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THE PATHFINDER ROLE OF NUCLEAR ENERGY

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Hypotheticality and the New Challenges: The Pathfinder Role of Nuclear Energy

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To those who for many years have been active in the promotion of nuclear energy, the opposition of the public to the large-scale application of peaceful nuclear energy has come as a surprise. The experience of public hearings and face-to-face discussions with the opponents of nuclear energy has made them aware of modes of thought and criteria of judgement which they had not encountered previously. It is now necessary to reflect on these alternative modes of thought and judgement in order to arrive at new ones, and, by so doing, to improve the basis for rational action.

Further, it appears that these alternative modes of thought and judgement and the responses which should be called forth by them do not arise on the occasion of large-scale uses of peaceful applications of nuclear energy alone. The new modes of thought which are being generated in consequence of the opposition are only adumbrations of a broader and more general development in thinking about science and technology. In this paper, I attempt to exemplify this development. I will begin with a brief account of the development of nuclear energy.

The Development of Nuclear Energy

The development of the peaceful applications of nuclear energy was related to its military applications in various degrees which changed with the times and which were different in various parts of the world. Originally basic scientific and technological research was to the forefront. But, more and more, the technological problems of large nuclear components, facilities and plants were the ones which attracted both scientists and engineers and funds for research and development. It was from this development of nuclear energy that the phenomenon of "big science" emerged as a new form of scientific organisation and as a new category of thought about science policy. The use of nuclear power for the production of electricity had to be competitive with fossil fuels, which in the 1950s and 1960s were temporarily cheap. It was thought that even if nuclear power turned out not to be fully competitive, fossil power would continue to be available inexpensively and in any amount desired. The drive for the development of nuclear power came also from an unquestioned belief in the desirability of technological innovation. This was particularly the case in the highly industrialised states without nuclear weapons.[1]

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[1] Häfele, Wolf and Seetzen, Jürgen, "Prioritäten der Grossforschung" in Grossner,

The order for the Oyster Creek nuclear power plant given to the General Electric Company by the Jersey Central Power and Light Company promoted the commercial breakthrough towards nuclear power. Since then, 150,000 MWe have been firmly ordered, have been under construction or in operation in the United States. The corresponding figures for Germany and Japan are 13,000 MWe and 15,000 MWe. Practically all of these are light water reactors (LWR's). In Great Britain and France, experience in the design, construction and operation of gas-cooled, graphite-moderated reactors, which demonstrates a remarkable technological capacity, has been considerable. However, it was not possible to translate this experience into a commercially feasible operation.

The development of reactors must be accompanied by the establishment of a fuel industry, the operation of which is commercially feasible. Since fuel elements have to be available prior to the operation of power plants, such a nuclear fuel industry is now being established. The problem here is the minimum size of the fabrication plant. To meet this requirement a single fabrication plant has to serve several thousand megawatts of nuclear power plant capacity. For many decades, enrichment will continue to be necessary since the present nuclear power plants make use of enriched uranium. Thus far, the gaseous diffusion process has been demonstrated as technologically and economically feasible. In the years to come, such feasibility may also be expected for the centrifuge process. In addition, the nozzle process must be mentioned. Again, a large capacity of nuclear power plants to be served is required to make enrichment a practical economic undertaking.

After irradiation in such nuclear power plants, the spent fuel elements must be chemically reprocessed; such reprocessing is therefore a late step. Again, for commercial feasibility, the power plant capacity must be several thousand megawatts. The number of commercial reprocessing plants in operation today is still very small. Their technological feasibility has been demonstrated in the past, even though the scale of these demonstrations was limited. If reprocessing is to be done on a very large scale, the feedback into the ecosphere will also be very large. This, in my judgement, will lead to an extension of today's technology. This extension does not appear to be a problem of technological feasibility: it is a matter of effort and of funds.

If chemical reprocessing is a late step, the final stage of waste disposal is an even later one. If very large-scale reprocessing probably requires an extension of today's technology, this—to say the least—also holds for the technology of the disposal of final waste. Disposal in adequately selected

Claus, *et al.* (eds.), *Das 198. Jahrzehnt: Eine Team-Prognose für 1970 bis 1980* (Hamburg: Christian Wegener Verlag, 1969), pp. 407–435; Servan-Schreiber, Jean-Jacques, *Le Défi Américan* (Paris: Denoël, 1967).

salt mines seems a suitable approach to this problem, and demonstration plants are being operated today.[2]

The picture of the peaceful application of nuclear energy for the economically competitive production of electricity is, therefore, today rather a simple one. LWR nuclear power plants are commercially feasible and are being installed and operated on a large scale. Those parts of the nuclear fuel cycle which must be carried out prior to, or at the same time as, the start of the operation of power plants are now commercially feasible also. Those parts of the nuclear fuel cycle which come into the picture only after the combustion of fuel elements require, in my judgement, an extension of present-day technology. The later they come into the process, the more they require the extension; such an extension is feasible. If, in the past, the nuclear power plant was the main target for research and development, in the future it will be that part of the fuel cycle which, in time, is last.

A similarly positive assessment can be made for commercial ships operating under nuclear power. The United States, the Soviet Union, Germany, and, soon also, Japan have or will have demonstrated the successful operation of such ships.

Only 10 years ago the picture was by no means as clear. There was an overwhelmingly large variety of competing types of nuclear power plants and the various features of the fuel cycle were not so readily discernible. There are now essentially two types of nuclear power plants which have evolved as second generation counterparts of the LWR. These are the high temperature, gas-cooled reactor, and the fast breeder reactor. I need not elaborate on the technical details, but will observe only that high temperature, gas-cooled reactors are capable of providing nuclear power at temperatures of 1,000°C. and more. This has certain advantages if electricity is to be produced. But the main thing is that, by virtue of high temperatures, nuclear power becomes applicable as chemical process heat. This means an extension of nuclear power beyond the production of electricity. In order to appreciate this feature fully one must realise that only roughly 25 per cent. of the total demand for primary energy is a demand for the production of electricity. The remaining 75 per cent. go in roughly equal parts into the sectors of transportation, domestic, and other industrial uses. The advantage of the high temperature, gas-cooled reactor is that it can make nuclear power applicable to these sectors.

The fast breeder reactor places the provision of fuel for nuclear power on a completely different basis. Fast breeder reactors extract on average roughly 100 times more energy from a given amount of natural uranium than can other nuclear reactors, including the high temperature, gas-cooled

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[2] Wittenzellner, R., "Storage of Solid Radioactive Waste", and Tuohny, T., "Managing Liquid Radioactive Waste", discussions on the storage of nuclear waste, 20 September, 1973, at the 17th Regular Annual Session of the IAEA General Conference, Vienna, 18–24 September, 1973 (proceedings to be published).

reactor. In the short term, this results in a remarkable stability in the price of uranium ore. At present ore prices, only one thousandth of the cost of generating electricity arises from the provision of ores. As a result, almost any uranium price can be afforded. This implies that even those ores which are of average richness can be processed. In the long run, this leads to a situation where nuclear power is capable of providing enough energy for several hundred thousand, if not million, years. The LWR of today can do that only for some decades. Both the high temperature reactor and the fast breeder complement the LWR remarkably well, and strategies can be identified which will ease the transition from market situations in the present day to world-wide problems of energy demand and supply in the future.[3]

In discussing the present position of nuclear energy, the element of time must be emphasised. The development of nuclear energy originally had a highly complex and sometimes disturbing appearance. Consideration of the temporal aspect led to a process of selection, in the course of which the valid parts of this development became evident. Those who were involved had to be educated and again this required time. For instance, it was through a step-by-step process that the electricity-producing firms—and national laboratories too—came to understand how to act in the development of nuclear power. Over and above all this, there is an inherent temporal dimension to such complex technological and organisational developments.

Large and complex developments have to pass over three thresholds. The first of these is the threshold of scientific feasibility: in the development of nuclear power for peaceful applications, the principal step towards scientific feasibility was taken by Enrico Fermi as early as 1943. The definitive consolidation of these steps occurred between 1943 and 1950. The second threshold is that of technological and industrial feasibility: to pass this threshold is a step the size of which is often underestimated. In the development of light water reactors in the United States this step comprised the successful establishment and operation of the Dresden, Yankee, and Indian Point—roughly 200 MWe—demonstration plants; in Western Germany, the plants at Obrigenheim and Lingen performed this function. The significance of operating these demonstration plants only began to be clearly evident in the early 1960s. In other words, it required nearly two decades to pass from the threshold of scientific feasibility to the threshold of technological and industrial feasibility. Fast breeder reactors and high temperature, gas-cooled reactors are passing the latter threshold only now.

The third threshold is that of economic and commercial feasibility. As a result of its complexity, this appears to be the most difficult threshold to

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[3] Häfele, Wolf and Schikorr, Winfried, " Reactor Strategies and the Energy Crisis " IAEA Study Group on Reactor Strategy Calculations, Vienna, 5–9 November, 1973 (proceedings to be published).

those who have lived through the various stages of such a development. Let us recall that there were quite a number of reactor types which were technologically and industrially feasible but which were unable to pass over the third threshold. This is true for instance of the gas-cooled, graphite-moderated, natural uranium reactors which were developed in the United Kingdom and France. Economic and commercial feasibility implies that industry is able to sell its product at competitive prices without public subsidy. It also requires that the utility companies must be able and willing to place orders necessary for such very large-scale industrial projects and that the governmental bodies must have taken the necessary regulatory measures. It is this last step which turns out to be of outstanding importance. In the United States and, for instance, in Western Germany, acceptance of their appropriate roles and responsibilities by the various partners involved has been a long and sometimes complicated process.

Even now, about 30 years after Enrico Fermi's historic accomplishment, the process has not come to an end. The larger public has recently begun to realise the dimensions of this development. It is assuming a role in the third stage of the development which it did not accept in the first two phases. The objections to nuclear power which have been raised by certain parts of the larger public must therefore be taken seriously and fully understood.

Objections to Peaceful Nuclear Energy

These objections have arisen during recent years not only in the United States but also in Western Germany, Sweden, Switzerland, the Netherlands and Japan. It may be observed in passing that such opposition has not taken place—or at least not to such an extent—in Canada, the United Kingdom, France, Italy, and certain other countries. Generally speaking, the main objections to peaceful nuclear power appear to be the following: (1) the routine operation of nuclear power plants creates dangers of radiation; (2) if nuclear power is produced on a large scale, it is impossible to exclude the risk of a major accident, resulting in even greater dangers of radiation; (3) since fissile material can be used for both peaceful and non-peaceful purposes, there is a risk, in handling large amounts of fissile material, of the illegal diversion of such fissile material; (4) the operation of nuclear power plants necessitates the storage and disposal of radioactive wastes for periods of time which exceed human experience; (5) the large-scale operation of nuclear power plants involves the handling of large amounts of plutonium which must be kept out of the ecosphere; (6) the operation of nuclear power plants results in the production of large amounts of waste heat; (7) the erection of nuclear power plants requires too much land; and (8) the demand for more energy which is to be met by nuclear power is not real but is a product of manipulation.

These objections must be met. Many writers have been doing this over the past few years,[4] but this is not the task to which I am addressing myself in this paper. Rather, I wish to reflect on these arguments and to consider them in new categories, which will allow for a better understanding not only of the objections but also of the answers. To this end, I will consider more specifically a few of the objections.

The Routine Operation of Nuclear Power Plants: Today's routine operation of nuclear power plants leads to a radiation danger which is smaller than 5m rem/year. Recently it has also been made mandatory for LWRs to make the radiation danger smaller than 5m rem/year; the regulation said " as low as practicable." The question now is whether such a limit is acceptable. Originally the regulatory limit was 170m rem/year, but the practice was not to exceed 5m rem/year. A large margin therefore evolved. Dr. Gofman and Dr. Tamplin then made it a point to argue that not only the practical value but the regulatory limit as well should be correspondingly low. Their argument was as follows: there is experimental evidence to show that applying 1 rem induces about 20 additional cases of leukaemia per million persons. The relevant experiments were made at about 50 rem or more. If all kinds of cancer besides leukaemia are taken into account, the figure may be as high as 120 persons per rem per million persons. Then they calculated the number of cases of cancer by straightforward algebra, considering only 0·17 rem/year (i.e., 170m rem/year) and 200 million persons (equalling the population of the United States). This leads to $17 \times \cdot 10^{-2} \times 2 \cdot 10^{-8} \times 120 \times 10^{-6} \sim 4{,}000$ additional cases of cancer. Their conclusion was that this figure is too high.[5] A tremendous public debate resulted with much talk about the effects of poisonous nuclear power. It also led to new regulations by which a formal interpretation of the wording " as low as practicable " was required. The regulation now provides that the radiation danger be smaller than 5m rem/year.[6] This figure leads to 120 cases instead of 4,000.

The question necessarily arises: why is that the right figure? There is of course no answer to this. One cannot argue in the domain of absolute figures—comparisons by means of a yardstick are the only reasonable pro-

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[4] See, for instance, " The Nuclear Controversy in the USA ", International Workshop, Lucerne, Switzerland, 30 April–3 May, 1972, sponsored by the Swiss Association for Atomic Energy in cooperation with the United States Atomic Industrial Forum: and " Energie und Umwelt Informationsdienst der Zeitschrift ", which appears in each issue of *Atomwirtschaft—Atomtechnik.*

[5] Actually, the figure which Drs. Gofman and Tamplin were talking about referred to 30,000 persons, because they employed a different set of medical data. But this does not influence the logic of the argument presented here. Gofman, J. W. and Tamplin, A. R., *Poisoned Power: The Case against Nuclear Power Plants* (Emmäus, Pennsylvania: Rodall Press, 1971).

[6] United States Atomic Energy Commission, " Proposed Rule Making, Licensing of Production and Utilization Facilities. Light-Water-Cooled Nuclear Power Reactors. /10 CFR Part 50/ ", *Federal Register,* XXXVI, 111 (June 1971). See also, United States Atomic Energy Commission, " As Low as Practicable Numbers could end the Radiation Controversy . . . .", *Nucleonics Week,* XII, 22 (June 1971), p. 4.

cedure. Such a yardstick can only come from placing the problem in the setting of nature. The " natural " radiation is, on average, 120m rem/year. The variation of that figure is high. Changing positions on the surface of the earth can easily lead to an increase of 50m rem/year. This is the case if one moves, for example, from Pittsburgh to the Smoky Mountains in the United States. Similarly, living in a concrete building leads to an increase of roughly 20m rem/year. In view of both, the average value and the variation of the natural radiation, 5m rem/year is a small figure. "Embedding" the problem into the normal conditions of life therefore does provide a yardstick. Similarly, one should make the comparison with the number of cancer cases which ordinarily occur. In the United States, there are 300,000 cases per year, so it is this figure against which the additional number of 4,000, or 120, as the case may be, must be assessed.

Many of the opponents of nuclear energy now say that statistical considerations are inhuman, and that any additional life which is "willingly" sacrificed is too much. Human beings have names. But this argument, by virtue of the simple algebra given above, implies a causal relation between the additional 5m rem/year and the additional 120 cases of cancer. While experimental evidence for this causal relation can be demonstrated, at the level of 50 rem, i.e., the ten-thousandfold value, this is certainly not the case at 5m rem. It is a problem of the extrapolation to low rates of dosage. Such an extrapolation is very hypothetical because there is no way of proving it experimentally. Further, such re-extrapolation requires that all other parameters be held constant. There is no individual, with a name, for whom this can be done. It is obvious that entering the hypothetical domain leads into strenuous debates which become so animated because they can never be resolved. " Embedding " is the way out of this dilemma. The normal conditions of life provide a yardstick or standard.

The International Committee on Radiological Protection (ICRP) deals with standards by establishing limits of radiological dosage on an international basis. This requires understanding the causal relations between rates of dosage and damage. Understanding these causal relations, however, is only one side of the coin. The other side of the coin is the standard of what is acceptable. This, too, is done through the process of "embedding". The ICRP shows it is aware of this by making the following observation:

> Any exposure to radiation is assumed to entail a risk of deleterious effects. However, unless man wished to dispense with activities involving exposures to ionizing radiations, he must recognize that there is a degree of risk and must limit the radiation dose to a level at which the assumed risk is deemed to be acceptable to the individual and to society in view of the benefits derived from such activities.[7]

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[7] ICRP, " Recommendations of the International Commission on Radiological Protections ", *ICRP Publication*, pt. 9, A (34) (Oxford: Pergamon Press).

" Embedding " entails the establishment of a criterion which incorporates both of the actions recommended—in this case, the erection and operation of nuclear power plants—and the benefits and risks of the alternatives. The most straightforward way of doing this is to consider the ratio. Up to now, the ICRP has refrained from identifying the denominator of that ratio, the benefit, on the grounds that the benefit varies from society to society and from one situation to another. The assessment of radiation standards in a situation of oil shortage, for instance, is one thing; considering such standards in a situation where large amounts of very inexpensive energy exist is another. In addition, benefits may appear differently to poor countries and rich ones. For these reasons, the ICRP decided to leave the evaluation of such benefits, and therefore the ratios of benefits to risks, to the respective national bodies.

There is a further point: the ICRP talks of risks. There is little doubt that if the process of radiation damage were completely understood it would be possible to assess that radiation damage deterministically. Damage could be assessed with certainty. Risks of the kind we are discussing refer to events governed by laws of nature of which we have incomplete knowledge.[8] If our knowledge were complete, the ratio in question would become a ratio of benefit to damage. The problem would not be one of the acceptability of risks but of the acceptability of damages which are certain. In either case, it is acceptability which is at issue.

Comparing risks—or damage—arising from a proposed activity with those occurring in nature is one way of dealing with the problem of acceptability. Another way is to ask for alternatives to the activity proposed. For instance, are there alternative possibilities of producing sufficient amounts of energy at prices which purchasers are willing to pay? Such alternatives are features of the world we live in and this also might therefore be viewed as "embedding". For some time to come the possibility of energy production by the combustion of fossil resources will remain. For the moment we will leave aside the problem of the adequacy of resources. The point here is rather that the use of fossil fuel is also accompanied by pollutants which damage health. The most notable is SO_2. Of course a Gofman-Tamplin analysis can be made here too. It has been reported that for every 100 persons-ppm-year, there is roughly one death which is a result of respiratory infection.[9] In larger cities, SO_2 concentrations in the order of 100 ug/m^3 of SO_2 can often be observed. This relates to the order of 0.1 ppm. Making the assumption here that about 60 million persons in the United States live in areas of such SO_2 content, this results in $6 \cdot 10^7 \cdot 0.1 \cdot 10^{-2} = 60{,}000$ deaths/year as a result of SO_2. The problem raised by Drs. Gofman and Tamplin is therefore not peculiar

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[8] This is a general observation. See the recent discussion of this problem in Brooks, Harvey, " Science and Trans-science ", in Correspondence, *Minerva*, X, 3 (July 1972), pp. 484–486.

[9] Wilson, R., " Tax the Integrated Pollution Exposure ", *Science*, CLXXVIII, 4057 (October 1972), pp. 182–183.

to nuclear energy. It can always be raised when low rates of dosage of any toxin or drug are considered. Needless to say, in the case of SO_2, as in that of radiation, the question of the causal relationship must be considered. Again we enter the domain of the hypothetical.

For each of the various pollutants, such as SO_2, a standard must be established; the analogous problem of the establishment of radiological standards must then be treated in the same manner. This immediately raises the problem of how we can ensure that all the standards in question are equally rigorous. The question necessitates a comparison of risks—or damage—of completely different kinds. How does pollution by SO_2 add to that of dust, and does the sum of both compare to 5m rem/year. The difficulty is, however, broader than that. How is a dusty atmosphere related to a risk of having a $\frac{1}{2}$ per cent. increase in the rate of mutation within a few generations? The time element complicates the issue even further.

Up to now the approach to these questions has been implicit or pragmatic. In the past this was satisfactory because the related issues were of limited size and therefore of limited significance. But in the life of coming generations, with the increased use of technology which produces more pollution and the prospect of a greatly increased population and a greater demand for energy, this becomes a question of much greater urgency. It is necessary therefore to look for methods to approach these problems in a more coherent and systematic way. Furthermore, the interest of mathematicians in these problems has helped to make for a greater awareness of the possibility of treating the problems more systematically through the use of concepts like the value problem, vector, value optimisation, the decision process, and others.[10] The problem of the evaluation of risk raises basic methodological problems. Only very little knowledge is available,[11] and much work is required in this field.

The task may be formulated in summary form along the following lines: it is necessary to establish standards for the impacts of certain technological measures. In doing this we will contribute to the evaluation of related problems. The establishment of standards entails relating, as thoroughly as possible, ambient rates of dosage to physiological and other damage. At the same time, we must establish criteria and rules of acceptability, including both damage which is certain and the risk of damage. This requires "embedding" the standards and criteria into the normal conditions of life. For the evaluation of alternatives, it is necessary to establish standards of a completely different nature. This inherently requires their comparison and involves a process of decision, i.e. a problem of value.

[10] Raiffa, Howard, *Decision Analysis: Introductory Lectures on Choices under Uncertainty* (Reading, Mass.: Addison-Wesley, 1968).

[11] See, for instance, Starr, Chauncey, "Benefit-Cost Studies in Socio-Technical Systems", Colloquium on Benefit-Risk Relationships for Decision-Making, Washington, D.C., 26–28 April, 1971, sponsored by the United States National Academy of Engineering. See also, Otway, Harry and Erdmann, Robert, "Reactor Siting and Design from a Risk Viewpoint", *Nuclear Engineering Design*, 13 (1970), p. 365.

Rare but Major Accidents: Nuclear power plants are made to be safe on the basis of passive or active engineering measures. This means that engineering measures either act by their mere existence—for example, as shields and locks—or by positive action—for example, as moveable control rods. Any such engineering measure can fail and in an advanced state of technology it is possible to assess a probability of such failures. This has been done in electronics in particular. While small, such probabilities of failure are nevertheless finite. If the probability of failure is considered to be too high, a second line of defence has to be installed. Safety components must be installed which are redundant. By the successive staging of such safety devices, it is possible to make the probability of failure smaller than any given small number[12]; but it is not possible to reduce it completely to zero. This, then, raises a number of problems. The first of such problems was stated by Dr. Starr as " How safe is ' safe enough ' ? " In recent years, the concept of failure rates has been introduced. A rate of failure of, for example, 10^{-x} per year, might be considered. For instance, x could be between 3 and 7. This leads into the intricate problem, which is partly a semantic one: is a plant of a failure rate of 10^{-7} really 10 times safer than a plant of 10^{-6}? If the term " safe " is clearly defined by such failure rates, this is certainly so. But is this definition adequate? What is the more general meaning of " safe " to a wider public? And can such a more general meaning really be quantified?

When we ask " How safe is ' safe enough '?" we are again led into the process of " embedding ". Other risks have to be considered and alternatives have to be evaluated. Solar power and geothermal energy resources must be considered and compared with nuclear power. These alternatives have their own risks. If the residual risk of operating a nuclear power plant is to be compared with these risks, one has to reflect on the fact that the residual risk in the case of nuclear power is not a risk to be considered without reference to alternatives. There is little doubt that the laws of nature which are employed in the design and operation of, for example, a control rod are quite adequately understood. But, for the application of these laws of nature, knowledge of all initial and boundary conditions is also required. These initial and boundary conditions are not part of the laws of nature but are required if the laws of nature are to be applied to a particular case. This is necessarily so. The generality of the laws of nature results from the abstraction of the elements of the actual case, which are the initial and boundary conditions. As an example, let us think of the differential equation for a mechanical movement. Newton's law is general and governs all mechanical movements. But if the fall of a particular apple from a particular tree is to be predicted, the locus and the momentum of the apple at a given moment in time must be provided.

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[12] Häfele, Wolf, " Ergebnis und Sinn des SEFOR Experiments ", in Scheibe, E. and Süssman, G. (eds.), *Einheit und Vielfalt, Festschrift für C.F. von Weizsäcker zum 60. Geburtstag*, (Göttingen: Vandenhoeck and Ruprecht, 1972), p. 248.

Measurement is the only way to accomplish this. This is a principal observation. The difference between the nature of initial and boundary conditions and the laws of nature has been dealt with recently by Professors Carl Friedrich von Weizsäcker and Erhard Scheibe,[13] who have described the nature of initial and boundary conditions as contingent. In so doing, they employ the medieval philosophical term *contingere*, which is a translation by Boethius of the more basic Greek word ἐνδέχομαι. It means encountering an event without being able to predict it; it simply happens. In this context, my usage of the word "contingent" is different from the common English word "contingent", which has a somewhat different meaning but which has the same root. Leaving aside the still more basic problem of interpretations in quantum theory, one must make the further observation that it is impossible to measure initial and boundary conditions with the completeness and accuracy necessary for a fully deterministic prediction of the performance of a technical component or device. This is where risk resides. It is not a risk of the type which is related to uncertainties in the knowledge of the employment of the laws of nature. It is a risk of the kind which refers to incomplete knowledge of initial and boundary conditions. While, at least in principle, it is possible to eliminate risks of the first kind, there is no possibility of doing so with risks of the latter kind. We can always improve our knowledge about contingent elements, but we can never make it complete. This restates the proposition that the residual risk can be made smaller than any given small number but it cannot be reduced to zero.

The traditional engineering approach to eliminating risks of the second kind—the risks which are integral to contingency—is trial and error. The engineer learns by experience to make better and safer machines. This is close to the scientific approach: an hypothesis is made which is followed by experiments, which in turn lead to an improved hypothesis, which again is followed by experiments. In this way a theory evolves which is true, i.e., is in touch with reality: *Veritas est adequatio rei et intellectus.*[14] It is precisely this interplay between theory and experiment, or trial and error, which is no longer possible for new technologies which are designed to master unique challenges. In the case of reactor safety this is obvious. It is not acceptable to learn reactor safety by trial and error. Before we continue this line of reasoning, another observation is in order.

Reactor engineers face this dilemma by dividing the problem of engineered reactor safety into sub-problems. For instance, the integrity of a pressure vessel is investigated as a sub-problem, and so is the operability

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[13] von Weizsäcker, Carl F., "Komplementarität und Logik", *Die Naturwissenschaften*, XLII, 19 (1955), p. 521. See also Scheibe, Erhard, *Die kontingenten Aussagen in der Physik* (Frankfurt: Athenäum, 1964), and *The Logical Analysis of Quantum Mechanics* (Oxford: Pergamon Press, 1973).

[14] Aquinas, Thomas, *Quaestiones disputatae de veritate*, verit 1. 1c. This formula has been widely referred to in the history of medieval philosophy and stresses the objectivity of things.

of control rods and pumps. To use the performance of such components to draw conclusions about the performance of the whole nuclear plant of course requires a certain preconceived idea of the various interactions which must be considered when the components are combined. In combining such components more contingent elements come into the picture. The aim is to minimise the impact of incomplete knowledge of contingent elements. Therefore, in designing the needed experiments—which are tests, in this context—the largest possible units are sought. But, by the same token, the generality of the conclusion is reduced just because it was the contingent elements which led to these tests of large technological units. In persisting further and further along this line of reasoning, one arrives at a situation where the truly large-scale test can only result in the statement that a given device functioned at a particular time and place. A general conclusion is impossible. Because of the fact that the test stressed the contingent aspect of the elements, all generality is eliminated. Reactor engineers are familiar with this feature of reality. To some extent, the term " integral test " refers to it. We should recall the debate on the advisability of reactor tests of the Borax type,[15] where the argument was raised that almost nothing general could be concluded from such an integral test. Only large instrumentation could justify such an expensive test. But this refers exactly to the measurement of contingent elements. At the extreme, one may call such large-scale integral tests " happenings ".

Let us again return to the general line of the reasoning followed in this paper. Reactor safety in its ultimate meaning cannot be evaluated by trial and error. Subdividing the problem can lead only to an approximation to ultimate safety. The risk can be made smaller than any small but predetermined number which is larger than zero. The remaining " residual risk " opens the door into the domain of " hypotheticality ". At this stage, it becomes clearer that the concept " hypotheticality " is crucial in this analysis. A few words of explanation are therefore necessary. Hypotheticality, of course, is not a word in regular usage but its logic expresses precisely what must be expressed in the line of reasoning presented here. Its logic is the same as that of the word " criticality ", for example, a term which is familiar to reactor engineers. The rule followed is that for Latin words ending in *-itas*, for example, *veritas* or *felicitas*. Such substantives point to features which exist in principle and which if actualised, lead to the fact that something can have a certain property: a reactor can become critical or a situation can be considered to be hypothetical. The process of iteration between theory and experiment which leads to truth in its traditional sense is no longer possible. Such truth can no longer be fully experienced. This means that arguments in the hypothetical domain neces-

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[15] Dietrich, Joe R., " Experimental Determination of the Self-Regulation and Safety of Operating Water-Moderated Reactors ", *Proceedings International Conference on Peaceful Uses of Atomic Energy*, August 1955, Geneva, United Nations, New York, vol. 13 (1956), pp. 88–101.

sarily and ultimately remain inconclusive. I think that this ultimate inconclusiveness which is inherent in our task explains, to some extent, the peculiarities of the public debate on nuclear reactor safety. The strange and often unreal features of that debate, in my judgement, are connected with the " hypotheticality " of the domain below the level of the residual risk.

Why is it impossible to apply the method of trial and error to ultimate reactor safety? It is impossible because the consequences of so doing would be too far-reaching. Every country is too small for that—eventually even the globe itself is too small. The magnitude of the technological implications thus becomes comparable with the magnitude of the constraints which determine our normal life. This inapplicability of the scheme of trial and error may be regarded as a kind of cost—or risk. But nuclear power is to be justified by its capacity to provide practically infinite amounts of energy for even a highly populated and industrialised world. This is an unusual kind of benefit which exceeds any so far experienced. The appropriate concern therefore is whether the ratio of such costs and benefits is adequate. To complete the picture, the magnitude of engineered safeguards also is inherently very large, and is hitherto unexperienced. The inverse failure rates which relate to the periods of time within which to wait for a failure are an indication of that. The magnitude of the constraints of the world we live in corresponds, if properly interpreted, with the magnitude of the costs—or risks—the magnitude of the engineering measures needed to guard against it, and the magnitude of the benefits.

In dealing with reactor technology, we should realise that nothing less than this is at stake. I think that it is insufficient to look at nuclear power plants as mere substitutes for the present more conventional power plants which use fossil fuels.[16] In line with this reasoning, it is perfectly legitimate to look for alternatives to nuclear power. These alternatives must, however, be evaluated by means of the same global standards or within the same magnitude and scope as nuclear power. To give an example: tidal power is not an alternative. It cannot provide the same amount of power as can nuclear power.[17] If nuclear power proves superior to other alternatives when properly evaluated, it will be fully legitimate to proceed with what will then be the truly large-scale development of nuclear power.

Let us for a moment consider some of these choices. As mentioned before, one such alternative is solar power. At first inspection, solar power appears to be a clean source of energy. Solar power has, however, the disadvantage of being dispersed; one cannot hope to harvest more than, say, 20 W/m^2. Large areas of the globe must therefore be utilised to provide very large amounts of solar energy. The present consumption of energy in the world is at $8 \cdot 10^{12}$W; in the future, $60-150 \cdot 10^{12}$W must be

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[16] Weinberg, Alvin, private communication.

[17] See, for instance, Hubbert, M. K., " The Energy Resources of the Earth ", *Scientific American*, CCXXV, 3 (September 1971), p. 60.

prepared for, as the world population increases and the poorer countries begin to obtain their share. A figure of $100 \cdot 10^{12}$W at 20W/m^2 implies a figure of $5 \cdot 10^{12}$ m^2. This is about 20 times the area of the German Federal Republic. To take such a step might not be impossible eventually but its size and nature imply a kind of impact on the normal conditions of life—including the political aspects of such normal conditions—which indeed offers little advantage over the impact of other alternatives. If produced on a very large scale, solar power would not offer a solution which left the normal conditions of life unchanged.

There are other repercussions of the development of solar power besides the use of very large tracts of land. The energy balance of the atmosphere above these large areas would of course change accordingly. One has to realise that such changes would be likely to happen in stages. The most probable first stage would be a change in the pattern of rainfall, but not in the global average of the amount of rainfall. Even if nothing else were to happen, there would be dramatic consequences: the continuous drought in North Africa which we experience today is indicative of that. In the next stage, the average amount of rainfall and its pattern would alter together with regional changes in climate. One result might be a regional change of average temperatures and winds. In the third stage, the global climate would change with a change in the average global temperature. This could cause an ice-age or melting of ice-caps. It is not good enough to point out that even large-scale harvesting of solar energy would make up only 1 per cent. or so of the total solar input and might therefore be negligible. The question is more delicate than this since regional instabilities of weather and climate are at stake. It is equally inadequate to point out that regional uses of solar power are desirable and clean in many if not all respects. Only if solar power can be produced on a very large scale can it be considered to be a legitimate alternative to nuclear power. It may very well be the case that eventually a combination of solar, nuclear and possibily even other additional forms of energy might turn out to be the optimal condition. I mentioned earlier that a major effort is now under way to develop comprehensive computer programmes for the largest computers available, and to develop appropriate global systems for monitoring weather conditions, pollutants, and other parameters such as the CO_2 content of the air.[18] This will bring significant progress. But it will always be impossible to run truly integral experiments as they were discussed above in the case of nuclear reactor safety. The prediction of man's impact on the climate will never be fully proven experimentally, or, to be more exact, by trial and error. The magnitude of the risk which is involved again corresponds to the magnitude of the constraints which determine our normal life. A residual risk will

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[18] World Meteorological Organisation and International Council of Scientific Unions, "The First GARP Global Experiment, Obejectives and Plans", *GARP Publication Series*, nr. 11 (March 1973).

therefore remain. Again one finds oneself in the domain of " hypotheticality " and the debate on the related issues will be inconclusive.

It is now clear that a similar argument holds for the very large-scale " harvesting " of the heat in the earth's crust. This statement implies, among other things, that the risk of inducing large-scale earthquakes is unacceptable. Furthermore, contrary to a widespread belief, the fusion reactors which are hoped for would by no means be a source of clean power.[19] More systems-analyses comparing various alternatives for the provision of energy are now urgent, although it is unlikely that one of the alternatives would turn out to be clearly superior to all others.

The ecological impact of human activities is also of that nature. Once ecological equilibria are destroyed, it takes periods of time beyond human experience for their re-establishment. In this case, too, trial and error, or, rather, the iteration of theory and experiment, cannot provide a definitive solution. Residual risks will remain.

Many more examples of this situation can be found. The tasks which we confront in the assessment of nuclear power are prototypical of a wider range of emerging problems; in this sense, the analysis of the problems of nuclear power is a pathfinding undertaking. If properly interpreted and understood, the public concern about nuclear power is not unfounded. But that concern is not a simple function of a peculiarity of nuclear power. It is, rather, the general condition of civilisation towards which we are moving; it is a condition where the magnitude of human enterprises becomes comparable with the magnitude of the widest determinants of our normal existence. Nuclear power turns out to be a forerunner, a pathfinder, of that.

Nuclear Material Safeguards: Another objection raised by the opponents of nuclear power asserts that it will render easier the illegal diversion of nuclear material for military purposes. This is sometimes called the problem of safeguards. A vast international effort has been made to deal with the problem. The conception, negotiation and commencement of the Treaty on the Non-Proliferation of Nuclear Weapons marked a great step forward in this respect. A major effort of systems-analysis and development led to the establishment of the safeguards system of the International Atomic Energy Agency (IAEA). The continued operation of the European Atomic Energy Community as well as the United States Atomic Energy Commission safeguard systems have also contributed to a considerable reduction of the risk of illegal diversion of nuclear material.[20]

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[19] Häfele, Wolf and Starr, Chauncey, " A Perspective on Fusion and Fission Breeders ", *Journal of the British Nuclear Energy Society* (forthcoming).

[20] International Atomic Energy Agency, " The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons ", IAEA, Vienna, Information Circular 153, 1971. See also, Häfele, Wolf, " Systems Analysis in Safeguards of Nuclear Material ", *Proceedings Fourth International Conference on Peaceful Uses of Atomic Energy*, September 1971, Geneva, United Nations, New York, IAEA, Vienna, vol. 9 (1972), p. 303.

As in other situations in which risks of catastrophic dimensions must be dealt with, so in the case of safeguards also the establishment of standards was in the forefront of interest. In order to establish thresholds of significance, it was necessary to obtain experimental values for the material unaccounted for (MUF), since the accountability of nuclear material is the corner-stone of the present safeguard systems. The side of the task which deals with causal relations of a scientific or technological nature was more or less readily taken care of. To that end a number of experiments were designed and executed. The result was that the amount of MUF for the various nuclear facilities such as reprocessing plants was established. On the other side, it was necessary to reflect on the demands for such accountability. Was the IAEA system of safeguards to be designed to account for kilogrammes, grammes, or milligrammes of nuclear material? And what were the periods of time during which the detection of diversion had to take place? It was a painful and lengthy process to explain to politicians that it would be impossible to account for absolutely all the nuclear material. A residual percentage would go into MUF; there was bound to be a residual risk in the case of safeguards, as in other situations of the kind under discussion.

What then is acceptable? In the case of international safeguards against the illegal diversion of nuclear material, the need to accept residual risks has led to highly hypothetical considerations. One such hypothetical problem was whether it would be considered feasible that someone should drill little holes into thick concrete walls for the diversion of x grammes of uranium. The domain of the hypothetical comes even more clearly into focus if I report here on the concern that there might be someone in a hidden back room in the basement of a power plant preparing plutonium without paying attention to any radiation this might cause. As a result of an intensive international effort under the guidance of IAEA for several years, it was eventually possible to narrow the gap between the demand for international safeguards and their feasibility. It was possible to assess the acceptability of residual risks. Yet absolute certainty of the safeguards cannot be provided; a residual risk remains and therefore the situation is " open-ended ".

The responses which can be given to those who object to the development and use of nuclear power are pretty much the same for all the arguments. There is one exception. This is the argument which asserts that the demand for energy is the result of manipulation and is not " real ". It is an interesting question, but it does not involve scientific or technical considerations of the kind which I have been treating in this paper. Hence, I shall not deal with it here.

Marginal Remarks on the Energy Problem

It nevertheless seems appropriate to make a few remarks on the nature of the problem of energy which industrial countries are facing, as this establishes the scope for any systems-analytical evaluation or assessment of nuclear energy or related phenomena. It is most important to realise that the problem of energy appears in phases over time, the features of which are sometimes very different. In the first phase of the problem, it is the oil shortage which is to the forefront. This phase will last for at least 15 years because any technological measure requires that much time before its impact attains substantial economic significance. During this phase, research and development on the substitution of synthetic hydrocarbon fuels for oil are urgently needed. The second phase is likely to be characterised by the large-scale use of nuclear power in the production of electricity and of coal for the non-electrical sector of demand for secondary energy. This phase may last for a few decades.

In the long run, i.e., in the third phase, all demand for primary energy must be met by other than fossil fuels. There are four alternatives: nuclear fission energy, nuclear fusion energy, solar power, and geothermal energy from the earth's crust. All four alternatives can provide very large amounts of energy, although in different degrees.

During the second phase, preparations for changing to one of these alternatives or to a combination of them must be made. These preparations will require more than the exclusive consideration of the supply of fuel. The procedure of " embedding " is needed in order to arrive at an optimal solution. The problem of fuel supply must be " embedded " in the atmosphere, the hydrosphere, the ecological sphere and the sphere of social life. The demand for and supply of energy and their embedding have to be considered on a scale which might be something like 25 times larger than today's scale. It must be assumed that the world's population will increase and that the poor countries will begin to approximate the consumption of energy *per caput* which is close to that of the rich countries.

This, then, is the setting for assessing the various technological alternatives for providing enough energy and their various advantages and disadvantages. The promulgation and comparisons of standards, the assessment of residual risks, " hypotheticality " and " embedding ", are the intellectual procedures which must accompany the technological developments of tomorrow.[21]

" *Hypotheticality* " *and Arms Control*

It is probable that " hypotheticality " will characterise the next stage of human enterprise. The magnitude of technological enterprises will be so great that it will not be possible to proceed with the absolute certainty that there will be no negative consequences. The magnitude of the undertaking and the intellectual impossibility of eradicating all contingency

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[21] Häfele, Wolf, " Energy Systems ", in *Proceedings of the IIASA Planning Conference on Energy Systems*, Laxenburg, Austria, International Institute for Applied Systems Analysis, July 1973 (also to be published in *American Scientist*).

make the prospect for " hypotheticality " even more certain. But if we are condemned to " hypotheticality ", are there ways to deal with it? Most of these ways are still to be explored. The case of arms control, however, might illustrate the way of proceeding which is available to us. It was recognised in the case of nuclear armament earlier than in other spheres that it was leading into qualitatively new conditions. The yield of atomic weapons exceeded all previous experience and the means of delivering such weapons permitted delivery from almost any part of the earth's surface to almost any other part. The magnitude of the military and technological implications became comparable with the magnitude of the determinants which set the framework of our normal existence. Furthermore, it is impossible to develop the art of nuclear warfare by trial and error, as was previously always the case with innovations in military technology. Hence, residual risks became evident in the field of atomic warfare. This happened early and a number of schools of thought have evolved to deal with these residual risks and to develop a practicable rationale or doctrine.[22]

The kind of reasoning which developed in these schools of thought soon became very specialised. It was not easily possible for a citizen who was not a scientist, or even for scientists who were not working intensively in this field, to follow these developments. The debate on anti-ballistic missile systems (ABM), on multiple independently targeted re-entry vehicles (MIRV), and other such problems, demonstrated this. The reasoning involved in these decisions was extremely complicated and abstract. It was also extraordinarily difficult to propound absolutely conclusive arguments. There was always another view and there was no way of ultimately proving one's own position. At the same time, the whole domain of nuclear armament was vitally urgent. It was considered to be a matter of life and death to have a strategic doctrine which would deter one's visible and rational opponent from engaging in nuclear warfare. This feature of being extremely unreal—abstract and irrelevant—and at the same time extremely real—and relevant—developed into a serious gap in the late 1960s when the ABMs and MIRVs came into the picture. At that time SALT negotiations started. For a long period it was not clear whether a treaty would be agreed to. But even if they had not resulted in such a treaty, it would indeed have been an achievement to have held the SALT negotiations. In the course of these negotiations the two antagonistic parties talked to each other and came to understand better each other's rationale of nuclear strategy. It was a matter of enhancing the prospect of the survival of the human race. It gave a hint about how to deal with " hypotheticality ".

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[22] A well-known example is contained in Wiesner, Jerome B., " Comprehensive Arms-Limitation Systems ", in *Arms Control, Disarmament and National Security* (New York: George Braziller, Inc., 1961), pp. 198–233.

This simultaneity of two contradictory modes of appearance is well known in the rigorous interpretations of the meaning of quantum theory. In order to overcome contradictions such as that between wave and particle modes of appearance, it was necessary to have recourse to more pronounced abstractions. Thus, it was no longer feasible to describe the laws of quantum theory—and hence the laws of nature for that matter—in the ordinary space-time domain. Only the abstract Hilbert space was feasible for the description of the laws of nature. At this level of abstraction, there was no longer a contradiction between the two modes of appearance. But the translation of statements which belong to Hilbert space in the ordinary space-time domain always leads to some kind of strange phenomena, like the principle of uncertainty, which are difficult to cope with if such abstraction is not employed.

Nuclear warfare and arms control were the first human activities which touched upon the constraints and conditions which are imposed on us by living on our finite earth. The rational treatment of nuclear warfare and arms control leads immediately into the domain of " hypotheticality " with all its peculiarities. Nuclear warfare and arms control not only touch the finite limits of the earth; they bear very intimately on our interdependent large-scale civilisation in which there are no isolated areas for instructive trial and error.

The Formalised Debate

Many of the statements and actions of the opponents of nuclear energy are wrong and even harmful. It is by no means the purpose of this article to imply that they are right. They are not. But they have led to debate and hence some of their effects must be estimated positively. These debates have positive consequences. The regulatory interpretation of the phrase " as low as practicable " in the case of LWRs is one such positive consequence. To have aroused a more acute awareness of the potential—and hypothetical—dangers is another positive result. Such results depend upon antagonists talking to each other and listening to what the other has to say. For this to happen on a large scale is not easy. But in a democratic society it must occur on a large scale because, eventually, decisions about acceptability profoundly affect every member of society. These issues are beyond the powers of science but they are of vital concern to citizens. Dr. Alvin Weinberg has called the domain of these issues " trans-science ".[23] To facilitate a general debate on these issues a high level of formalisation appears to be necessary. Abstract and complex problems beyond human experience or the experience of everyday life must be dealt with.

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[23] Weinberg, Alvin, " Science and Trans-science ", *Minerva*, X, 2 (April 1972), pp. 209–222.

The licensing process which is required for the construction and operation of nuclear power plants in the United States has already established such a formalised debate. The necessity of taking a position under the pressure of deadlines is very conducive to hard thought. Design engineers, including myself, have tried to come to such conclusions before the formal licensing procedure by strenuous thinking and by prior consultations with the individual members of the licensing bodies. However, these methods have not been satisfactory. Only the formalised confrontation with the antagonist's arguments, when the licensing body is acting in full responsibility, permits the kind of analysis needed for a design in a particular case.

The treatment of particular cases by a formalised procedure for dealing with particular situations forces abstract considerations to take concrete form. All this imposes time-limits and enforces specificity and concreteness in analysis. The licensing process takes place in several rounds. It is an iterative process which usually produces convergence from diverse positions. This iterative process in time supplants the iterative scheme of trial and error: *Veritas est adequatio rei ad intellectum.*[24] It bridges the gap which is imposed on us by " hypotheticality ". But formalisation goes even further. It allows a great number of parties to state their case. In a formalised debate, this accentuates the iterative process. This also tends to bridge the gap of " hypotheticality ".

In this setting too, nuclear energy, by leading to this kind of a licensing process, has turned out to perform a pathfinding function. Formal licensing procedures using public hearings are now being applied to situations other than those involving nuclear energy. If in the previous paragraph on arms control it became apparent that it is the element of debate which is necessary and, further, that a stride towards more abstraction is required if one wants to meet present and future challenges, now, following the observations of this last paragraph, it seems possible to go on a step further and to identify the object of such abstraction. It is the debate itself. Procedures must be devised which permit the intangible to be made tangible. A rationale for the formalisation of the debate here envisaged must be established.[25] It appears that in this respect too nuclear energy serves as a pathfinder.

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[24] This formula and similar ones have been widely used in the history of medieval philosophy to stress things as objects of comprehension, in contrast to Thomas Aquinas' formula.

[25] To some extent this is concerned with the problem of the role of scientists as advisors. This problem has been examined in *Minerva*, X, 1 (January 1972), pp. 107–157; X, 2 (April 1972), pp. 280–294; X, 3 (July 1972), pp. 439–451; X, 4 (October 1972), pp. 603–613; XI, 1 (January 1973), pp. 95–112; and XI, 2 (April 1973), pp. 228–262.

However, the point which is developed here is not exactly the problem of scientific advice. It is rather the function of science in designing the rationale of a formalised debate. The partners in such a debate can be of many different kinds. Science is not necessarily the leading partner in this.

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