BNL 40444,
INFORMAL REPORT

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BNL--40444

DE88 004589

Department of Nuclear Energy

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**UNDER CONTRACT NO DE-AC02-76CH00016 WITH THE
UNITED STATES DEPARTMENT OF ENERGY**

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How Safe Are Nuclear Plants? How Safe Should They Be?

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We are becoming so accustomed to thinking about safety of nuclear plants in terms of risk as defined by the WASH-1400 study that some of the implications for the non-specialist escape our attention.

Even putting the question in these terms upsets many people. Many do not like to be reminded of their mortality, and they become frightened when it is suggested that some one thing can be singled out as possibly having a chance of ending their lives. This is especially true if that something is unfamiliar to them.

It gets worse when we start to discuss nuclear plant safety in probabilistic terms. Probabilities are not widely appreciated. Perceptions of probability are clouded by widespread belief in good luck and bad luck as an attribute of people or circumstances. It is usually not helpful to people who believe that big shifts in luck are commonplace to be told that some event has only a very low probability.

Yet we know that a rational program to understand safety, to identify unsafe events, and to use this kind of information or analysis to improve safety, requires us to use the methods of quantitative risk assessment.

How can we make this process more understandable to a broader group of non-technical people? And how can we develop a wider acceptance of the results of the process?

These are questions that have been struggled with for some time in the world of nuclear plant safety. The Nuclear Regulatory Commission examined them for several years as it moved toward developing a position on safety goals for nuclear plants, a requirement that had been assigned it by Congress. Opinion was sought from a broad spectrum of individuals, within the field of nuclear power and outside it, on the topic that was popularly called, "How safe is safe enough?" Views were solicited on the answer to the question and also on the way the answer should be framed when it was adopted.

A first workshop led to a coalescence of opinion that quantitative safety goals should be developed. Simplistically, these could be in the form that a nuclear plant should be so safe that the risk from accidents should not exceed x early fatalities and y late fatalities each year. Following these conclusions, it was pointed out that this would be interpreted by the public at large and even by political circles such as Congress that the Nuclear Regulatory Commission thought it would be all right if a nuclear plant killed x people outright and caused y fatal cancers each year. That spelled the end of strictly quantitative safety goals for nuclear power plants.

A second workshop was held. The conclusions changed. There was now a reasonably broad consensus that safety goals had to be qualitative; that they had to ensure safety of nuclear plants in the context of nothing being absolutely safe in this world, but nuclear plants being better than the rest.

After some deliberation, the Nuclear Regulatory Commission adopted this course last year. It adopted two qualitative goals. The first was that nuclear plants should not entail any significant additional risk to life and health. This goal limits the risk from nuclear plants relative to the risks from ordinary living.

The second safety goal ~~states~~ that the risk from a nuclear plant should be comparable to or less than the risks from viable competing technologies for generating electricity, and should not be a significant addition to other societal risk.

The goals when stated in these forms should be understandable to non-technical people, though they do include a potential problem in that they use the word "risk" in its WASH-1400 technical meaning while seeming to substitute it for a word like "danger" for purposes of public interpretation.

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Though the intention to state understandable goals was probably accomplished by this adoption, the goals were not very useful in this form for the regulatory staff. They were not a clear yardstick that could be used in

determining when they were met or were not met. So the Commission also settled on what were called quantitative objectives, that restored some of the features of the quantitative goals that had been discussed in the workshops.

One of these referred to the early effects of potential accidents on people living near nuclear plants. It said that the risk to an individual living in the vicinity of a nuclear plant of being killed as the result of a reactor accident should not exceed one-tenth of one percent of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are normally exposed.

The second said that the risk to the population near a nuclear plant of dying from cancer caused by a nuclear accident should not exceed one-tenth of one percent of the sum of cancer fatality risks resulting from all other causes.

These quantitative objectives were augmented by what was called a "general performance guideline" to the effect that the chance of a reactor accident leading to a large release should be less than one in one million per year of reactor operation.

In adopting these goals, objectives, and the guideline, the NRC quietly overturned a position it had taken several years earlier when it attacked the concept of risk assessment generally and WASH-1400 in particular, and said

that these methods should not be used in regulatory applications. This new policy on safety goals could not be implemented other than through use of risk assessment methods. In fact, the safety goals policy simply gave formal recognition to the reality that risk assessment by the best available means has turned out to be a powerful and even a necessary tool for ensuring and improving the safety of nuclear plants. It has put important new meaning into such time-honored phrases in nuclear safety as, "without undue risk to the health and safety of the public."

Let's now examine the implications of these positions taken by the Nuclear Regulatory Commission. The Center for Disease Control of the U.S. Public Health Service issues statistics on the causes of death in the United States. In the December 19, 1986 issue of the Morbidity and Mortality Weekly Report can be found statistics for the year 1984. Injuries or accidents accounted for 4.6% of all deaths. According to the first quantitative safety objective, nuclear plant safety would therefore require that nuclear plants meet the criterion that nuclear plant accidents will not lead to a probability of accidental death greater than 4.6×10^{-5} for individuals at risk.

The same publication states the relative mortality rate from malignant neoplasms as 22.1%. The second quantitative safety objective therefore implies that for the population living near nuclear plants, these plants should not contribute more than a probability of 2.2×10^{-4} of incidence of fatal cancer over lifetime.

These are cold-sounding statistics, of the kind that have a tendency to disturb most people. They give an impression that nuclear power safety advocates first determine that there is a hazard attached to a nuclear plant, and then they say - go right ahead with it after all. There are plenty of unprincipled politicians ready to take advantage of this kind of public gut reaction, and the country is plentifully supplied with other individuals who are eager to take advantage of public fears to further their private objectives.

But I do not see how we could avoid use of such statistical methods if we are to improve safety of nuclear power plants, any more than we could avoid use of similar statistical methods to determine where to find the most urgent areas for research against mortality from disease, or to locate the region of the country most in need of improved measures for commercial air safety.

Other safety goals and safety criteria than the ones adopted by the NRC have sometimes been proposed, and some are incorporated in more or less obscure forms in some standards and regulations. One of the oldest is that nuclear power plants should not directly contribute to a time-averaged increase in radiation level by more than some factor times the natural rate. This has been the basis for some ICRP and NCRP standards and recommendations regarding radiation levels from normal operation of nuclear facilities. Another concept has been proposed to the effect that nuclear plant activities should contribute a time-averaged radiation level not exceeding the variability in radiation dose absorbed in connection with variability of choice by individuals. This is apparently the basis for the EPA regulation 40CFR190.

The former of the two criteria would lead to an annual average radiation level to an individual from all causes attached to operation of nuclear plants of no more than about 140 mR/year. A direct comparison between this and the NRC's safety objectives is not possible. For one thing, interpretation and use of the NRC objectives requires use of a dose response curve with inherent difficulties as to widespread acceptance and as to how to add long-term and one-time doses. For another, the annual dose limit of 140 mR/year would have to be added up over a lifetime to determine mortality statistics. Naive use of the BEIR-3 value of LET dose per cancer at low dose, low dose rate implies that the 140 mR/yr value exactly coincides with the NRC delayed fatality safety goal for an individual exposed at this level for ten years of his life. The latter criterion based on the effect of variability in choice would be comparable to the NRC delayed fatality objective for an individual who spent his full lifetime at the 140 mR/yr annual radiation level.

I summarize all of this by noting that all of the objectives and criteria that have been discussed are in approximate agreement. They are in much better agreement numerically than the uncertainties in the numbers themselves. Risk assessment is still an inaccurate science.

There are other interesting aspects to the question of how safe nuclear plants should be. Analysis of the source term of fission product release from postulated severe accidents to nuclear power plants of the type used in the United States now makes it clear that the off-site consequences of a severe

accident would depend very strongly on the length of time the containment remained intact, holding in any fission products released from the reactor's primary system into the containment. If an accident were to lead to melting of the core of a reactor, if the fission products escaped from the primary system into the containment, and if the containment remained intact for a few hours longer, say more than three or four hours, the effects of plateout and of agglomeration and settling of aerosol particles would dramatically lower the amount of fission products available for release to the environment. It is found that almost all the contribution to risk is the result of severe accidents that could lead to early containment failure. Mechanisms for this have been identified, and recent NRC-sponsored research has addressed the probability of early containment failure and the effect on consequences of severe accidents.

It is found that the NRC safety goals and the numerical safety objectives are met if the probability of a severe accident with early containment failure is less than approximately 10^{-5} for an average nuclear plant. This finding has considerable uncertainty associated with it, much being the result of variation in meteorology, population distribution, design of the plant, and general difficulty in accurate analysis of risk.

This raises an important problem which will be solved only very slowly in the future. I referred a few moments ago to risk assessment as an inexact science. This leads to lack of ability to be absolutely sure if the goals

and objectives are met. We are using a yardstick whose length is somewhere between one foot and ten feet.

This means that for the time being, at any rate, the ability to meet the Nuclear Regulatory Commission's safety goals can be only one index to the safety of nuclear power plants. It is widely accepted that these methods cannot be used to settle absolutely the question of adequate safety of a particular nuclear power plant. Probabilistic analysis has to be added to other methods to reach an overall conclusion based on many perspectives. Other kinds of questions that need addressing are: How well is the plant managed? What is its operating record? What is the character of the operating staff - how experienced are they? How well-trained? How well do they know their plant? How well do design and operation of the plant avoid potential problem areas that have come to be recognized over the years?

From answers to all of these questions can be developed a profile that can be used to identify weaknesses that might undermine the safety of a specific plant.

The safety goal structure of the Nuclear Regulatory Commission is more usable to assess the safety of the nuclear power industry, where the inputs from many risk assessment analyses should lead to some improvement of the statistical results and where an accumulation of historical information begins to be useful.

This leads us into the second of the two questions I want to explore. This is, how safe are nuclear plants? I want to consider this point from the standpoint of how well nuclear plants have measured up historically to the NRC's safety goals. This aspect of the question is especially important in view of the emphasis on Chernobyl in the title of this symposium.

But before we consider the implications and impacts of Chernobyl, let's concentrate on the United States, where nuclear plants very different from Chernobyl's RBMK design are used.

The United States has specialized in nuclear power plants with water-moderated and water-cooled reactors. All but two U.S. nuclear plants are of this general class; one of the exceptions is a small, demonstration size plant in Colorado using a gas-cooled reactor, and the other is a government-owned plant at Richland, Washington which produces plutonium for nuclear weapons and also supplies steam to turbine-generators operated by the Washington Public Power System.

As is well-known, the one substantial nuclear plant accident in the United States occurred in 1979 at the Three Mile Island Unit 2 nuclear plant in Pennsylvania. This accident destroyed the reactor and led to permanent shutdown of Unit Number 2. Though hydrogen was generated as a result of extensive oxidation of the zirconium-based nuclear fuel cladding during the accident, and the hydrogen was released into the containment building where it

burned, the integrity of the containment structure was preserved, and it was apparently not threatened. The only radioactive material released from the plant because of the accident consisted of the noble gas inventory and about 18 Ci of active iodine. Radiation levels outside the plant were far below life-threatening values and the total population dose was about 5000 man-REM. According to the BEIR-3 model this is assumed to be productive of a probable 0.8 cancers over the period of 30-50 years following the accident.

About 1000 reactor years of U.S. commercial water reactor experience have now been accumulated. A similar number of reactor years has been accumulated in other countries with nuclear plants of the same type. This is not enough for an adequate statistical basis for a test of meeting of the safety goals and objectives, but it is close. So far there have been no early fatalities in the U.S. or elsewhere as a result of accidents to water reactors, and an upper limit to the rate at which light water nuclear plants may have induced cancer is about 4×10^{-4} per operating year (we use the full 2000 reactor years of experience in deriving this number). There are now almost 400 light water nuclear plants in the world, so another 1000 reactor years of experience will be accumulated every 2-1/2 to 3 years. Thus accurate historical tests of the safety goals and objectives are almost at hand.

Let me recall that the second NRC safety goal compares electrical generation by nuclear plants against viable competing technologies. The principal competition is coal. To make a comparison between the two, I draw on some

analyses made four years ago by Hamilton and co-workers. The comparison is made for the full fuel cycle, including not only electrical generation but also mining and transportation. It is seen that in all categories the risk from the nuclear option is lower than that for coal. The comparison is, however, not as reliable as one would like it to be. The range of the estimate of mortality from air pollution reflects the great uncertainty in use of a linear hypothesis for the effects of pollution at low doses. If anything, the use of this sort of hypothesis for organic pollutants and other components of smoke from a coal plant is more questionable than it is for effects of nuclear radiation.

To summarize, the safety goals and objectives established by the Nuclear Regulatory Commission seem to be met for nuclear plants in this country, for the industry as a whole. The statistical evidence supporting this conclusion is not yet adequate in some respects, but the statistical situation is improving rapidly.

These conclusions also seem to apply to other countries using water cooled and moderated nuclear plants of the western type.

What is the effect of Chernobyl on all of this? In the averaging process that tells the historical story of safety of nuclear plants, there is some temptation to add to the effects of TMI those from Chernobyl. I have thought about this possibility, and believe that for any international objectives that

consider the effect of nuclear power world-wide, and that contemplate improvement of nuclear safety world-wide, there is some merit to this. But in doing so one should realize that any averages formed this way are taken over two very disparate distributions. The RBMK's in the Soviet Union are so different in their design and their safety features, and their mode of operation has been so singular, that averaging over the two sets loses a great deal of meaning. Certainly to form such an average would not improve our understanding of how safe U.S. types of nuclear plants are, when operated by U.S. practices.

The Soviet government gives all signs of believing that the past characteristics of RBMK's and their mode of operation at Chernobyl are not acceptable according to safety objectives of the Soviet Union. A number of physical changes are being made to RBMK reactors. New operational practices have been substituted for old discredited ones. Management personnel from Chernobyl have been subjected to criminal trials, found guilty, and are undergoing punishment. I believe that it would be wrong under the circumstances to use the historical record of RBMK's including the Chernobyl accident in evaluating the safety of these plants under present circumstances, and it would be even more wrong to apply such results to U.S. nuclear plants.

At the end of an analysis such as that preceding, I am left still unsatisfied as to the way the conclusions would be received by a broad public. The case for nuclear plant safety will probably have to become so clear that the

analyst is obviously innocent of any charge of using numbers to obscure reality. Nuclear plants will have to show in real life a level of safety that reassures the public through pervasive excellence. I believe that it is not the function of the Nuclear Regulatory Commission to achieve this. They have developed a set of safety goals that I believe are rational and laudable, and which are suited to the responsibility of a regulatory body of this type. There should be no tightening of the screws by the NRC simply to reassure the public.

Achieving a level of excellence beyond that required by the regulators should be the responsibility of the nuclear industry. They are the only group able to do this, and they should do so as an act of social responsibility. If they are to have any sponsors and helpers in the Federal establishment in their enterprise, it should probably be the Department of Energy, which still has such a responsibility according to the Atomic Energy Act.

SAFETY GOAL

**RISKS COMPARABLE TO OR LESS THAN THAT FROM
VIALE COMPETING WAYS TO GENERATE ELECTRICITY.**

LOSS OF LIFE EXPECTANCY

ACCIDENTS	435 DAYS
AUTOMOBILES	207 DAYS
BEING MALE	306 DAYS
10% OVERWEIGHT	1.3 YEARS
CIGARETTES (1 PACK PER DAY)	4.5 YEARS
BEING PRESIDENT	5.1 YEARS
INSULATING YOUR HOUSE	32+DAYS

SAFETY GOAL

**NO SIGNIFICANT ADDITIONAL RISKS
TO LIFE AND HEALTH.**

SAFETY GOALS

NOT A SIGNIFICANT ADDITION TO OTHER SOCIETAL RISK.

QUANTITATIVE OBJECTIVE

NO ONE HAS AN ACCIDENT ACCIDENT RISK FROM A
NUCLEAR PLANT MORE THAN ONE-ONE THOUSANDTH
OF ALL OTHER ACCIDENT RISKS.

QUANTITATIVE OBJECTIVE

THOSE NEAR NUCLEAR PLANTS HAVE A
LONG-TERM RISK OF CANCER MORTALITY
FROM THE NUCLEAR PLANT LESS THAN
ONE-ONE THOUSANDTH OF ALL OTHER
CANCER MORTALITY.

SOURCES OF MORTALITY

(NUMBERS ARE PER 1000 MWE PLANT PER YEAR)

COAL:	MINING ACCIDENTS	0.15-1.5
	BLACK LUNG	0.6-1.5
	TRANSPORTATION	1.0-3.2
	PLANT ACCIDENTS	0.1-0.2
	POLLUTION (PUBLIC)	0-77 (15)
NUCLEAR:	MINING ACCIDENTS	0.1-0.4
	MINE RADIATION	0.15
	TRANSPORTATION	0.1
	PLANT ACCIDENTS (PUBLIC)	0.1

1 SEVERE ACCIDENT EVERY 10,000 OPERATING

PLANT YEARS MEETS THE SAFETY GOAL.

COMPARISON TO SAFETY GOALS

FATALITY RATE: 0 IN ABOUT 10^3 OPERATING YEARS

0 PER OPERATING YEAR

CANCER RATE: 0.8 IN 10^3 OPERATING YEARS

8×10^{-4} PER OPERATING YEAR

(4×10^{-4} WITH OTHER EXPERIENCE)

TMI CONSEQUENCES

3000 MAN REM

NO EARLY FATALITIES

GENERAL PERFORMANCE GUIDELINE

CHANCE OF A REACTOR ACCIDENT WITH A LARGE
RELEASE LESS THAN ONE PER MILLION PER YEAR
OF REACTOR OPERATION.