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D.A. Meneley

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Abstract
Can nuclear plants be made safe enough to be suitable for worldwide large-scale use? Can the radioactive wastes generated be safely managed over long terms? This paper addresses these questions from a vantage point within the nuclear industry. It also provides a scenario of the possible development over the next century of the Bruce nuclear energy centre on Lake Huron as an illustration of why it is worthwhile to further nuclear technology.

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Nuclear Safety in the Next Century

D.A. MENELEY

Can nuclear plants be made safe enough to be suitable for worldwide large-scale use? Can the radioactive wastes generated be safely managed over long terms? This paper addresses these questions from a vantage point within the nuclear industry. It also provides a scenario of the possible development over the next century of the Bruce nuclear energy centre on Lake Huron as an illustration of why it is worthwhile to further nuclear technology.

Est-ce que la sécurité des installations nucléaires peut être suffisamment améliorée au point de permettre d'envisager leur implantation à grande échelle au niveau de la planète? Est-ce que la gestion des déchets radioactifs générés peut rester sécuritaire à long terme? La question est envisagée d'un point de vue interne à l'industrie nucléaire. Un scénario possible de développement du centre d'énergie nucléaire de Bruce, sur le lac Huron, au cours du siècle prochain, sert aussi d'exemple pour exposer les raisons de continuer à développer la technologie nucléaire.

Dan Meneley is Vice President and Chief Engineer, AECL CANDU, Mississauga, Ontario.

Introduction

The vantage point of this paper is from about 100 years in the future. The paper represents the author's judgement of the nuclear safety situation as it might exist at that time. Prediction is a hazardous affair; I can offer only a limited justification based on personal experience. Figure 1 shows OECD electrical generation over a 15 year period. The nuclear contribution represents the output of over 300 plants (of more than 400 existing in the world). This capacity has displaced oil and contributed to meeting the large increase in demand during the period. For the purpose of this paper the graph indicates both the broad acceptance of nuclear fission as an energy source and the fact that it is a large contributor to the supply. Further, it is taken to indicate that electricity will be an important energy source in our future scenario.

At the present time, developed countries have the truly rare opportunity to incorporate a new primary energy source into use by world society. This new source is the first to be

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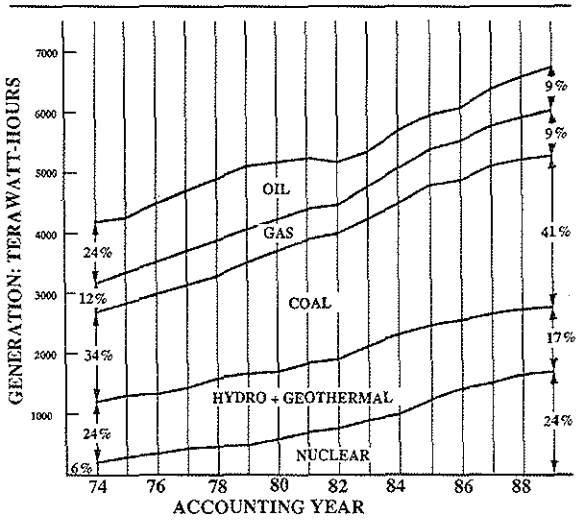

Figure 1: Electricity Usage in OECD Countries

discovered in several hundred years, remembering that coal, oil, gas, and direct solar energy have been in more or less common use for centuries. The new source is, of course, nuclear fission energy. It now produces a larger fraction of the world's energy than does hydroelectric power, and this only 50 years after the first scientific discovery of the process.

Two large questions usually are posed over this energy source. First, can the plants be made safe enough to be suitable for worldwide, large scale use; and second, can the radioactive wastes generated be safely managed over long time periods? This paper will address both of these questions.

Before these questions are discussed, I wish to present a brief picture of why the large task of introducing this technology is worth the effort required. I will do this by illustrating one logical development of the Bruce nuclear energy centre now operating near Kincardine on Lake Huron.

A Future Energy Centre

The Bruce site now consists of eight CANDU reactors of roughly 800 MWe production capacity each, arranged as two 4-unit stations called Bruce A and Bruce B. In addition, the site contains waste storage (not disposal) facilities and heavy water production. Operator training and testing facilities are provided. A large steam line supplies heat to off-site greenhouses from the Bruce A station. The site provides more than 6000 jobs for people living in the surrounding towns and villages. Essentially 100% of the equipment, facilities, and fuel for the site are produced in Canada.

Fuel for the Bruce reactors is brought by truck from manufacturing plants in Port Hope and Peterborough. Electricity is transmitted via several high-voltage lines into the provincial distribution system. Produce is shipped from greenhouses to stores around the province.

What is the future of the Bruce site? In the short term the four older (about 15 years) units will be refurbished, with new tubing in the heart of the reactor along with several other maintenance jobs. The new tubing will be of an improved type developed at Chalk River Laboratories; the new tubes will last for at least 30 years. This is part of an ongoing maintenance and upgrading program which is more or less continuous at plants of this type. Some components are replaced before they might fail, while others are tested during service so that they are certain to function if and when called upon.

Depending purely on economic factors affecting the 'repair or replace' decisions, these plants are expected to operate for at least 100 years. They will be kept in 'as new' condition until it is cheaper to replace them rather than to repair.

Waste storage facilities on the site will change slowly as some facilities are filled and new ones take over. The water-filled bays which now hold used fuel will be reserved for fuel newly discharged from the reactors; older fuel will be transferred to dry storage containers. There is space on site for several hundred years of storage. At some time within the next one or two hundred years, used fuel may be transferred to permanent storage facilities located in deep mines somewhere in the Precambrian rock of the Canadian shield.

There is a very large amount of uranium fuel in Canadian reserves. There is enough to supply all Canadian needs for at least 10,000

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years, even using the relatively inefficient energy conversion processes typical of today's nuclear plants. Fully developed methods exist for extracting nearly 100 times as much energy from each ton of uranium mined; these methods are not used now because they cannot compete economically with existing cheap natural uranium.

Existing heavy water plants have a somewhat shorter life, typically about 25 years, due to inevitable chemical corrosion. New heavy water separation technology is being developed for use in future plants. In any case, operating reactors need only a very small heavy water makeup supply. This supply can be manufactured in Canada or purchased on the world market.

As reactors and plant equipment wear out they can be replaced, and eventually the whole plant can be dismantled and replaced. All components and structures can be disposed of as required by their level of radioactive contamination. A new electricity generating plant might use similar or completely new technology. If we assume that a similar technology is used we can construct a scenario of a generating system which could deliver about 11,000 MW of electrical energy for at least 10,000 years, beginning 50 to 100 years from today.

Such a system is outlined in Figure 2; the dashed lines indicate those parts of the system which do not exist in 1992. This futuristic energy centre consists of about twelve advanced CANDU reactors operating on slightly enriched fuel and one "fuel factory" in the form of a metal fuelled fast reactor whose main role is conversion of U238 to Pu239 for use in the CANDU's. All of the reactors are capable of burning excess actinide materials (heavy elements), thereby removing them from the long-term waste management stream. Excess heat from all units is used in agricultural and industrial processes.

Pyrometallurgical processing is used for recycling used fuel to on-site fabrication plants, so that the only significant waste stream is relatively short-lived fission products. Following storage, these products are vitrified and disposed of in deep drill holes directly under the site.

The site is nearly self-contained; only natural uranium is delivered on-site and only electricity (capacity output: 11,600 MWe) and reject heat are transported off the site. Process heat and low-temperature condenser cooling water are the most important forms of reject heat.

This system can be operated for an indefinitely long period, subject only to economic competitiveness with other available technology. About 200 such energy centres located in the OECD countries could supply 100% of these countries' present electricity demands, for at least the next millennium and probably one hundred times as long.

Safety of the Energy Centre

Thermal fission reactors have only two essential parts - fuel and moderator. These components are arranged to produce a self-sustaining chain reaction. The chain reaction releases heat energy, which is the *raison d'être* of a power reactor. Heat is used to boil water into steam. The steam is sent to an ordinary turbine connected to an electrical generator. Electricity flows through wires to industries and homes.

Electricity flow must be steady; since electricity cannot be stored this means that the generator, turbine, and reactor also must produce a steady flow of energy. The reactor must be controlled, fuelled and maintained steadily. Waste emissions must be contained and wastes must be packaged for storage and disposal. It is useful to compare the processes which take place inside a nuclear reactor with their equivalent in a more familiar system — a coal-fired power plant.

In a coal-fired furnace coal is burned with oxygen as shown in the left-hand side of Figure 3. As the chemical bonds of complex hydrocarbons that make up the coal are broken, energy is released. More energy is released in combustion than is required to break the chemical bonds. Of the total combustion energy some is lost: either through the walls of the furnace or via the smokestack along with the waste products. Some energy is used to break

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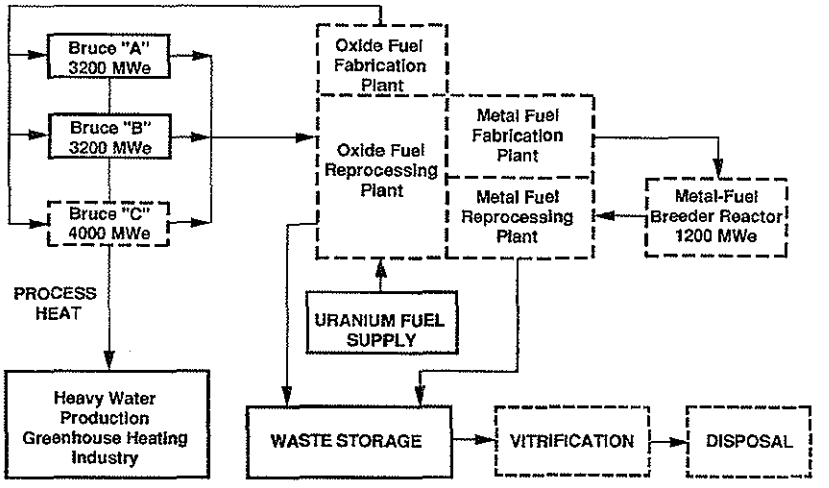

Figure 2: Example of a Possible "Energy Centre" Developed at the Bruce Nuclear Generating Station on Lake Huron

further chemical bonds; the majority is used to boil water, make steam, and so to spin the electrical generator. Wastes are emitted continuously in the form of gases and solids.

The combustion rate in a coal furnace is controlled by regulating the amount of oxygen and fuel supplied to the system. The temperature limit of the furnace is set by the energy levels of combustion products, flame dynamics, and radiative losses. Temperature is strictly limited to a maximum value called the "flame temperature."

The process schematic diagram of a nuclear reactor is shown in the right hand side of Figure 3. Neutrons entering uranium nuclei break the nuclear bonds; energy is released. Excess neutrons produced in the reaction are recycled to induce more fission reactions. Some neutrons are released via leakage or absorption. Heat flows to the turbine and to the lake as before. Vanishingly small amounts of waste are released from the nuclear power plant in normal operation; used fuel is removed periodically for storage so that it can be replaced by fresh fuel. All wastes from fission are contained in the fuel.

Reactor heat production is controlled by adjusting the number of neutrons, and therefore the fission rate. There is no theoretical maximum temperature; in reality the temperature is limited by the maximum amount of heat which can be removed from the reactor. If this limit were exceeded the reactor would heat up steadily and eventually would collapse. Radioactive fission products would be released from the fuel when it reached a high temperature. Prevention of fuel overheating and mitigation of its effects if it occurs are the essence of the discipline of reactor safety engineering.

In summary, a nuclear reactor produces essentially no waste during operation except for used fuel, which is discharged periodically to safe storage.

Engineered Safety Systems

Given the fact that fission products are located in the fuel, the essentials of safety will be achieved if the fuel can be kept cool at all times. Engineers design and install reactor control systems, shutdown systems, and emergency heat removal systems for this purpose. High reliability and proven effectiveness are demanded. These systems *prevent* the release of radioactive materials from the fuel.

In case the shutdown and cooling systems do not work perfectly, reactor systems are surrounded by containment systems, and the public is separated from the plant by an isola-

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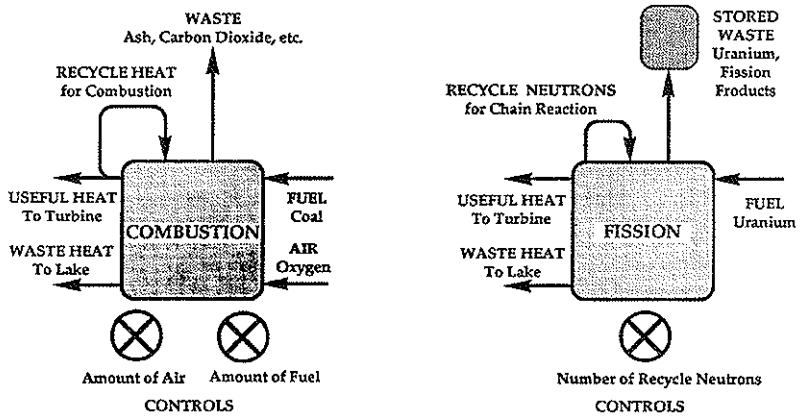

Figure 3: Coal Combustion Processes Compared with Nuclear Fission for Boiling Water

tion zone. These systems *mitigate* the health consequences if radioactive materials are released from the fuel.

Diversity, redundancy, and independence of systems are built into the design so that inadvertent failure of one system during the progress of an accident does not result in consequential failure of some other system. The whole network of preventive and mitigative systems is arranged to achieve defence in depth against damage to human health, as shown schematically in Figure 4.

The achievement of public safety in the world's civilian nuclear industry up to 1992 is remarkably good even when the disastrous Chernobyl-4 accident in the USSR in 1986 is included in the statistics, considering that this is a very young technology. Without counting Chernobyl-4, over 5000 power plant years have been accumulated to date around the world in the complete absence of public or worker injuries or deaths due to radiation. Many minor accidents do happen each year; these can be used to monitor individual safety systems' performance and reliability.

The Human Element

Recent experience in modern nuclear stations indicates that at least half of the accidents which occur are directly due to human failure. This might be expected in a system where continuous improvement has been made in all types of equipment over the last forty years; at some level, the error rate of human operators begins to dominate. Increased training, better procedures, and so on can be used to improve operators' performance but there is apparently a limit to which training can improve performance.

In the future, I expect to see a progressively higher level of automation in plant designs, so that the operator's job becomes more and more one of plant monitoring and overseeing of the operation of automatic systems. At the same time, operator aids will be used more and more to guide those operating decisions which must be made with the help of human intellect.

Limits to Safety

The safety demands stated either explicitly or implicitly in government regulations have become more and more stringent over the past quarter century, to the point where the highest allowable individual life risk per year is lower than the life risk due to electrical storms. If this low risk level is actually achieved in operation, it represents a considerably higher safety level than most other human activities.

Intuitively, though, there must be a limit beyond which safety of a given activity cannot be improved at any feasible cost; if such a level is reached then that industry goes out of busi-

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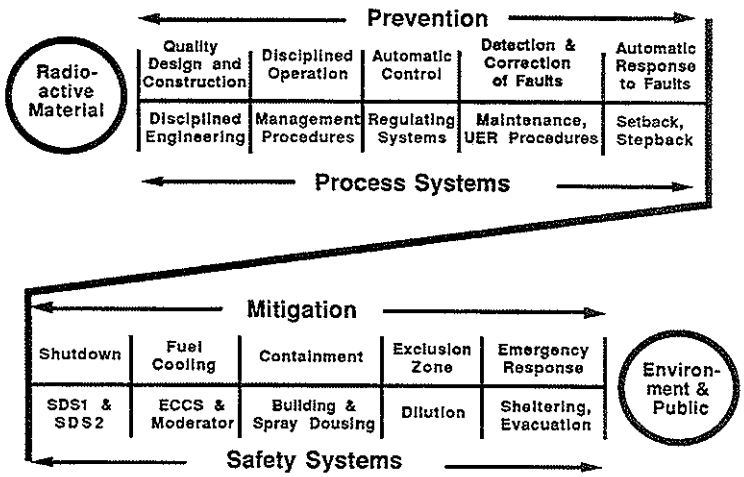

Figure 4: Defence-in-Depth Safety Principle as Applied to CANDU Nuclear Power Plant Design and Operation

ness. Since "safety" becomes a subjective judgement rather than an actuarial figure at very low levels of risk, the nuclear power industry itself is now at risk of being put out of business through various types of political action.

Passive Safety

One idea for improving plant safety performance is to design systems which include so-called "passive" protection systems instead of the much more common "active" systems. In this context, the term passive refers to a system which converts an unsafe failure to a safe failure without any intervention; it must be a truly automatic system. One example is a free-convection heat removal system at the outer surface of a metal containment structure; it works whenever the structure is warm (that is, when heat removal is necessary), requires no initiation signal, and is demonstrably reliable.

Such passive systems have been proposed in partial solution to the public acceptance issue. The logic goes that these systems are so clearly and simply reliable that anyone can understand and accept them as safe. Unfortunately they have proven to be extraordinarily difficult to design within reasonable limits of cost. The plant design simply becomes too expensive and is, therefore, not ordered by any utility customer.

A reasonable resolution of this dilemma appears to be systems which maximize reliability and testability within the bounds of manageable cost.

Radioactive Waste

The second most-often-stated concern with the nuclear industry is the disposal of used fuel, miscellaneous waste, and active components from decommissioned plants. The view from inside the industry is that this is a completely manageable problem for which technical solutions already exist. The basic reason for this is the small volume of this waste compared with the energy which can be extracted from the fuel; that is, one can do a very thorough waste management and disposal job without adding significantly to the cost of electricity.

This non-problem is a public acceptance problem of considerable magnitude. Many disposal projects around the world have been stopped through intervention of one kind or the other. The best solution is to plan for slow progress with a great deal of public comment at each stage. It is very unlikely that a new technical solution will make much difference to public acceptance.

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Future Improvements

Figure 5 shows a judgemental list of the most important ways to improve nuclear reactor safety in the future. In addition to the items shown, it might be useful to investigate introduction of new working fluids to both the primary and secondary heat transport circuits. The objective in this case would be to decrease operating pressures, to improve reactor accident characteristics, and reduce plant cost.

Selectively increasing automation of plant operation effectively simplifies the operator's job; he then can spend most of the time monitoring the plant operation to be sure that the systems are operating correctly.

- SELECTIVELY INCREASE AUTOMATION OF PLANT SYSTEMS AND IMPROVE OPERATOR INFORMATION DISPLAYS
- IMPROVE COMMUNICATIONS BETWEEN NUCLEAR OPERATING STAFFS WORLDWIDE
- STRENGTHENING TECHNICAL SUPPORT TO OPERATIONS FOR MAINTENANCE AND INSPECTION ACTIVITIES
- USE OPERATING EXPERIENCE RECORDS TO IDENTIFY AND ELIMINATE UNRELIABLE COMPONENTS
- INCREASE USE OF PASSIVE SAFETY CONCEPTS
- USE OF NEW WORKING FLUIDS IN PRIMARY AND SECONDARY CIRCUITS

Figure 5: Some Potential Improvements in Nuclear Design and Operation

Summary

Nuclear fission energy has the potential of providing a large part of human energy needs over a long time into the future.

There is no doubt that the technical and public safety aspects of nuclear energy use are amenable to reasonable solutions. The public acceptance aspect is not, however, in order at present. More time is needed for the industry to demonstrate that this is an acceptable large-scale energy source.

A recent paper by J. Chernilin of the Kurchatov Institute in Moscow clearly states the problem:

> Strictly speaking there is no contradiction between safety and economics. The risk of an accident has its monetary expression, and an unsafe plant can never be economically viable if correctly assessed. In other words, the only way to use the advantages of nuclear power is to ensure a negligible probability of accidents at a nuclear power plant and to convince the public that it has been ensured. Both sides of the matter are equally important. There is no use to raise safety if no one believes in it, and if safety is not proven to be satisfactory there is no ground for arguing in favour of nuclear power development.

The first job, now that the nuclear industry has reached technical maturity in many parts of the world, is to convince the people that the plants are good neighbours in every sense of the word. This probably will be a long process, most likely of the order of a generation or two. The requirements are really quite simple. The industry must operate about five hundred power plants safely and economically without serious accidents for about fifty years.

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