ per 10 t of dissolving fuel, one gets an inherent, retention factor of $10^{-5}$ to $10^{-6}$ for the actinides involved.

Table 4. Transuranium activity of $10^3$ t of spent LWR fuel* (H.M.) 1-3 years after shutdown (in curies).

| | |
|---|---|
| Pu238 | $8.2 \cdot 10^6$ |
| 239 | $3.3 \cdot 10^5$ |
| 240 | $3.3 \cdot 10^5$ |
| 241 | $1 \cdot 10^8$ |
| Am241 | $5 \cdot 10^5$ |
| 243 | $2 \cdot 10^4$ |
| Cm242 | $2 \div 30 \cdot 10^5$ |
| 244 | $3 \cdot 10^5$ |
| α Activities $t_{\frac{1}{2}} > 1a$ | $1.3 \cdot 10^7$ |

*Without Pu recycling.

Source: SYSTEC, Düsseldorf, 1975.

It is then possible to apply absolute filters or combinations thereof. Additional retention factors of $10^4$ to $10^5$ are then technologically feasible. To maintain such filter factors for all conditions of the day by day operation of a reprocessing facility requires not only absolute filters as such, but also a mode of operation in which all other maintenance and repair steps are consistent with the high filter factors. This might be more cumbersome than expensive; yet it can be done. We therefore arrive at overall retention factors in the order $10^{-10}$ which today must be considered as technologically feasible.

What does such a retention factor imply? As shown above, something like 300,000 t of spent LWR fuel is expected to have passed reprocessing in the late 90s. According to Table 4, we get about $3.3 \cdot 10^5$ Ci of $Pu^{239}$ per $10^3$ t of such fuel. The total is therefore $10^8$ Ci. Applying a retention factor of $10^{-10}$ we get $10^{-2}$ Ci of $Pu^{239}$, or the equivalent of a fraction of one gram. This is obviously acceptable in view of the fact that it represents the OECD total. For comparison one should recall that all the weapon tests of the 50s and 60s released a total of 5 to 10 t of Pu to the global atmosphere. This result requires an interpretation:

a) We are dealing with orders-of-magnitude considerations and not with exact figures.

b) Not only $Pu^{239}$ and reprocessing facilities, but all fuel cycle facilities must be taken into account.

c) By the year 2015 or so, the total of reprocessed LWR fuel is expected to be higher by a factor of about 10. Accordingly, a fraction of 10 g of Pu would be released.

d) We have studied the technological feasibility of retention factors of $10^{-10}$. To be consistent with such high retention factors under all practical operating conditions indeed requires a very high degree of meticulousness.

Let us return to consideration of the reference time periods. The orders of magnitude given above clearly show that we are on the safe side if retention factors of $10^{-10}$ are installed. In that case one buys time, learning can take place, experience can accumulate. Let us now consider the fuel cycle as a whole. At the International Institute for Applied Systems Analysis, R. Avenhaus, W. Häfele and P. McGrath studied the large scale deployment of a nuclear fuel cycle for 3600 GW(th) [4] the scenario dealt with fast breeders and high temperature reactors only; if we are interested in order-of-magnitude considerations, this is equally significant for 3600 GW(th) of

LWR. One may relate this to 1 TW(e) of LWR capacity, which, as mentioned, fits nicely with the OECD LWR estimates for the mid-90s. The intent of the IIASA study was a broader one. We wanted to understand:

a) the order of magnitude of the total impact of deploying such a fuel cycle;

b) the priorities with which attention must be given to the various parts of the fuel cycle;

c) the kinds of regulatory decisions involved.

Basically we considered expectation values for dose rates. By expectation values we imply their mathematical meaning: the linear average of high and low values and over time. Figure 2 explains the procedure. Two types of dose rates were considered: That for an individual in $\left[\frac{\text{mrem}}{\text{year}}\right]$, and that for a population in

Normal Operational Losses

Dose Rates = (Emission) · (Meteorology/Population) · Biology

$$B \left[\frac{\text{mrem}}{\text{year}}\right] = Q \left[\frac{\text{Ci}}{\text{sec}}\right] \cdot s \left[\frac{\text{sec}}{\text{m}^3}\right] \cdot \varphi \left[\frac{\text{mrem/year}}{\text{Ci/m}^3}\right]$$

$$BM \left[\frac{\text{manrem}}{\text{year}}\right] = Q \left[\frac{\text{Ci}}{\text{sec}}\right] \cdot \int dF \cdot s(r) \cdot f(r) \left[\text{km}^2\right] \cdot \left[\frac{\text{sec}}{\text{m}^3}\right]\left[\frac{\text{man}}{\text{km}^2}\right] \cdot \varphi \cdot 10^{-3} \left[\frac{\text{rem/year}}{\text{Ci/m}^3}\right]$$

Accidental Losses, Substitution

$$Q \longrightarrow P \cdot \frac{d}{3.15 \cdot 10^7} \left[\frac{1}{\text{sec}}\right] \cdot C \left[\text{Ci}\right]$$

C: Curies Released at Once

d: Exposure Time (sec)

Figure 2. Dose rates.

$\left[\frac{\text{manrem}}{\text{year}}\right]$. These dose rates are obtained by multiplying the emission in question by a typical meteorology factor and ICRP values for the biological/health impact. In view of the broad purposes of the study we kept a high level of aggregation or simplification; the idea was to get an overview. Table 5 gives results for typical normal operating losses for 3600 GW(th). Consistently with the above observations on the rigorous meaning

Table 5: Typical normal operating losses for 3600 GW(th (larger than $10^{-3}$ only).

| | Reactor | | | Reprocessing and intermediate Waste Storage | | | | Fabrication Plant | Waste Solidification |
|---|---|---|---|---|---|---|---|---|---|
| | Kr85 Air | Xe135 Air | H3 Water | Kr85 Air | H3 Water | Pu Water | Actinides Air | Pu Air | Cs137 Air |
| $\frac{B}{B_o}$ * | $5.3 \cdot 10^{-3}$ | $2.9 \cdot 10^{-3}$ | $1.4 \cdot 10^{-3}$ | 0.31 | $2.5 \cdot 10^{-3}$ | $2.1 \cdot 10^{-3}$ | $1.5 \cdot 10^{-3}$ | $10^{-2}$ | $2.4 \cdot 10^{-2}$ |
| $\frac{BM}{BM_o}$ † | $5.3 \cdot 10^{-3}$ a) | | | 0.24 b) | | | | | |
| RF Retention factor | ‡ | ‡ | ‡ | 1 | $10^2$ | $10^7$ | $10^8$ | $10^8$ | $10^5$ |

* $B_o = 110 \frac{\text{mrem}}{\text{year}}$ ,

† $BM_o = 4 \cdot 10^7 \frac{\text{manrem}}{\text{year}}$ , Population Meteorology Factor = $\begin{cases} \text{a) } 2.7 \cdot 10^{-3} \\ \text{b) } 2.8 \cdot 10^{-4} \end{cases} \left[\frac{\text{mansec}}{m^3}\right]$

‡ Consistent with today's technology

of expectation values, we examined the ratios of these dose rates to the existing natural radiation dose rates. Only values larger than $10^{-3}$ are shown in Table 5. The results indicate that Kr85 releases from reprocessing facilities are not acceptable; retention factors of $10^{3}$ or so must be enforced. All other relative dose rates are very small. This very reassuring observation, however, rests on the choice of the other retention factors given in the table. For Pu we had assumed $10^{8}$ in the study. As we have seen, values of $10^{10}$ can be considered feasible. The relative burdens then go down to values of $10^{-4}$ and less; and this illustrates--in terms not of reference time periods but of relative dose rates--the degree of precaution this choice of retention factors implies. This translates into reference time periods accordingly.

The IIASA study also considers accidental situations. Thus we replaced the emissions of the normal operating case by the product of a probability per second and the anticipated release of radioactivity. But here a normative approach was chosen. We fixed the dose rates and back-figured the accident probabilities thus implied, which then serve as target values for reliabilities; i.e., we have a normative approach. The actual design basis accident probabilities of a given facility must then be smaller than this target. Reliability control studies such as those by Rasmussen and his team for the LWR case provide sufficient assurance that this is so. The IIASA study considers not only accidents of facilities but also physical protection and the international spreading of plutonium. Table 6 shows some of the results of that study. It must be realized that small values of normative accident probabilities reflect a precarious situation, while large values indicate an inherent permissiveness of the technological situation in question. It is surprising to learn from Table 6 that reprocessing, plutonium contamination, and the explosion of a crude device whose plutonium was obtained by inadequate physical protection, are of less concern than intermediate waste storage, the case of a Pu fuel fabrication plant, and final waste disposal. It is obviously unavoidable that certain assumptions are made in all these rather straightforward calculations.

A special case is final waste disposal, where the underlying assumptions heavily influence the ordering of concerns. Figure 3 illustrates the scenario we had assumed. Waste is stored in glass cylinders of 20 cm diameter where a break-in of groundwater occurs because of unforeseen geological events. Fraction $F_1$ of the total glass cylinder surfaces is exposed to the water. We further assumed ad hoc that the groundwater circulates in a closed loop--the soil filters the water, resulting in a filter factor $F_2$--and that people would have to use the groundwater as drinking water for 10 years, the period needed for appropriate measures to stop groundwater circulation.

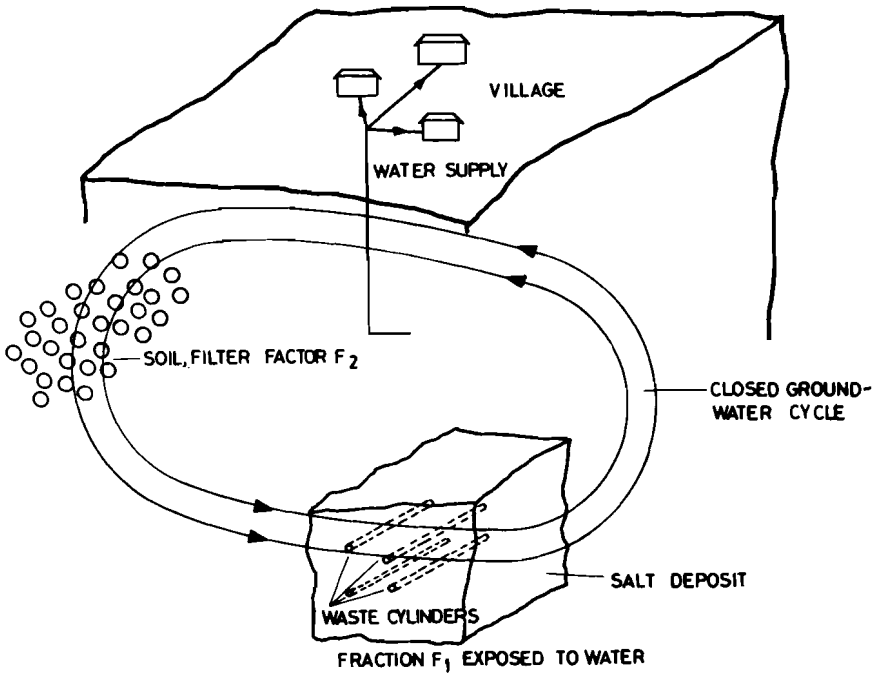


Figure 3. A waste disposal accident scenario.

Given this scenario, the resulting normative accident probability in Table 6 follows: this means that the site of final waste disposal must be selected in such a way as to have a geological probability for water break-in that is smaller than the normative accident probability. For each final waste disposal site considered, the accident scenario will probably be different and has to be properly assessed. More generally, the resulting normative accident probabilities should not be smaller than approximately $10^{-4}$ per year. Smaller values would be required if the waste inventory, together with leach rates and other technical parameters, were so high that they in turn implied these low accident probabilities. Instead, waste inventory and technical parameters should be such that the resulting normative accident probability is one in 10,000 years or so. In this case geologists can probably make assessments; 10,000 years are a short time period in geological terms.

This reasoning is not meant to lead to this or that geological assumption or this or that choice of an accident scenario; experts will do that job. The point is rather to

Table 6. Normative accidental losses for 3600 GW(th).

$$\left(\text{FOR } \frac{B}{B_o} = \frac{25}{8}\right) \quad *$$

| | Reprocessing | Intermediate Waste Storage | Fabrication Rlant | Final Waste Sorage | Contamination | Crude Explosive Device |
|---|---|---|---|---|---|---|
| $\frac{BM}{BM_o}$ † | $7.2 \cdot 10^{-5}$ | $3 \cdot 10^{-3}$ | $2.5 \cdot 10^{-5}$ | 0.15 | $3.2 \cdot 10^{-4}$ | 0.02 |
| $P_D^o \left[\frac{1}{yr}\right]$ | 0.4 | $5 \cdot 10^{-3}$ | $P_D^o \cdot X = 1.4 \cdot 10^{-3}$ \|\| | $P_D^o \cdot F_1 \cdot F_2 =$ $4.2\ 10^{-6}$ § | $P_D^o X = 14$ \|\| | 0.05 |

* $B_o = 110 \left[\frac{mrem}{year}\right]$

† $BM_o = 4 \cdot 10^7 \left[\frac{manrem}{year}\right]$ Population Meteorology Factor: $2.8 \cdot 10^{-4} \left[\frac{mansec}{m^3}\right]$

|| Amount of X[g] Pu released

§ $F_1$ : Percentage of waste cylinders exposed to water

$F_2$ : Soil filtration factor

show that a design basis accident scenario must be anticipated, and that resulting normative accident probabilities must be derived from permissible dose rates. Thereby upper bounds for required reliabilities are introduced, and one cuts the otherwise prevailing openendedness of debates on final waste disposal problems. In other words, once the specifications are given engineers can do their job of designing and constructing final waste disposal facilities. The problem is not engineering; it is rather to identify such specifications. And this is a soft problem of regulations.

## A SET OF REGULATORY DECISIONS

Regulatory decisions for rational deployment of large scale nuclear power can be logically organized, and Figure 4 shows the structure reflecting this organization.

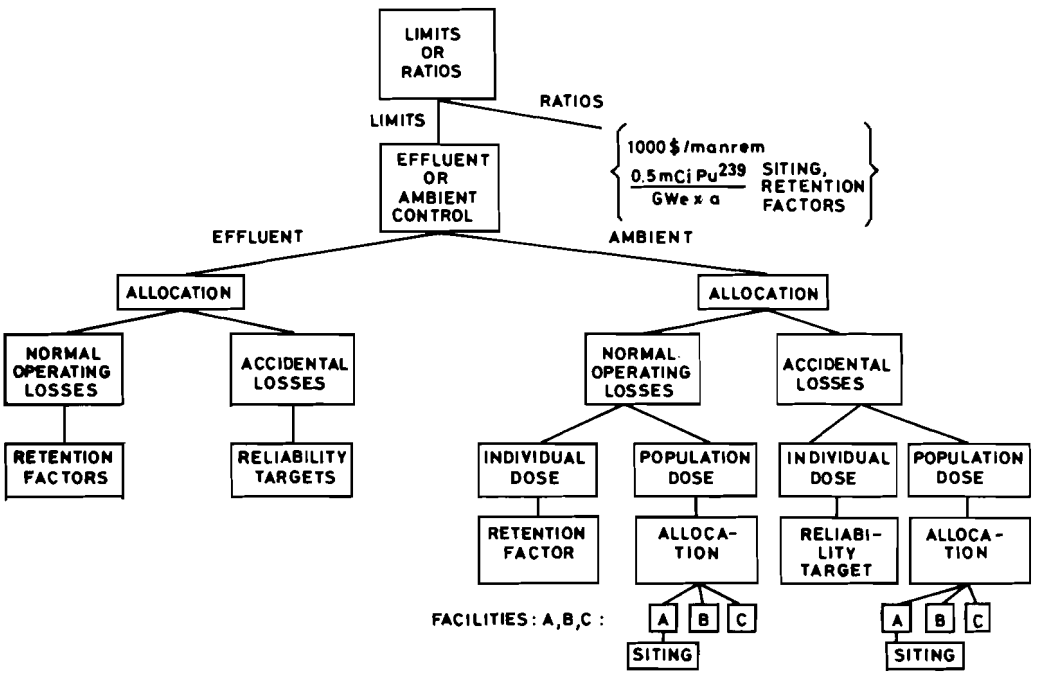


Figure 4. Sequence of decisions for large scale nuclear power.

A first decision is whether one wants to establish limits or cost benefit ratios. The famous 5 $\frac{\text{mrem}}{\text{year}}$ for LWR are an example of a predetermined limit, and in each particular case the actual dose rate must be below that limit. The alternative is a cost benefit ratio. Recently the U.S. Environmental Protection Agency conceived such a ratio by stating that for each GW(e) year a release of 0.5 mCi of $Pu^{239}$ should be tolerated. One GW(e) year relates to roughly 200 kg of Pu and thus $\approx 10^4$ Ci of $Pu^{239}$. 0.5 mCi/GW(e) therefore implies a retention factor of $10^8$. If other $\alpha$-activities are taken into account, one becomes consistent with the retention factor $10^{10}$ elaborated earlier in this paper. Another cost benefit ratio is the value of e.g. \$1000/manrem. It implicitly relates to the value of a life. If 1000 rem are considered a lethal dose the value of a life is rated to be \$1 million. J. Linnerooth recently made a survey of mathematical techniques used in assessments of the value of a human life [7].

If one opts for limits, the next decision to be made is whether one wants to control effluents or ambient dose rates. The difference is in pathways and meteorology. Ambient dose rates take account of this difference. Effluent control is easier to assess on the one hand; on the other, it implies that effluents should be limited even if ambient dose rates permit higher values, because diffusion and accumulation mechanisms are not fully known or because any release into the environment is considered detrimental.

In both branches allocations must be made between normal operating dose rates and dose rates due to accidents. If there is an upper limit, one must reflect on a certain reserve for accidental situations; not all the allowance can be used up for normal operating conditions. This too must be viewed as a normative decision.

In case one has opted for effluent control one can straightforwardly calculate the required retention factors and the normative accident probabilities, which in turn establish a target for plant reliability.

In case of ambient dose rate control one has to identify a dose rate for the individual and one for the population, as explained earlier. It might be considered to be of relevance whether or not a dose rate permitted for an individual is applied to a major share of a population. For instance, genetic considerations could raise this issue. The individual dose rate would again lead to retention factors and reliability targets. Population dose rates would require an allocation to the various facilities of the fuel cycle, and criteria for siting these facilities could be derived. One should realize that only regulations on population dose rates would lead to such siting criteria, while individual dose rates would not.

Today only individual dose rate limits for normal nuclear reactor operation are fully established. What is particularly needed is the establishment of dose rate limits for accidental situations. The political and psychological difficulties in doing so are more than obvious. But I should like to observe here that it is this lack of regulatory decisions which, in my judgement, is the greatest obstacle to mastering the problems of a large-scale deployment of nuclear power. The hardware, that is engineering, is not the problem. It is the software that is missing: if regulations are not established, the situation of nuclear power is openended, and this very openendedness endangers the deployment of nuclear power.

This situation is summarized in Figure 5. One may call this scheme: How to deal with the unknown? Traditionally engineers anticipated certain accidental events--by necessity within limits, as it was then possible to take engineering measures against the anticipated unknown. In view of the large scale consequences typical of many of the new technologies, it is now felt that the whole spectrum of accidental situations must be anticipated. This means anticipation of the unknown without limits and leads to the question of C. Starr: "How safe is safe enough?" Residual risks necessarily occur, as any engineering measure is limited by its very nature while anticipation of the unknown is without limits. Residual risks must thus be embedded into the natural and manmade risks that exist in any case. This requires an understanding of these risks, and an understanding of their perception by individuals and society. The joint IAEA/IIASA group is working toward

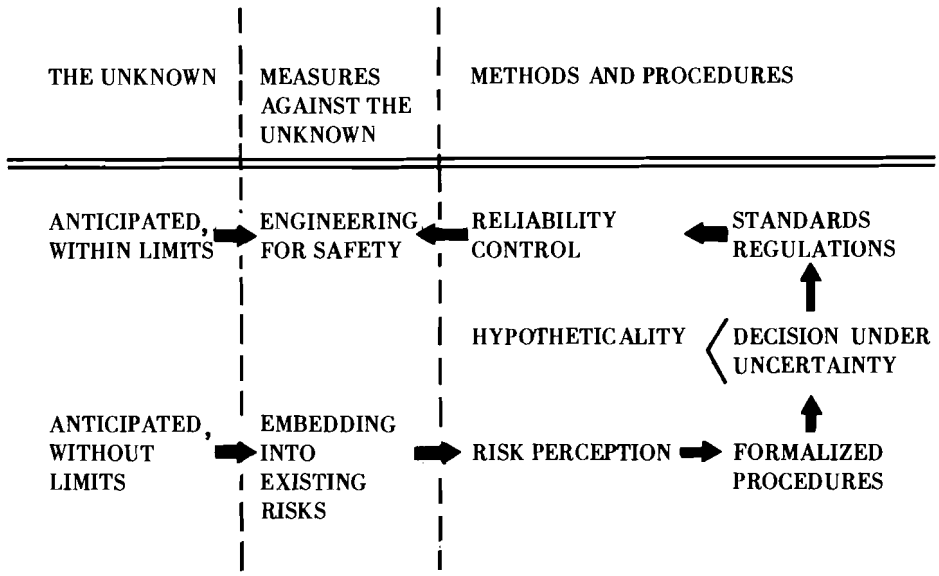


Figure 5. How to deal with the unknown.

this end [8]. Against that background it is then necessary to establish regulations and standards providing targets, along with reliability control to prove that a given design meets these targets. The LWR Rasmussen study is the most prominent example of this reasoning. Again one arrives at engineering measures for safety; but they must now be seen in conjunction with the embedding of residual risks.

## NUCLEAR POWER BEYOND ELECTRICITY GENERATION

Up to now nuclear power has been concentrating almost exclusively on the generation of electricity. It is a well-known fact that only about 25% of the primary energy demand is for electrical purposes. In terms of demand for secondary energy it is only 10%. Figure 6 shows expected trends for forms of secondary energy. The share of electricity will rise to 20% or so but not much beyond. There is also a trend for gaseous secondary energy carriers to increase their share, while the shares of solids in particular, and of liquids to some extent, will decline. One must realize, therefore, that large scale nuclear power should generate not only electricity but also a gaseous secondary energy carrier. The most prominent candidate is hydrogen. To a lesser extent ammonia may be considered,

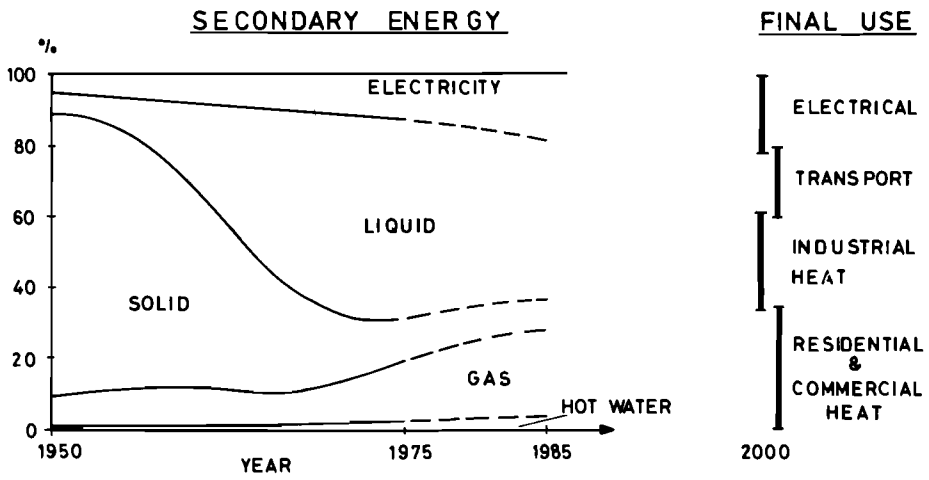


Figure 6. Partitioning and final use of secondary energy (F.R.G.).

and gasification of coal must also be envisaged. It is not our intention to elaborate on this here. Instead, reference is made to an earlier paper of the author [9], and particularly to the work of C. Marchetti e.g. [10]. The foreseeable future of nuclear energy will be characterized by the LWR; yet one should realize that there are natural ways of combining near term LWR generation with fast breeders and high temperature reactors to allow for the production of electricity and a gaseous secondary energy carrier. Figure 7 explains this reactor combination. The Pu production of LWR is used for first core inventories of fast breeders. The breeding gain of these breeders could be in terms of U233, for instance by providing a radial blanket of thorium elements. The U233 produced would then be used to comply with the net requirements of a THTR. In this scheme LWR and breeders are expected to generate electricity, while the THTR is expected to generate the gaseous secondary energy carrier. It should be noted that, for an energy demand that evolves only slowly, the FBR/THTR combination can operate independently once the first core inventories are provided for. It would operate on the breeding principle, thereby essentially de-coupling this power generation system from the problem of resources. At IIASA the transition to an all-nuclear energy supply scenario was studied by W. Häfele and A.S. Manne [11]. A. Suzuki extended these studies

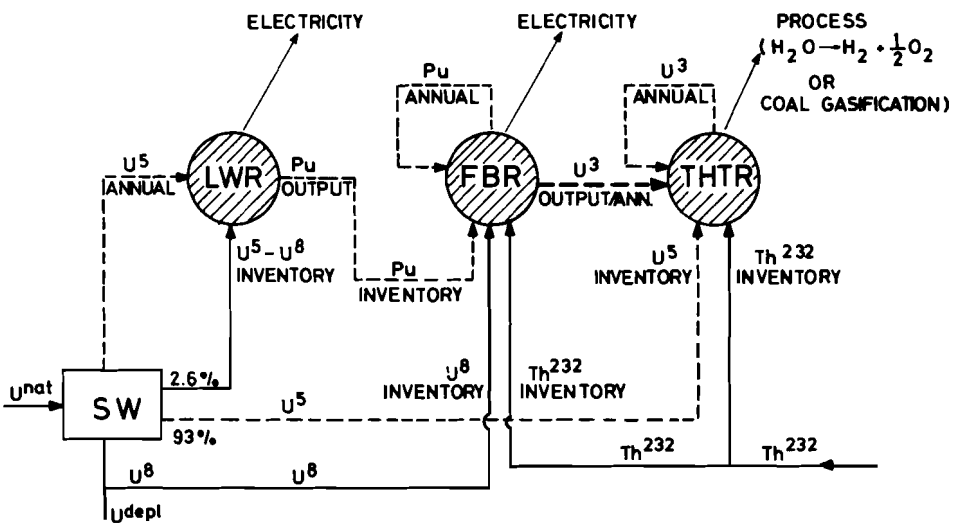


Figure 7. Transient reactor system.

considerably and enriched their results by disaggregating energy demand and by considering also solar power and coal power [12].

## THE CASE OF PLUTONIUM AND ENERGY PARKS

It is not only the problem of radiation dose rates that matters. Earlier in this paper we discussed these considerations in some detail. It is therefore important to extend the scope of considerations of the deployment of large scale nuclear power to the problem of physical protection. There are four classes of required physical protection, as outlined in Figure 8. The least problematic class is that of irradiated fuel elements. These are essentially self-defending by their own strong radiation. Besides, they are heavy equipment and not easy to divert. The timing of their appearance can be seen in Table 3 (LWR reprocessing); as explained earlier, there is a time lag of about 15 years compared with the appearance of fresh nuclear material. Fresh nuclear material forms the second class of required physical protection if its enrichment is less than for instance 5%. This material is not self-defending; it is already in use in significant quantities but would require further enrichment for explosive purposes.

| CLASS | CHARACTERISTICS | TIMING | REQUIRED PROTECTION |
|---|---|---|---|
| 1 IRRADIATED MATERIAL | SELF-DEFENDING | TO COME | VERY SMALL |
| 2 MATERIAL ENRICHMENT < 5% | NOT SELF-DEFENDING ENRICHMENT REQUIRED | IN USE | SMALL |
| 3 Pu, $U^{233}$ | NOT SELF-DEFENDING NO ENRICHMENT REQUIRED | TO COME AFTER REPROCESSING | SIGNIFICANT |
| 4 MATERIAL ENRICHMENT > 20% | READY MATERIAL | NO LARGE AMOUNTS SO FAR HTGR ? | HIGH |

Figure 8. Four classes of required physical protection.

A third class consists of Pu and U233. It appears after reprocessing, is not really self-defending and requires no additional enrichment for explosive purposes. Clearly, the fourth class is made up of highly enriched uranium. Apart from chemical conversion, it is readily usable for explosive purposes. This classification is helpful in conceiving a decision tree for the deployment of a large nuclear fuel cycle. This decision tree is given in Figure 9.

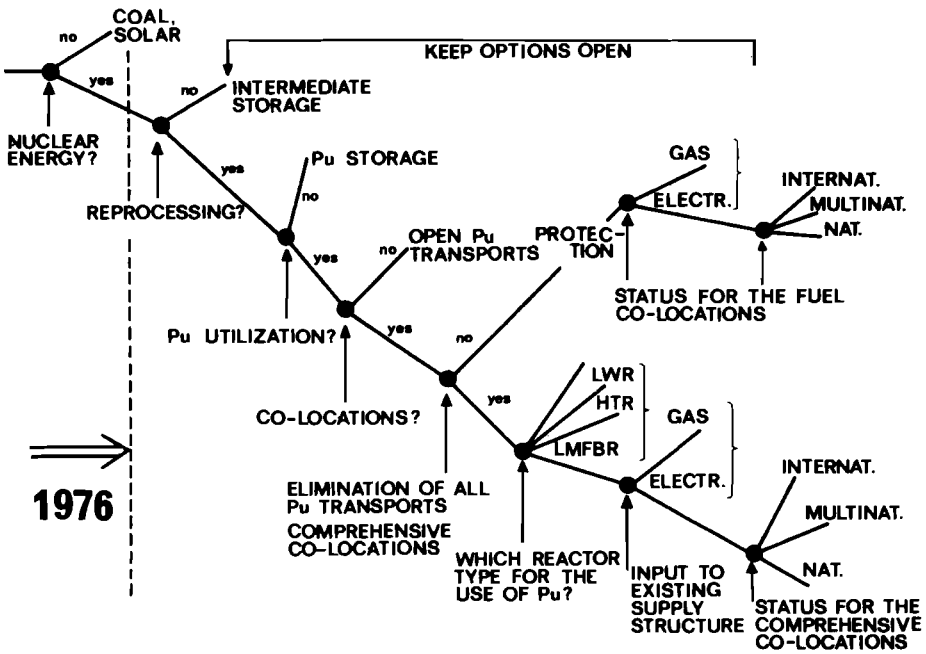


Figure 9. Decision tree for the deployment of peaceful nuclear energy.

Obviously the first decision is whether to use nuclear power or not. If not, it is necessary to identify alternatives, thereby trying to understand the implications of that decision. If yes, the next decision is whether to go into chemical reprocessing or not. If not, strategies for intermediate waste storage and appropriate final waste disposal have to be identified. One should realize that this implies some kind of chemical processing in any case. If yes, the next decision is whether to go into plutonium utilization or not. If not, plutonium storage is required. If yes, the next decision is whether to avoid transport of open plutonium or not. If not, one faces all the problems of physical protection for Class 3 as well as related environmental concerns. If yes, one is led to the scheme of co-locating the fuel cycle facilities for

reprocessing, scrap recovery and plutonium fuel fabrication. The AGNES facilities in South Carolina follow that scheme, and the same is intended for the F.R.G. The next decision is whether to eliminate also the transport of freshly fabricated plutonium-bearing fuel elements. If not, physical protection problems of Class 3--in the milder form, for strongly encapsuled plutonium--have to be faced. If yes, one is led to the scheme of having on one site both the fuel cycle facilities and the reactors using fresh plutonium-bearing fuel elements. One must obviously decide on the appropriate reactor type. In view of the reasoning of the last section, one may decide to have these co-located reactors produce a gaseous secondary energy carrier. The incentive for doing so is the ease of long distance energy transportation in the GW domain. Comprehensive co-locations really mean strong centralization. As indicated in Table 3, about 2300 t of fissible plutonium isotopes will be available within the OECD by the year 2000. For quick orientation let us assume that these plutonium amounts would be used as first core inventories in fast breeders, much along the lines of Figure 7. One can expect a rating of roughly 1 MW(th)/kg of fissile Pu; therefore 2300 t of fissile plutonium would correspond to roughly 700 GW(e) of Pu fueled reactors (if allowance is made for an out-of-pile inventory). This is roughly 40% of the expected overall OECD capacity in the year 2000. If distributed over five comprehensive co-locations, i.e. energy centers, this would mean 140 GW(e) for each of them. Long distance transportation of such electric power quantities may be beyond available technology, while transportation as a gaseous secondary energy carrier is clearly within existing technology. If one now recalls the necessity for large scale nuclear power to produce a gaseous secondary energy carrier besides electricity, one is led to a natural division of tasks: normal nuclear power stations, based on U235 fueling and along the lines of the technical experience now available, would continue to function as electric power stations on a decentralized basis. The irradiated fuel elements would be transported to the co-locations with Class 1 of physical protection (very little protection required), and the Pu would never again leave these energy centers. Instead, it would fuel reactors that would probably produce mainly the process heat for synthesizing a gaseous secondary energy carrier, with subsequent easy transportation in an (already existing?) pipeline system. Of course, we do not want to exclude electricity generation in such energy centers, when appropriate.

One therefore arrives at a sequence of modes for the geographical deployment of nuclear energy as shown in Figure 10. With time, and as the capacity of a modern energy system evolves, we move from a transition from coal to oil and are beginning to see the transition to local nuclear plants on the basis of U235 fuel. The nuclear community now faces the problem of appropriate uses of large plutonium amounts. We here suggest as a further transition the use of this plutonium in comprehensive co-locations, i.e., in large centralized energy centers, possibly offshore. It is encouraging to know that Japanese scientists

such as H. Murata of JAERI at Tokai Mura pursue such a concept steadily and consciously.

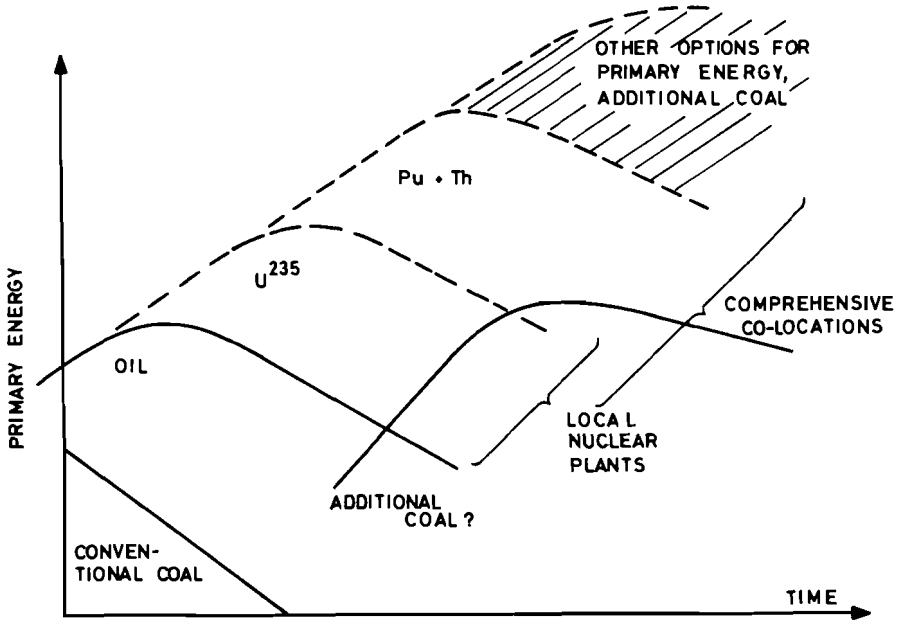


Figure 10. Modes for the geographical deployment of nuclear energy.

It should also be noted that the provision of a gaseous secondary carrier allows for the easy integration of other primary energy sources to come, such as solar power. Solar power, by inherent necessity, requires large scale energy storage. This can be achieved naturally on the basis of a gaseous secondary energy carrier which would then, in fact, significantly increase the versatility and resilience of a modern energy system [9].

## A REMARK ON MULTINATIONAL ENERGY CENTERS

It was mentioned at the beginning of this paper that present oil supplies bridge global distances. Transportation in large tankers facilitates the shipment of about 25 million barrels per day, the equivalent of 1.7 TW(th). We also saw that the problems of installing large scale nuclear power are the problems of entering the TW domain. The scale of nuclear power expected for the OECD by the year 2000 demonstrates this and also, inherently, the amount of Pu to be expected.

We saw that by the year 2000 the equivalent of 700 GW(e) would be based on plutonium. In this context one must recall that one gram of plutonium is the equivalent of one ton of coal power per year. Note that this is not only a physical equivalent; it also relates the effort and attention accompanying one ton of coal per year to that required for the adequate handling of one gram of plutonium. In this perspective, then, it is not surprising if the concept of energy parks is visualized. Energy parks mean the transition of nuclear power from the GW to the TW domain. We related the nuclear energy park concept to the production of a gaseous secondary energy carrier. A gaseous secondary carrier can be liquefied. In case of ammonia this is conventional technology; it can also be done for hydrogen, and hydrazine should be envisaged as well. Energy centers in the TW domain could therefore serve as an artificial substitute for natural oil fields, and, unlike these, would be inexhaustible.

By this reasoning we are led to the possible conception of energy centers on a multinational basis. This would also smoothly eliminate the concern about non-proliferation of nuclear weapons and adequate physical protection. It is obvious that the problems of implementing such a scheme are not of a technological nature; engineeringwise it can be done. The problems are soft ones: who is responsible for the operation of such centers, who is liable, who gives the commercial guarantees for timely delivery, and who guarantees security? In the reasoning of this paper it is not surprising that it is the soft aspects which pose the problem, and not the hard technology.

## LEVELS OF ABSTRACTION/UTILITY

Completing a total system of nuclear power has led us to considerations in the TW domain. It may be helpful to realize the more subtle implications of such a step as explained in Figure 11. Until 100 years ago mankind operated with horses and other animals as energy systems; this was the kW domain. A distinct evolutionary step was taken when physicists realized the more abstract and thus more general meaning of the term energy. It took them beyond mechanics into thermodynamics and electrodynamics. Maxwell's name may stand for that. On the utility side, James Watt and Werner von Siemens may characterize the amplification of technological possibilities accompanying that step. The change from the kW to the MW domain had begun. Physicists went on to conceive quantum mechanics, realizing the more abstract and thus more general meaning of the term information: it is broader and more powerful than energy. The name of Heisenberg may symbolize this level of abstraction. On the utility side, it led to the technology of information processing and to nuclear energy technology. The names of John v. Neumann and Fermi may be representative. This meant a change from the MW to the GW domain.

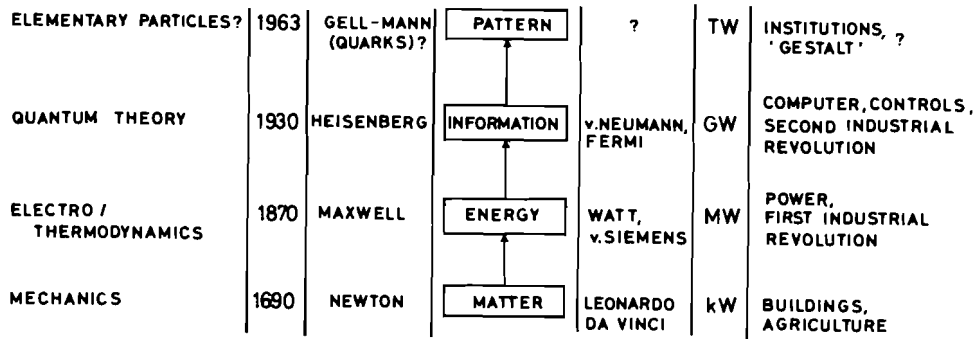


Figure 11. Levels of abstraction/utility.

We should not be surprised nowadays that if we want to enter the TW domain, this again means a new and qualitative step. One may conjecture that it relates to a step physicists may have taken recently. The theory of elementary particles is more a problem of patterns than of information. The quark concept of Gell-Mann points in that direction.

Again on the utility side, one must now also anticipate a new element. This paper has stressed that the problems of bringing nuclear power into the TW domain are soft in nature: they all point to management and institutional problems. Mere information is no longer doing the job. We need more than information, something that may be called "gestalt" or a body of institutional capabilities.

It is time therefore to realize that a distinct cultural step is needed to enter the TW domain--one quite comparable with the evolutionary step the old civilizations in the large valleys managed to take when they tamed rivers such as the Euphrates, the Tigris or the Nile. The problems were neither to build a dam here and there, nor to install gates, water the land and develop new agricultural methods. The basis for supporting peoples was formed only when a "technology gestalt" on a (then) worldwide scale was combined with a new idea of managing benefits and risks on that scale: the advent of the idea of a State. New technology and a new social structure formed a symbiosis.

Upon reflection, our present difficulties in preparing for that appear to be in line with the process of natural evolution.

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