COSTS AND BENEFITS OF NUCLEAR POWER*

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NUCLEAR POWER, COST-BENEFIT ANALYSIS

The National Environmental Policy Act of 1969⁽¹⁾ (NEPA) compels all federal agencies to take environmental effects into account in each of their actions. This law is far more comprehensive than its title and short text might imply. A court interpretation, the Calvert Cliffs Decision,⁽²⁾ placed very broad requirements on the federal agencies in their implementation of NEPA. Included is the requirement for a cost-benefit analysis--not only for the action proposed--but also for appropriate alternatives thereto. The cost-benefit analysis must consider all environmental effects--a generality that can be construed to cover just about everything.

Basically, the cost-benefit analysis, that is required, amounts to a quantitative comparison of apples with oranges. For example, it seeks to incorporate in a single equation such diverse impacts as: strip mining of coal, emissions of SO₂, management of radioactive wastes, etc. Types of costs that must be considered are economics, land use, ecological damage, consumption of non-renewable resources, effects on public health, risks to the public safety, effects on historical and archeological sites, aesthetics. These must be balanced against the values to society of the derived products, employment opportunities, and advantages over alternative actions. Nobody knows how to quantify such diverse factors to a common base; however, a lot of people are being forced to try.

The licensing actions of the AEC are embraced by NEPA. Much of the litigation originating from NEPA has focused on the licensing of nuclear power stations, e.g., the Calvert Cliffs Decision.

An applicant for a nuclear power plant construction permit must expend some 40 to 80 man years of highly skilled engineering-type personnel to prepare the report required by NEPA.⁽³⁾ In addition, the AEC regulatory staff must make an independent assessment requiring several man years. Finally, the Atomic Safety and Licensing Board once again must independently weigh the costs and benefits. Hopefully at the end of this process the licensing decision will be much wiser than past decisions which were more dependent on the intelligent judgment and common sense of the men sitting on the Board. Perhaps this is one more giant step toward substituting computers for human intelligence.

Of course, the nuclear industry is not the only one affected by NEPA. Perhaps some of you work for companies that have encountered this Act. I suppose in time most businesses and industries will be affected one way or another. If you should suddenly feel the hot breath of NEPA on the back of your neck, you might want to refer to some of the AEC Licensing Dockets for guidance, particularly on traps to avoid.

If you ask the average man on the street what he thinks of NEPA, he would probably say its just great--long overdue (assuming he had ever heard of NEPA). Of course it is important for average Mr. Public to keep in mind that he will have to pay for actions taken as a consequence of NEPA. He will want to get his money's worth--spend his environmental dollar wisely. Perhaps he will want to do his own cost-benefit analysis.

This brings us to an interesting question: Who defends the interest of the Public in these matters? On one hand, we have agency officials and staff who have been designated by acts of congress to bear certain responsibilities--presumably to impartially defend the

interests of the public. On the other hand, are many citizens action groups, who frequently claim that they are protecting the interests of the public. Often these groups accuse the government agencies of prostitution. No doubt there are many cases in our history where this accusation has been justified. Of course, there have also been times when the dedicated, honest bureaucrat has been maligned.

PUBLIC OPPOSITION TO NUCLEAR ENERGY

During the past several years the Atomic Energy Commission has been under fire from many different citizens organizations. The Atomic Energy Act of 1954⁽⁴⁾ and various amendments charged the AEC with the responsibility for regulating the peaceful applications of atomic energy. It was also charged with the task of the development of atomic energy so as to "improve the general welfare, increase the standard of living and strengthen free competition in private enterprise."

Many of the critics contend that the AEC has fulfilled its developmental role better than its regulatory duties. They contend that the present rapid expansion of commercial nuclear power in the U.S. is the result of AEC promotional efforts and that the public is having nuclear power rammed down its throat against its will.

Most organizations identified with the environmental movement have adopted anti-nuclear platforms, and many organizations were formed for the exclusive purpose of combating nuclear "pollution." Thus, commercial nuclear power has become the number one target of "public opposition." It is difficult to judge how many citizens are actively involved in this campaign. The total membership of these groups numbers, perhaps, in the range of several hundred thousands. However, it appears

to me that only a few hundred people have been deeply involved, and are providing most of the initiative and ammunition. Of course, this is a popular subject with reporters.

THE NUCLEAR RECORD TO DATE

Perhaps it is worthwhile to take a moment to examine the present status of commercial nuclear power and the record to date. Strange though it may seem, the AEC has, in fact, been somewhat successful in meeting its several responsibilities as set forth by congress.

In regard to regulation, there have been no incidents at nuclear plants that have killed or injured the public. There have been no nuclear-related accidents that have killed or injured nuclear plant employees. I know of 2 employee deaths from a steam-vent malfunction which occurred while a nuclear plant was shutdown for maintenance. The insurance industry seems to be favorably impressed by this record. They continue to increase their share in the Price-Anderson insurance pool,⁽⁵⁾ and one of their officers has suggested that other industries could profit by emulating the nuclear safety programs.⁽⁶⁾ The world experience with commercial nuclear power is about 800-operating-years of which about 25% is with U.S. built reactors.

As far as the AEC's charge to "improve the general welfare, increase the standard of living," it is still too soon for large-scale benefits to have been realized. Last year the nuclear share of the gross energy input of the U.S. was about 0.6% of the total. This is about half as much as we derived from burning wood (see Table I). It is important to note, however, that the nuclear share is increasing

extremely rapidly, the rate increase being almost 100% per year right now. At the end of last year there were about 21 plants in operation. I say "about" because it depends on which plants you include in the census. Some of the earlier plants were demonstration projects and perhaps should not be counted. In 1972, about 12 new plants will start operation. Another 117 are under construction or ordered.

I think it is correct to state that the vast majority of these projects were undertaken as a result of initiative of the utility assisted by the persuasive salesmanship of the reactor vendors. They are not the result of AEC promotional efforts. It seems to me that the AEC has achieved great success in satisfying its statutory responsibility to "strengthen free competition in private enterprise" --at least in the light-water reactor field.

The situation is somewhat different in the case of the breeder reactor. This project is just approaching the demonstration stage, and the AEC has been vigorously promoting the first LMFBR. This promotional effort is in compliance with the President's Energy Message to Congress of June 1971 in which the LMFBR was identified as an important national goal.

EVALUATION OF COSTS-BENEFITS

The Costs-Benefits evaluation of most interest are comparisons between alternative actions or systems, e.g., nuclear vs. coal- or oil-fired steam plants.

Zero or Limited Growth: One alternative is to constrain the growth of electrical generating capacity, rather than attempt to satisfy the increasing demand. Many people urge "zero-growth" as an immediate goal.

It should be obvious to anyone who has examined the data on energy usage--resources, effluents, rate of use, and rate of growth--that we cannot continue much longer in our present pattern. If we do not take positive action to level off consumption, natural forces will do it for us--probably in a less desirable manner. In my opinion, one of our most urgent problems is to develop a wise and broad national policy which will reduce the rate of growth of energy consumption without causing the economy to collapse.

It seems to me that any attempt to limit growth or to achieve "zero" growth must be based on a rational consideration of the entire energy system and not on a few parts of the system. It is likely that such a policy would seek to encourage the exploitation of certain resources and discourage the use of others. Therefore, I do not think that "zero" growth should be considered as an alternative in evaluating costs-benefits in the limited context of individual power plants.

Basis for Comparing Alternatives: Let us briefly enumerate the factors that should be compared in deciding between a nuclear plant or its alternatives coal or oil. (Because of limited supply, natural gas is not a viable alternative.) The most important factors seem to me to be (1) resource base (including conservation), (2) public health effects, and (3) risk of accident. Of lesser importance are: (4) economics, (5) damage to land from extraction of fuel, (6) land use, (7) pollution from processing and transportation, (8) water pollution, (9) waste heat disposal, (10) effects of air pollution other than health effects, and (11) waste disposal.

There isn't enough time for me to cover all of these subjects in detail, so I will discuss only the few that are causing the most

public controversy. In making my comparisons, I will refer to a nominal 1000 MWe plant using technology that is readily available today. The basic characteristics of these are listed in Table II.

Presumably the primary benefit to society is the electricity produced. Using the 1971 national average purchase price, 1.69¢/kWh, society perceives the annual value of the product of the plant as \$96 million. What benefits society actually derived from the use of this electricity is a subject which I will skip.

WASTE HEAT

All these plants reject waste heat. The efficiencies listed for the coal- and oil-fired plants are the average of the ten best units in the country as of 1969. The nuclear efficiency is typical of modern LWR's. The damage from waste heat depends strongly on local conditions. I know of no successful attempts to place a dollar value on such damage.

RESOURCE BASE

Coal: The United States is blessed with abundant deposits of coal. Our present production rate is about 570 million tons per year⁽⁸⁾ of which about half is strip mined. The cumulative production through 1970 was about 40 billion tons.⁽⁹⁾ Estimated remaining recoverable resources are about 1600 billion tons of which 118 billion tons are strippable.^(9,10) We could, if necessary, convert almost entirely to a coal economy but to do so would require a five- or six-fold increase in production which would exact a fearful environmental toll. If coal production were to be substantially increased, new incentives would be required to attract the necessary capital for expansion of production, processing, and transportation

facilities. Also, something would have to be done to attract a much larger labor force.

Most of our low-sulfur coal is in the west, remote from the large markets, and adequate transportation systems do not exist to move this coal to where it is needed. Good technology for removing sulfur from coal does not exist, but some methods are under development.

Petroleum: Our domestic production of petroleum in 1971 was 3.256 billion barrels, a slight decrease from 1970.⁽¹¹⁾ The cumulative production through 1971 was 96.5 billion barrels and the remaining ultimate recovery was 134 billion barrels as estimated by the American Petroleum Institute.⁽¹¹⁾ Dr. M. King Hubbert of the U.S. Geological Survey considers the latter estimate too large.⁽¹²⁾ Last year we imported almost 40% of the petroleum that we consumed.⁽⁸⁾ Of the residual oil used to generate electricity in the northeastern U.S. more than 90% is being imported at the present time.⁽¹³⁾ Estimates of the National Petroleum Council indicate that our dependence on foreign oil will increase rapidly.⁽¹⁴⁾ Although most of our imported oil now comes from Canada and Venezuela, we will become increasingly dependent on Africa and the Middle East. Such dependence has two ominous features: The political unrest in the Middle East will have undesirable influence on our foreign policy, and our balance of payments will be seriously eroded.

Uranium: The AEC makes an annual estimate of domestic uranium resources for various cost ranges from \$6 to > \$200/lb U_3O_8 . The latest estimates show reasonably assured and potential resources of approximately one million tons of U_3O_8 at \$10/lb or less, and more than seventeen million tons at \$100/lb or less.⁽¹⁵⁾ The assured reserves of low-cost uranium have

doubled since 1965 despite the fact that there has been little economic incentive for new exploration. It is reasonable to anticipate that further discoveries lie in the future and that the total resource base is much larger than the present conservative estimates.

Projections for commercial nuclear power requirements indicate that 463,700 tons of U_3O_8 will be required by 1985 at which time the annual demand will be 66,600 tons (and rising). Exports from the U.S. will almost double this estimate. The total demand, domestic and export, is estimated at ~907,000 tons through 1985.

It is often pointed out that the contemporary light-water-moderated reactor uses only ~1% of the energy potential in uranium. These reactors run primarily on the ^{235}U in fuel; however, for each ^{235}U atom consumed about half an atom of ^{239}Pu is produced (i.e., the LWR conversion ratio ≈ 0.55). High temperature gas-cooled reactors make somewhat more efficient use of the fuel, producing about 3/4 of an atom of ^{239}Pu (or ^{233}U) for each fissile atom consumed (i.e., the HTGR conversion ratio ≈ 0.75). Of course, the ^{238}U (or ^{232}Th) which is not consumed will not be wasted. It will remain available for future use as fertile material for a breeder reactor.

The breeder reactor converts ^{238}U (non-fissile) into ^{239}Pu (fissile) at a rate such that more ^{239}Pu is produced from the fertile material than is consumed as fuel (i.e., the conversion ratio > 1.0). The liquid metal cooled fast breeder reactor (LMFBR) is expected to extract 70 to 75% of the total energy potential of the uranium entering the fuel cycle.

If breeder reactor development falls several years behind present target dates, the cost of uranium feedstock for LWR's will increase

as the cheaper uranium is consumed. However, this will have little effect on the cost of nuclear electricity because the cost of uranium contributes very little to the total; e.g., if the price of U_3O_8 feedstock rises by a factor of ten (from \$8/lb to \$80/lb) the cost of producing electricity in an LWR would rise by only ~10%.

If breeder reactors can be developed, the cost of electricity becomes almost independent of the price of uranium or thorium feedstock. In such a case, the resource base of uranium and thorium ores exist in large enough quantities to meet the entire energy needs of the human race for several centuries. (16)

Cost-Benefits of Domestic Resource Base: In summary either coal or nuclear energy can be based on domestic resources for the foreseeable future, whereas an oil economy must be largely based on foreign resources. I do not know how to place a dollar value on these factors, other than listing the differential costs of the imported oil. This, of course, neglects the risks of international conflict posed by heavy dependence on imports.

Extraction Costs: Comparison of societal costs of mining for a 1000 MWe coal-fired and a nuclear plant include the land defaced, and the human toll from accidents to miners. The quantities of ore and fuel which must be extracted are listed in Table III.

The nuclear plant requires about 90,000 tons of ore per year as fuel-cycle feedstock, whereas the coal plant requires more than two million tons. In both cases surface mining and underground mining contribute about equally. I have no good estimate of the dollar cost of land damage. If we assume the damage is proportional to the tonnage extracted, then the 1000 MW coal plant is ~20 times as destructive. I have not attempted

to compare land abuse from petroleum extraction. It is interesting to note that an average of ~1400 oil wells are needed to supply our nominal 1000 MWe power plant.

Mining is a hazardous occupation. Although it seems somewhat callous to attempt to evaluate the cost of injuries and fatalities in terms of dollar values, there is probably no better method at the present time. Dr. Leonard Sagan has recently attempted such an evaluation in an article in Science.⁽¹⁷⁾ I shall adopt his values, i.e., the cost of an injury at \$100/day including medical expenses, and \$300,000 for a fatal accident. The share of the nominal 1000 MWe plants of mining injuries and fatalities are estimated in Table III.

Miners are subject to occupational diseases, particularly lung diseases. Only 29 uranium miners are needed to supply fuel for a nuclear plant, whereas 480 are needed for an equivalent coal-fired plant. Because of the small number of miners required to supply uranium, the cost in lung cancer is only 0.0154 cases per year. If we assume that lung cancer costs the same as a fatal accident the annual cost is \$4620 for the nuclear plant. Black lung disease is a common affliction among underground coal miners. At the end of 1971, federal disbursements for black lung disability was running \$336 million annually, with ~150,000 miners or their widows receiving compensation. An additional 163,000 miners had applied for compensation but were denied.⁽¹⁸⁾ A 1000 MWe coal plant would have an estimated \$1.176 million share of the federal compensation, and about 120 new cases of black lung disease each year. The compensation listed is only \$2107 per case. The cost estimates I have cited are very rough and undoubtedly will change as analysis becomes more precise.

GASEOUS EMISSIONS

Fossil-Fueled Plants: Health effects from air pollution are not well understood. Most mortality and morbidity data relate to episodes in which a large number of fatalities occur among the aged and chronically ill, following a period of high pollution. One study suggests that the death rate from acute respiratory disease increases linearly with SO_2 concentration. (19)

A further difficulty in evaluating the impact of fossil-fueled plants is to derive a population dose from known stack emissions, weather conditions and population distributions. Obviously, such evaluations are needed for comparison with the nuclear emissions.

Nuclear Plants: The radiation doses to population surrounding nuclear plants have been under intense surveillance by several federal and state agencies. Radiation doses are measured in terms of the unit, rem, which corresponds to a deposit of 100 ergs of energy per gram of tissue for electromagnetic radiation. Doses from other forms of radiation can be converted into the rem by a multiplication factor determined experimentally. A full description of the dose must specify the parts of the body exposed, e.g., whole body, skin, lungs, thyroid, etc.

Everyone is exposed to natural background radiation, from natural radioactive atoms in the body, radioactive minerals in the soil, water and air, and cosmic radiation. Natural background varies with geographical location and elevation. The average natural radiation dose rate in the United States is about 130 mrem/yr (1 mrem = 1/1000 rem). (20) The dose rates range from ~70 to ~225 mrem/yr being lowest in sandy beach areas (Long Island) and highest in the Colorado plateau.

For very low exposure rates, such a natural background, it is convenient to express the population dose in terms of "man-rem" which is the sum of the individual doses over the population. For example, if ten people are exposed to 100 mrem, the dose for that population would be 1 man-rem. The population dose for the U.S. population of 205 million people exposed to the average natural background is $206 \times 10^6 \times 0.130 = 26.6 \times 10^6$ man-rem.

A recent evaluation by the EPA indicates that the U.S. population dose in 1970 from commercial nuclear power was 430 man-rem. These data are summarized in Table IV. The population dose for the more modern nuclear plants runs about 4 man-rem per plant.

The biological costs of radiation are probably better understood than any other pollutant in our environment. Various estimates of the cost per man-rem range from \$5 to \$500.⁽¹⁷⁾ Sagan has derived a value of \$30 which I shall arbitrarily adopt. Using this number we estimate the biological cost due to gaseous radioactive emission from a modern nuclear plant as approximately \$120.

Radiation from fuel reprocessing, transportation and storage of wastes will not double this cost.

When occupational exposures are taken into account for employees in the power station and fuel reprocessing plants an additional dose of ~240 man-rem must be added and a cost of ~\$7200 per year.

The doses from liquid emissions taking into account food chains and other pathways to man are found to be negligible.⁽²⁰⁾

Cost-Benefits of Decreasing Reactor Emissions: Because of public concern about the hazards of radioactivity many utilities have added additional

waste treatment facilities to reduce radioactive emissions. Of course, the extra costs of such equipment will be paid for by the consumer. An examination of the costs-benefits indicate that such expenditures are unwise.

As an example, consider the case of one proposed power plant. The estimated population dose rate based on the original design was 12 man-rem/s per year (cost ~\$360/year). Addition of a \$1 to 2 million dollar filter system reduced the design dose of 4 man-rem/s. Thus the cost of dose reduction will be \$125,000 to \$250,000 per man-rem. It can be seen from Table IV that the largest man-made radiation burden is from medical x-rays. It has been estimated that the costs of modifying x-ray equipment to reduce dose without compromising on the quality is about \$7 per man-rem.⁽²¹⁾ I suggest that these numbers indicate that we could invest the public money more wisely if we acted on a rational basis.

RISKS FROM ACCIDENTS

Much of the public concern about nuclear power stems from fear of a major accident that might release massive quantities of radioactivity. For the past nine months the AEC has been holding public hearings in Washington on whether or not their regulations concerning emergency core cooling systems are adequate. The news reports on these hearings have been frightening (e.g., see the "News and Comments" series by R. Gillette in recent issues of Science⁽²²⁾). These hearings concern the type of failure that is expected to occur with a likelihood in the range of 10^{-5} to 10^{-6} per reactor-year.

A recent report from UCLA⁽²³⁾ concludes that: "The public health risk due to accidental releases from either a nuclear- or oil-fired plant are both of the same magnitude, and about one hundred thousand times smaller than the risk from routine operation of the plants," and "The maximum hypothetical accidents associated with either plant type are not likely to be sufficiently large to have a significant public health impact when compared with the normal incident of disease." The report and its appendices present the analysis used in reaching these conclusions.

"Realistic" analyses of population doses from all credible accidents are a part of the AEC Regulatory environmental statement required by NEPA for each proposed power plant. The results from one such case are attached (Table 7.2).⁽²⁴⁾ As you can see the AEC Regulatory Staff evaluation indicates quite small population exposures from all accidents.

This brings us to an interesting question. Why is there such a disparity in the evaluation of risks associated with nuclear power? On the one hand, many critics perceive a very high risk--many suggest that we abandon nuclear power completely. On the other hand, "the Establishment"--the AEC Regulatory Staff, reactor vendors, utility engineers, university nuclear engineering departments--conclude that the risk is insignificant. Is it possible, as is often suggested by the critics, that "the Establishment" in its enthusiasm is guilty of over-optimism by a factor of a million or more?

There is not much that can be said in the limited time that will convince anyone either way. Some discussions of ECCS controversy appears in Appendix A, which is intended to illustrate the nature of the

arguments but cannot adequately discuss the merits of the complex technical questions. (See Appendix A.)

There are still many safety questions to answer. The engineer, the scientist always wants more data. Personally, I am satisfied that the lack of data at this stage does not compromise the public safety. Much of the information needed is of the nature that will enable costs to be reduced. Reactor safety systems are probably extremely over-designed and as more detailed knowledge is acquired, superfluous safety features can be estimated. As time passes, we will be able to assess the risks more accurately.

MEASURES OF DOUBTFUL VALUE

Because of the widespread public concern, utilities are being forced to incur enormous costs of doubtful value to society. Many of these measures need more careful scrutiny before they are implemented. As an example, many new power stations are incorporating cooling towers as a result of public pressure. The capital costs and the increased costs of producing electricity amount to hundreds of millions of dollars. In some localities such towers are probably needed, but in many cases it appears that the towers will be a disservice to the local environment.

Several utilities are turning to offshore plants as a solution to the siting problem. The incremental cost of offshore siting is staggering. Does society really benefit from offshore siting? Also, many proposals have been made for underground construction. The safety advantages are dubious and the costs are high. These are but a few of the increasing costs penalties to which nuclear power is being subjected.

CONCLUSION

The resources of our society are not infinite. It is important that we invest these wisely to meet the critical needs of society. It is possible that NEPA has created one instrument which will assist in reaching wise decisions. It will take a while to see how useful the effort will be. As you can gather from what I have covered, the Cost-Benefit Analysis required by NEPA is still in the primitive stages of development.

In the case of nuclear power, I think NEPA has already begun to clarify some of the issues by requiring information to be assembled in a useful form. Of course, the NEPA routine cannot solve disagreement over the technical validity of certain information, e.g., as in the area of accident assessment, much remains to be done. Judging from the present sentiment of the public I think it is unlikely that the NEPA Environmental Reports will become routine and stereotyped until the hard questions are adequately answered in a manner which the public can understand.

TABLE I
1971 U.S. ENERGY CONSUMPTION^(a)

<u>Energy source</u>	<u>Consumption (10¹⁵ Btu)</u>	<u>Percent</u>
Coal	12.560	18.2
Petroleum (Crude oil)	27.940	40.5
Natural Gas (Liquids)	2.552	3.7
Natural Gas (Dry)	22.734	32.9
Hydropower ^(b)	2.833	4.1
Nuclear ^(c)	0.391	0.57
Wood ^(d)	<u>(~0.8)</u>	--
TOTAL	69.010	

(a) Data taken from Ref. 8.

(b) Theoretical input computed at 10,494 Btu/kWh.

(c) Nuclear fission heat input computed at 10,660 Btu/kWh.

(d) Estimate of energy derived from wood used as fuel.

TABLE II

Characteristics of 1000 Mw Steam Electric Plants, a
65% Plant Factor is Assumed.

	<u>Nuclear</u>	<u>Oil</u>	<u>Coal</u>
Heat rate (Btu/kWh)	10,342	9319	8838
Net efficiency	0.330	0.366	0.386
Waste heat (MW)	2030	1732	1591
Total fuel/year (tons)	60	1.4×10^6	2.0×10^6

BENEFITS

Electricity produced (kWh) 5.7×10^9
 Retail value (@ 1.69¢/kWh) $\$96 \times 10^6$

TABLE III

Costs of Extraction of Year's Supply of Fuel

	<u>Nuclear</u>	<u>Oil</u>	<u>Coal</u>
Quantity extracted (tons)	9×10^4 (ore)	1.4×10^6	2×10^6
Source dependence	domestic	40% imported	domestic
Foreign exchange	---	$\$9 \times 10^6$	---
<u>HUMAN COSTS</u>			
Number of miners	29		480
Injuries and fatalities	\$46,000	---	\$716,000
Occupational disease	\$ 4,620	---	$\$1.2 \times 10^6$

TABLE IV

Estimate of U.S. Population Radiation Dose
(Source: EPA)

Doses in million man-rem per year

	<u>1970</u>	<u>2000</u>
Natural Background	26.6 (63.0%)	41.7 (62.7%)
Medical X-Rays	14.8 (35.1%)	23.1 (34.7%)
Weapons Tests	0.8 (2.0%)	1.6 (2.4%)
Nuclear Power	<u>0.004 (0.01%)</u>	<u>0.14 (0.2%)</u>
TOTALS	42.2	66.5
U.S. Population (millions)	205	321
World Nuclear Capacity (GWe)	20	2000

TABLE 7.2

SUMMARY OF RADIOLOGICAL CONSEQUENCES OF POSTULATED ACCIDENTS

DETERMINED BY THE A.E.C.

<u>Class</u>	<u>Event</u>	<u>Estimated Fraction of 10 CFR Part 20 Limit of Site Boundary^{1/}</u>	<u>Estimated Dose to Population in 50 mile Radius, man-rem</u>
1.0	Trivial incidents	<u>2/</u>	<u>2/</u>
2.0	Small releases out- side containment	<u>2/</u>	<u>2/</u>
3.0	Radwaste system failures		
3.1	Equipment leakage or malfunction	0.44	29
3.2	Release of waste gas storage tank contents	1.8	120
3.3	Release of liquid waste storage tank contents	0.002	0.1
4.0	Fission products to primary system (BWR)		
4.1	Fuel cladding defects	<u>2/</u>	<u>2/</u>
4.2	Off-design transients that induce fuel failures above those expected	0.018	3.0
5.0	Fission products to primary and secondary systems (PWR)	N.A.	N.A.
6.0	Refueling accidents		
6.1	Fuel bundle drop	0.009	0.62
6.2	Heavy object drop onto fuel in core	0.077	5.1

TABLE 7.2 (continued)

<u>Class</u>	<u>Event</u>	<u>Estimated Fraction of 10 CFR Part 20 Limit of Site Boundary^{1/}</u>	<u>Estimated Dose to Population in 50 mile Radius, man-rem</u>
7.0	Spent fuel handling accident		
7.1	Fuel assembly drop in fuel storage pool	0.017	1.1
7.2	Heavy object drop onto fuel rack	0.031	2.1
7.3	Fuel cask drop	0.66	43
8.0	Accident initiation events considered in design basis evaluation in the safety analysis report		
8.1	Loss-of-coolant accidents		
	Small break	<.001	<0.1
	Large break	0.12	68
8.1(a)	Break in instrument line from primary system that penetrates the containment	<.001	<0.1
8.2(a)	Rod ejection accident (PWR)	N.A.	N.A.
8.2(b)	Rod drop accident BWR	0.021	3.6
8.3(a)	Steamline breaks (PWR's outside containment)	N.A.	N.A.
8.3(b)	Steamline breaks (BWR)		
	Small break	0.015	1.0
	Large break	0.079	5.2

^{1/} Represents the calculated whole body dose as a fraction of 500 mrem (or the equivalent dose to an organ).

^{2/} These releases will be comparable to the design objectives indicated in the proposed Appendix I to 10 CFR Part 50 for effluents (i.e., 5 mrem/yr to an individual from all sources).

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APPENDIX A

THE ECCS CONTROVERSY

The fission products, which accumulate in reactor fuel, release heat as they undergo radioactive decay. Fuel that has been subjected to large neutron fluence, such as power reactor fuel, must be cooled to prevent "self-" melting. The rate of heat production soon after shutdown is relatively insensitive to the irradiation time. Heat production decreases by a factor of five in the first hour, and more than ten in the first day (see Table A). Ten seconds after shutdown a 1000 MWe reactor will still be producing ~160 MWt of heat.

Early in the development of LWR's it was recognized that loss of cooling water would create the possibility of fuel meltdown even though the chain reaction would automatically terminate when the water density dropped below a critical value. Although some theoretical study was done on the consequences of a core meltdown, it was generally felt that emergency core cooling systems should be provided to preclude such an event.

In its licensing actions the AEC adopted regulations which specified the capabilities of such ECCS. The intent was to provide a wide margin of assurance that the prescribed ECCS would function reliably in such a way as to prevent melting. These regulations were revised in mid-1971. (A1) Public hearings on the adequacy of the new ECCS rules have been in progress since January 1972.

The questions which are pertinent to the problem are:

1. What is the likelihood of a loss-of-coolant accident?

2. Will the ECCS meeting regulations actually perform to prevent a meltdown? and,
3. What are the consequences of failure of the ECCS to perform as expected?

No actuarial data on the failure of reactor primary piping has accumulated. Some guidance could be obtained from general industrial experience with high quality, high pressure pipes. (A2) Results indicate that failure probability is in the range of 1.1 to $1.67 \times 10^{-3}/\text{yr}$, with complete severance rupture probability much smaller. Actual LWR experience (commercial power and naval reactors) indicates that this probability is pessimistic since no major failures have been recorded.

Numerous ECCS-related experimental studies have been carried out. These test various functions over limited ranges of temperature and pressures. No experiments have been done on full-scale systems under the ambient conditions of a real reactor. Data derived from the limited experiments are used in computer models to predict pressure and temperature transients in the reactor core for a spectrum of breaks from smallest to largest. Such calculations are common in engineering practise. The results indicate that the ECCS will perform as expected by a wide safety margin.

At each reactor, the components of the ECCS are subjected to regular required tests to insure that all pumps, valves, controls, emergency power supplies, etc., are maintained in a state of readiness.

NORMAL OPERATION OF ECCS

Let us consider the events that would follow a hypothetical massive leak. I will refer to a BWR since I am better acquainted with

that system. We will not be concerned with small leaks, but consider only the most extreme case where the break occurs in the largest pipe attached to the vessel. We shall also assume that the break occurs instantaneously and that an entire section of pipe disintegrates.

The high pressure hot water in the system represents an enormous stored energy and such a break would be an awesome event. As the pressure blowdown commences, the water in the core begins to boil more rapidly. The presence of more bubbles in the water terminates the chain reaction immediately. Many independent sensing units (pressure drop in vessel, increasing pressure in primary containment, water level sensors, temperatures, etc.) all signal for the control rods to be inserted. This automatic operation would be complete within about 2 seconds after the blowdown began.

The pressure blowdown would take several seconds, during which the core would be efficiently cooled (see Fig. A-1). Even after the water level had fallen below the bottom of the core, the fuel would still receive some cooling as some water continued to be driven into the bottom of the core by the recirculating system. However, at this time the temperature of the cladding would start to rise as the heat contained in the fuel pellets begins to reach the cladding. After about 20 seconds depressurization would proceed more rapidly as all available water had been ejected from the break and only steam could reach the break. At this point the water in the lower plenum of the pressure vessel would boil rapidly passing large quantities of steam up through the core. This would cool the cladding back toward normal temperatures momentarily, but when the water had boiled away, again the cladding temperature would start to rise.

Under normal operation, one of the emergency systems (the High Pressure Core Spray) would begin spraying water on top of the core during the blowdown. As the blowdown is completed three additional emergency systems would spray massive quantities of water on the top of the core and flood the core from the bottom. Any one of four independent redundant systems is capable of providing enough cooling water.

The temperature transient computed for the fuel cladding is shown in Fig. A-2. As the fuel cladding heats up above $\sim 1500^{\circ}\text{F}$ a few fuel elements would balloon and rupture at the weakest point along the clad tubing. This ballooning would partially block a few coolant channels but water could flow radially through the disrupted regions from other channels. At the higher temperatures some chemical reaction would occur between the zircaloy cladding and the steam. The AEC regulations intend to keep the ballooning and $\text{Zr-H}_2\text{O}$ reactions below specified levels.

CONSEQUENCES OF ECCS FAILURE

If the ECCS fails to operate the fuel cladding would begin to melt after several minutes and the UO_2 fuel pellets would fall to the bottom plate which supports the core. These would continue to heat until finally the melting point of UO_2 was reached ($\sim 4000^{\circ}\text{F}$). This molten mass would melt through the bottom of the pressure vessel in 1 to 6 hours, and eventually through the concrete structures below. Any water that was encountered would produce steam explosions. It must be assumed that the primary containment would be breached at the weakest points. This would release fission products into the secondary containment (if a BWR). (See Fig. A-3.) Some fission products would escape. Numerous studies of off-site exposures have been made. (A3)

In the fall of 1971, a group known as the Union of Concerned Scientists circulated several documents giving their analysis of ECCS. These were summarized in an article in Nuclear News. ^(A4) Their arguments were expanded in testimony prepared for the AEC ECCS public hearings. ^(A5) It is their contention that:

1. The AEC ECCS regulations are not adequate to insure proper operation of ECCS;
2. The experimental work on ECCS is deficient, and inadequate to support the vendor's claims of performance characteristics;
3. That the computer models are deficient;
4. That the AEC regulatory staff has not adequately checked the vendor's data and calculations; and
5. That a failure of ECCS could lead to a catastrophic release of fission products.

In a reply to their earlier article, ^(A6) A. P. Bray ^(A7) pointed out that the Union of Concerned Scientists had used only limited parts of the available literature, some of which was obsolete, and had, in several cases, taken material out of context. Other responses by the AEC Staff and reactor vendors were given in testimony at the AEC hearings.

I will only comment on their last contention ((5) above). They have arbitrarily equated a core meltdown to an unrealistic hypothetical event described in WASH-740. ^(A8) WASH-740 was a report prepared in 1957 by several of my colleagues at Brookhaven. (It is sometimes referred to as "The Brookhaven Report"--a somewhat inadequate description because Brookhaven has published some 20,000 reports in the past 25 years.) The purpose of the study was to provide Congress with an estimate of the

extreme limits of damage that could be expected from the nuclear industry. This was to serve as guidance in the passage of the Price-Anderson bill.

In sworn testimony given last year one of the authors stated: "To provide guidance for legislation, we were asked to estimate the cost in the lives and property damage if a maximum 'incredible' accident were to occur under the worst circumstances, i.e., a breach of the containment, and the worst meteorological conditions. We had to assume that a major part of the fuel and fission products had become airborne--in short, to assume the worst imaginable situation. It is no wonder that when we got through our calculations the answer was indeed terrifying."

The report^(A9) points out that no accident mechanism could be imagined which would produce the kinds of releases used in the calculations. Particularly, in order to obtain the most pessimistic results, it was necessary to assume that the solid fission products were emitted essentially as aerosols. Such an assumption does not correspond to reality. In short, WASH-740 was not intended to be a calculational model of the consequences of a real accident. Any conclusions based on it will be pessimistic in the extreme. Therefore, I regard the conclusions of the Union of Concerned Scientists about damage from an uncontrolled meltdown as meaningless.

I cast my ballot with the hundreds of professional experts on the AEC Staff, the Advisory Committee on Reactor Safeguard, the Atomic Safety and Licensing Boards who, after reviewing hundreds of technical reports on ECCS studies, are on public record in stating "this facility can be operated without undue risk to the public."

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TABLE A

Fission Product "Afterheat" Production for a
1000 MWe (3030 MWt) Light Water Reactor

Time after reactor shutdown	Fuel Irradiation Time		
	1 day	30 days (MWt)	∞
1 second	167	177	183
10 seconds	142	152	158
1 minute	95	105	111
1 hour	23.0	33.0	38.8
1 day	2.8	10.1	15.8
30 days	0.6	1.2	5.7

Reactor Vessel Water Level and Primary System Flows Immediately After a LOCA

Fig. A-1

Initial Clad Temperature Response Following the Maximum Recirculation Line Break

Fig. A-2

Fig. A-3