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WASH-1400

REACTOR SAFETY STUDY

AN ASSESSMENT OF ACCIDENT RISKS IN U.S. COMMERCIAL NUCLEAR POWER PLANTS

SUMMARY REPORT

UNITED STATES ATOMIC ENERGY COMMISSION

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1. INTRODUCTION AND RESULTS

The Reactor Safety Study was sponsored by the U.S. Atomic Energy Commission to estimate the public risks that could be involved in potential accidents in commercial nuclear power plants of the type now in use. It was performed under the independent direction of Professor Norman C. Rasmussen of the Massachusetts Institute of Technology. The risks had to be estimated, rather than measured, because although there are about 50 such plants now operating, there have been no nuclear accidents to date. The methods used to develop these estimates are based on those developed by the Department of Defense and the National Aeronautics and Space Administration in the last 10 years.

The objective of the Study was to make a realistic estimate of these risks and to compare them with non-nuclear risks to which our society and its individuals are already exposed. This information will be of help in determining the future use of nuclear power as a source of electricity.

The basic conclusion of this Study is that the risks to the public from potential accidents in nuclear power plants are very small. This is based on the following considerations:

a) The consequences of potential reactor accidents are no larger, and in many cases, are much smaller than those of non-nuclear accidents. These consequences are smaller than people have been led to believe by previous studies which deliberately maximized risk estimates.

b) The likelihood of reactor accidents is much smaller than many non-nuclear accidents having similar consequences. All non-nuclear accidents examined in this Study, including fires, explosions, toxic chemical releases, dam failures, airplane crashes, earthquakes, hurricanes and tornadoes, are much more likely to occur and can have consequences comparable to or larger than nuclear accidents.

Figures 1, 2 and 3 compare the nuclear reactor accident risks for the 100 plants expected to be operating by about 1980 with risks from other man-made and natural phenomena. These figures indicate the following:

a) Figures 1 and 2 show the likelihood and number of fatalities from both nuclear and a variety of non-nuclear accidents. These figures indicate that non-nuclear events are about 10,000 times more likely to produce large accidents than nuclear plants.

b) Figure 3 shows the likelihood and dollar value of property damage associated with nuclear and non-nuclear accidents. Nuclear plants are about 100 to 1000 times less likely to cause comparable large dollar value accidents than other sources. Property damage is associated with three effects, 1) the cost of temporarily moving people away from contaminated areas, 2) the denial of use of real property during the few weeks to a few months during which the radioactivity is cleaned up, and 3) the cost of assuring that people are not exposed to potential sources of radioactivity in food and water supplies. This latter cost reflects the efforts required to survey agricultural products, plus the loss of products which might be contaminated.

In addition to the overall risk information in Figures 1-3, it is useful to consider the risk to individuals of being fatally injured by various types of accidents. The bulk of the information shown in Table 1 is taken from the 1973 U.S. Statistical Abstract and applies to the year 1969, the latest year for which this data has been tabulated. The nuclear risks are very small compared to other possible causes of fatal injuries.

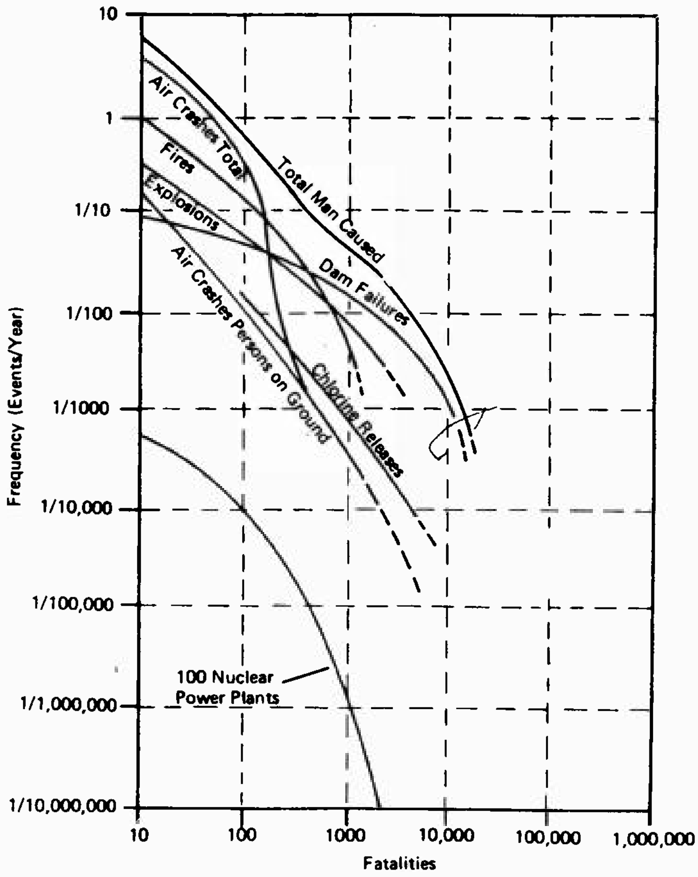

Figure 1. Frequency of Fatalities Due to Man-Caused Events*

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* *An example of the numerical meaning of Figures 1 to 3 can be seen by selecting a vertical consequence line and reading the likelihood that various types of accidents would cause that consequence. For instance, in Figure 1, 100 plants would cause this consequence with a likelihood of one in 10,000 per year. Chlorine releases are about 100 times more likely, or about one in 100; fires are about 1,000 times more likely, or about one in 10 per year; air crashes are about 5,000 times more likely, or about one per 2 years.*

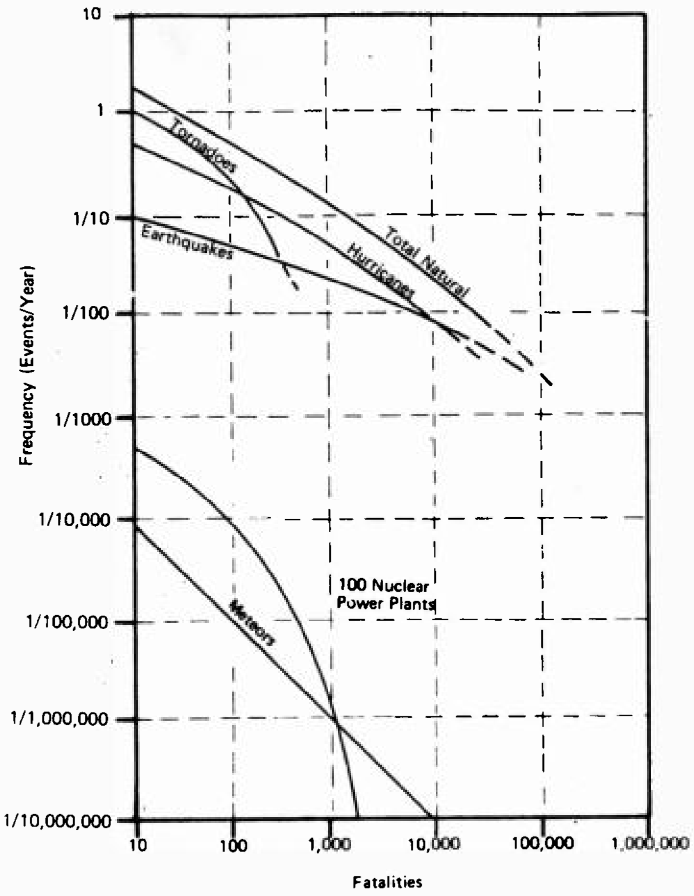

Figure 2. Frequency of Fatalities Due to Natural Events

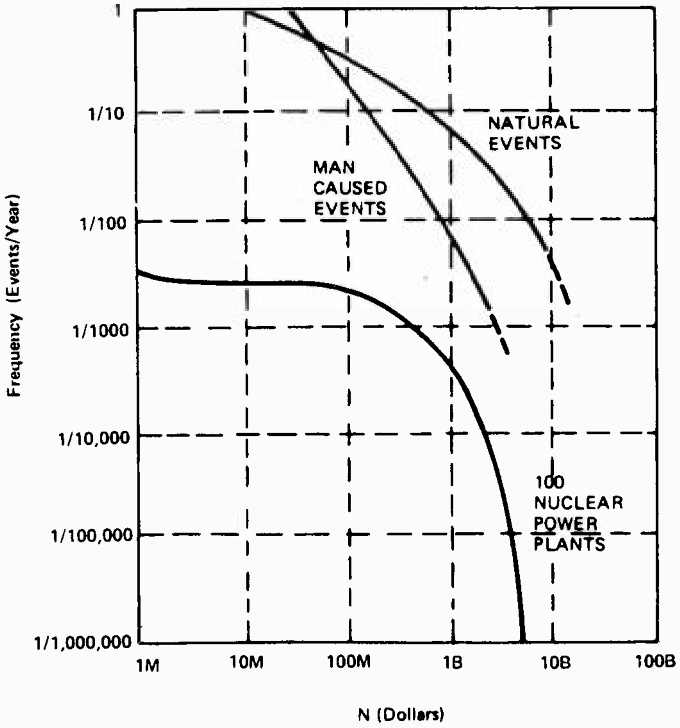

Figure 3. Frequency of Property Damages due to Natural and Man-Caused Events

TABLE 1

Risk of Fatality by Various Causes

Accident type	Total number	Individual chance per year
Motor Vehicle	55,791	1 in 4,000
Falls	17,827	1 in 10,000
Fires and Hot Substances	7,451	1 in 25,000
Drowning	6,181	1 in 30,000
Firearms	2,309	1 in 100,000
Air Travel	1,778	1 in 100,000
Falling Objects	1,271	1 in 160,000
Electrocution	1,148	1 in 160,000
Lightning	160	1 in 1,200,000
Tornadoes	91	1 in 2,500,000
Hurricanes	93	1 in 2,500,000
All Accidents	111,992	1 in 1,600
Nuclear Reactor Accidents (100 plants)	0	1 in 300,000,000

In addition to fatalities and property damage, a number of other health effects can be caused by nuclear accidents. These include injuries and long-term health effects such as cancers, genetic effects and thyroid gland illness. The injuries expected in potential accidents would be about twice as large as the fatalities shown in Figures 1 and 2; however, such injuries would be insignificant compared to the 8 million injuries caused annually by other accidents.

The number of cases of genetic effects and long-term cancers are predicted to be much smaller than the normal incidence rate of these diseases. Even for a large, very unlikely accident, the small increases in these diseases would not be detected.

Thyroid illnesses that might result from a large accident are the formation of nodules on the thyroid gland that can be treated by medical procedures and rarely lead to serious consequences. For most accidents, the number of nodules caused would be small compared to their normal incidence rate. The number that might be produced in very unlikely accidents would be comparable to their normal rate of occurrence. These would be observed during a period of 10 to 20 years following the accident and would be about equal to their normal incidence in the people exposed.

While the Study has presented the estimated risks from nuclear power plant accidents and compared them with other risks that exist in our society, it has made no judgment on the acceptability of nuclear risks. Although the Study believes nuclear accident risks are very small, the judgment as to what level of risk society should accept is a broader one than can be made here.

2. QUESTIONS AND ANSWERS ABOUT THE STUDY

This section of the summary presents more information about the details of the Study than was covered in the introduction. It is presented in question and answer format for ease of reference.

2.1 Who did this Study and how much effort was involved?

The Study was done principally at the Atomic Energy Commission headquarters by a group of scientists and engineers who had the skills needed to carry out the study's tasks. They came from a variety of organizations including the AEC, the national laboratories, private laboratories, and universities. About 10 people were AEC employees. The Director of the study was Professor Norman C. Rasmussen of the Department of Nuclear Engineering of the Massachusetts Institute of Technology, who served as an AEC consultant during the course of the study. The Staff Director who had day-to-day responsibility for the project was Mr. Saul Levine of the AEC. The study was started in the summer of 1972 and took two years to complete. A total of 60 people, various consultants, 50 man years of effort and three million dollars were involved.

2.2 What kind of nuclear power plants are covered by the Study?

The Study considered large power reactors of the pressurized water and boiling water type being used in the U.S. today. This present generation of reactors are all water cooled and therefore, the Study limited itself to this type. Although high temperature gas cooled and liquid metal fast breeder reactor designs are now under development, no large reactors of this type are expected to operate in this decade; thus they were not considered.

Nuclear power plants produce electricity by the fissioning (or splitting) of uranium atoms. The nuclear reactor fuel in which the uranium atoms fission is in a large steel vessel. The reactor fuel consists of about 100 tons of uranium. The uranium is inside metal rods about 1/2 inch in diameter and about 12 feet long. These rods are formed into fuel bundles of about 50-200 rods each. Each reactor contains several hundred bundles. The vessel is filled with water which is needed both to cool the fuel and to maintain the fission chain reaction.

The heat released in the uranium by the fission process heats the water and forms steam; the steam turns a turbine to generate electricity. Similarly, coal and oil plants generate electricity using fossil fuel to boil water.

Today's nuclear power plants are very large. A typical plant has an electrical capacity of 1,000,000 kilowatts, or 1,000 megawatts. This is enough electricity for a city of about five hundred thousand people.

2.3 Can a nuclear power plant explode like an atom bomb?

No. It is impossible for nuclear power plants to explode like a nuclear weapon. The laws of physics do not permit this because the fuel contains only a small fraction (3-5 percent) of the special type of uranium (called uranium-235) that is used in weapons.

2.4 How is risk defined?

The idea of risk involves both the likelihood and consequences of an event. Thus, to estimate the risk involved in driving an automobile, one would need to know the likelihood of an accident in which, for example, an individual could be 1) injured or 2) killed. Thus there are two different consequences, injury or fatality, each with its own likelihood. For injury, an individual's chance per year is one in 130 and for fatality, it is one in 4000. This type of data concerns the risk to individuals and can affect attitudes and habits that individuals have toward driving.

However, from an overall societal viewpoint, different types of data are of interest. Here, 1.5 million injuries per year and 55,000 fatalities per year due to automobile accidents represent the kind of information that might be of use in making decisions on highway and automobile safety.

The same type of logic applies to reactors. From the viewpoint of a person living in the general vicinity of a reactor, the likelihood of being killed in any one year in a reactor accident is one chance in 300,000,000 and the likelihood of being injured in any one year in a reactor accident is one chance in 150,000,000.

From a broader societal viewpoint, one individual of the 15 million people living in the vicinity of 100 reactors might be killed and 2 individuals might be injured every 25 years. This type of information might be of some use to the Congress or other decision makers in thinking about the overall risk to society from reactor accidents.

2.5 What causes the risks associated with nuclear power plant accidents?

The risks from nuclear power plants are due to the radioactivity formed by the fission process. In normal operation nuclear power plants release only minute amounts of this radioactivity under controlled conditions. In the event of highly unlikely accidents, larger amounts of radioactivity could be released that could cause significant risks.

The fragments of the uranium atom that remain after it fissions are radioactive. These radioactive atoms are called fission products. They disintegrate further with the release of nuclear radiations. Many of them decay away quickly, in a matter of minutes or hours, to non-radioactive forms. Others decay away more slowly and require months, and in a few cases, many years to decay. The fission products accumulating in the fuel rods include both gases and solids. Included are iodine, gases like krypton and xenon, and solids like cesium and strontium.

2.6 How can radioactivity be released?

The only way that potentially large amounts of radioactivitiy can be released is by melting the fuel in the reactor core. The fuel that is removed from a reactor after use and stored at the plant site contains considerable amounts of radioactivity. However, accidental releases from such fuel were found to be very small compared to potential releases of radioactivity from the full reactor core.

The safety design of reactors includes a series of systems to prevent the overheating of fuel and to control potential releases of radioactivity from the fuel. Thus, to get an accidental release of radioactivity to the environment there must be a series of sequential failures that cause the fuel to overheat and release its radioactivity. There must also be failures in the systems designed to remove and contain the radioactivity.

The Study has examined thousands of potential paths by which radioactive releases could occur and has identified those that determine the risks. This involved defining the ways in which the fuel in the core could melt and the ways in which systems to control the release of radioactivity could fail.

2.7 How might a core melt accident occur?

It is significant that not once in some 200 reactor years of commercial operation of reactors of the type considered in the report has there ever been fuel melting. To melt the fuel requires that a failure occur in the cooling system that allows the fuel to heat up to its melting point, about 5,000° F.

To those unfamiliar with the characteristics of reactors, it might seem that all that is required to prevent fuel from overheating is a system to promptly stop, or shut down, the fission process at the first sign of trouble. Although reactors have such systems, they alone are not enough since the radioactive decay of the fuel continues to generate heat (called decay heat) that must be removed even after the fission process stops. Thus, redundant decay heat removal systems are also provided in reactors. In addition, emergency core cooling systems (ECCS) are provided to cope with a series of potential but unlikely accidents.

The Reactor Safety Study has defined two broad types of situations that might potentially lead to a melting of the reactor core: the loss of coolant accident (LOCA) and transients. In the event of a loss of coolant, the normal cooling water is lost from the cooling systems and core melting would be prevented by the use of the emergency core cooling system (ECCS). However, melting could potentially occur in a loss of coolant if the ECCS were to fail to operate.

The term transient refers to any one of a number of conditions which can occur in a plant that require the reactor to be shut down. Following shutdown, the decay heat removal systems operate to keep the core from overheating. Certain failures in either the shutdown or the decay heat removal systems have the potential to cause melting of the core.

2.8 What features are provided in reactors to cope with a core melt accident?

Nuclear power plants have numerous systems to prevent core melting. Furthermore, there are inherent physical processes and additional features that remove and contain the radioactivity released from the molten fuel should core melting occur. Although there are features provided to keep the containment building from being damaged for some time after the core melts, the containment will ultimately fail, causing a release of radioactivity.

An essentially leak tight containment building is provided to prevent the initial dispersion of the airborne radioactivity into the environment. Although the containment will fail a number of hours after the core melts, until that time, the radioactivity released from the fuel will be deposited by natural processes on the surfaces inside the containment. In addition, plants are provided with systems to contain and trap the radioactivity released within the containment building. These systems include such things as water sprays and pools to wash radioactivity out of the building atmosphere and filters to trap radioactive particles prior to their release. Since the containment buildings are made essentially leak tight, the radioactivity is contained as long as the building remains intact. Even if the building were to have sizable leaks, large amounts of the radioactivity would be removed by the systems provided for that purpose or would be deposited on interior surfaces of the building by natural processes.

Even though the containment building would be expected to remain intact for some time following a core melt, eventually the molten mass would be expected to eat its way through the concrete floor into the ground below. Following this, most of the radioactive gases will be trapped in the soil; however, a small amount would escape to the surface and be released. Almost all of the nongaseous radioactivity would be trapped in the soil.

It is possible to postulate highly unlikely core melt accidents in which the containment building fails by overpressurization or by missiles created by the accident. Such accidents could release a larger amount of airborne radioactivity and have more serious consequences. The consequences of these less likely accidents have been included in the Study's results shown in Figures 1-3.

2.9 How might the loss of coolant accident lead to a core melt?

Loss of coolant accidents are postulated to result from failures in the normal reactor cooling water system, and plants are designed to cope with such failures. The water in the reactor cooling systems is at a very high pressure (between 50 to 100 times the pressure in a car tire) and if a rupture were to occur in the pipes, pumps, valves, or vessels that contain it, then a "blow out" would happen. In this case the water would flash to steam and blow out of the hole. This could be serious since the fuel could melt if additional cooling were not supplied in a rather short time.

The loss of normal cooling in the event of a LOCA would stop the chain reaction so that the amount of heat produced would drop almost instantly to a few percent of its operating level. However, after this sudden drop the amount of heat being produced would decrease much more slowly and would be controlled by the decay of the radioactivity in the fuel. Although this decrease in heat generation is helpful, it would not be enough to prevent the fuel from melting unless additional cooling were supplied. To deal with this situation, reactors have emergency core cooling systems (ECCS) whose function is to provide cooling for just such events. These systems have pumps, pipes, valves, and water supplies which are capable of dealing with breaks of various sizes. They are also designed to be redundant so that if some components fail to operate, the core can still be cooled.

The Study has reviewed a large number of potential sequences of events following. LOCAs of various sizes. In almost all of the cases, the LOCA must be followed by multiple failures in the emergency core cooling system for the core to melt. The principal exception to this is the massive failure of the large pressure vessel that contains the core. However the accumulated experience with pressure vessels indicates that the chance of such a failure is indeed very small. In fact the Study found that the likelihood of pressure vessel failure is so small that it does not contribute to the overall risk from reactor accidents.

2.10 How might a reactor transient lead to a core melt?

The term reactor transient refers to a number of events that require the reactor to be shut down. These range from normal shutdown for such things as refueling to such unplanned but expected events as loss of power to the plant from the utility transmission lines. The reactor is designed to cope with unplanned transients by automatically shutting down. Following shutdown, cooling systems would be operated to remove the heat produced by the radioactivity in the fuel. There are several different cooling systems capable of removing this heat, but if they all should fail, the heat being produced would be sufficient to eventually boil away all the cooling water and melt the core.

In addition to the above pathway to core melt, it is also possible to postulate core melt resulting from the failure of the reactor shutdown systems following a transient event. In this case it would be possible for the pressure to increase enough so that the normal reactor cooling system might rupture. This would create a loss of coolant accident and could lead to core melting.

2.11 How likely is a core melt accident?

The Reactor Safety Study carefully examined the various paths leading to core melt. Using methods developed in recent years for estimating the likelihood of such accidents, a probability of occurrence was determined for each core melt accident identified. These probabilities were combined to obtain the total probability of melting the core. The value obtained was one in 17,000 per reactor per year. With 100 reactors operating, as is anticipated for the U.S. by about 1980, this means that one such accident would occur, on the average, every one and three quarters centuries.

It is important to note that a melting of the core in a nuclear power plant does not necessarily involve an accident with serious public consequences. One of the major findings of the study is that only about ~~one in 10 potential co~~re melt accidents, occurring on the average of once every 17 centuries, ~~might p~~roduce measurable health effects.

2.12 What is the nature of the health effects that a core melt accident might produce?

It is possible for a core melt accident to release enough radioactivity so that some fatalities might occur within a short time (a few weeks) after the accident. Other people may be exposed to radiation levels which would produce observable effects which would require medical attention but from which they would recover completely. In addition, some people may receive even lower exposures which produce no noticeable effects but may increase the incidence of certain diseases over a period of many years. The observable effects which occur shortly after the accident are called short term or acute effects.

The delayed or latent effects of radiation exposure can cause some increase in the incidence of diseases such as cancer, genetic effects and thyroid gland illnesses in the exposed population. These effects would appear as an increase in these diseases over a 10 to 20 year period following the exposure. Such effects would be difficult to notice because the increase is usually small compared to the normal incidence rate of these diseases.

The Study has conservatively estimated the increased incidence of potentially fatal cancers over the 20 years following an accident. This has been done following a procedure which estimates the number by extrapolating data from high dose rates to low dose rates. It is generally believed that this procedure probably overestimates the effect considerably, but it is not possible to do experiments with large enough populations to determine these very small effects. The number of latent cancers are predicted to be very small compared to the normal incidence of cancer. Thyroid illness refers to small lumps on the thyroid gland that can be felt by an examining physician; they are treated by medical procedures that sometime involve simple surgery and rarely lead to serious consequences. For very large potential reactor accidents, the increase in nodules would be about equal to their normal incidence rate.

Radiation is recognized as one of the factors that can produce genetic effects which appear as defects in a subsequent generation. From the total population exposure caused by the accident, the expected increase in congenital defects in subsequent generations can be estimated. These effects are predicted to be very small compared to their normal incidence rate.

2.13 What are the most likely consequences of a core melt accident?

The most likely core melt accident would occur on the average of one every 17,000 years per plant. The sizes of the consequences of such an accident are given below.

Consequences of the Most Likely Core Melt Accident

	Consequences
Fatalities	<1
Injuries	<1
Latent Fatalities	<1
Thyroid Nodules	~ 4
Genetic Defects	<1
Property Damage*	$100,000

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* *This does not include damage that might occur to the plant.*

2.14 How does the annual risk from nuclear accidents compare to other common risks?

Considering the 15 million people who live within 20 miles of current or planned U.S. reactor sites, and based on current accident rates in the U.S., the annual number of fatalities and injuries expected from various sources are shown in the table below.

Annual Fatalities and Injuries Expected Among the 15 Million People Living within 20 Miles of U.S. Reactor Sites

Accident type	Fatalities	Injuries
Automobile	4,200	375,000
Falls	1,500	75,000
Fire	560	22,000
Electrocution	90	--
Lightning	8	--
Reactors (100 plants)	0.3	6

2.15 What is the number of fatalities and injuries expected as a result of a core melt accident?

A core melt accident is similar to many other types of major accidents such as fires, explosions, dam failures, etc., in that a wide range of consequences is possible depending on the exact conditions under which the accident occurs. In the case of a core melt, the consequences depend mainly on three factors; the amount of radioactivity released, the way it is dispersed by the prevailing weather conditions, and the number of people exposed to the radiation. With these three factors known it is possible to make a reasonable estimate of the consequences.

The Study calculated the health effects and the probability of occurrence for 4800 possible combinations of radioactive release magnitude, weather type, and population exposed. The probability of a given release was determined from a careful examination of the likelihood of various reactor system failures. The probability of various weather conditions was obtained from weather data collected at many reactor sites. The probability of various numbers of people being exposed was obtained from U.S. census data for current and planned U.S. reactor sites. These thousands of calculations were carried out with the aid of a large digital computer.

These calculations showed that the probability of accidents having 10 or more fatalities is predicted to be about 1 in 250,000 per plant per year. The probability of 100 or more fatalities is predicted to be about 1 in 1,000,000 and for 1000 or more, 1 in 100,000,000. The largest calculated value was 2,300 fatalities with a probability of about one in a billion.

The estimates given above are based on the assumption that evacuation procedures would be used to move most of the people out of the path of the airborne radioactivity. Experience has shown that evacuations have been successfully carried out in a large number of non-nuclear accident situations. Since nuclear power plants have evacuation plans prepared and since there is warning time before radioactivity would be released to the environment, it seems highly likely that evacuation would be effective in the case of nuclear accidents.

If we consider a group of 100 similar plants then the chance of an accident causing 10 or more fatalities is 1 in 2500 per year or, on the average, one such accident every 25 centuries. For accidents involving 1000 or more fatalities the number is 1 in 1,000,000 or once in a million years. Interestingly, this is just the probability that a meteor would strike a U.S. population center and cause 1000 fatalities.

The table shown below can be used to compare the likelihood of a nuclear accident to non-nuclear accidents that could cause the same consequences. These include man-caused as well as natural events. Many of these probabilities are obtained from historical records but others are so small that no such event has ever been observed. In the latter cases the probability has been calculated using techniques similar to those used for the nuclear plant.

Probability of Major Man-Caused and Natural Events

Type of events	Probability of 100 or more fatalities	Probability of 1000 or more fatalities
Man-Caused		
Airplane Crash	1 in 2 years	1 in 2000 years
Fire	1 in 7 years	1 in 200 years
Explosion	1 in 16 years	1 in 120 years
Toxic Gas	1 in 100 years	1 in 1000 years
Natural		
Tornado	1 in 5 years	very small
Hurricanes	1 in 5 years	1 in 25 years
Earthquake	1 in 20 years	1 in 50 years
Meteorite Impact	1 in 100,000 years	1 in 1,000,000 years
Reactors		
100 plants	1 in 10,000 years	1 in 1,000,000 years

In regard to injuries from potential nuclear power plant accidents, the number of injuries that could require medical attention shortly after an accident is about two times larger than the number of fatalities predicted.

2.16 What is the magnitude of the latent or long term health effect?

As with the short term effects the magnitude of latent cancers, treatable latent thyroid illness, and genetic effects vary with the exact accident conditions. The table below illustrates the potential size of such events. The first column shows the consequences that would be produced by core melt accidents, the most likely of which has one chance in 17,000 per plant per year of occurring. The second column shows the consequences for an accident that has a chance of 1 in million of occurring. The third column shows the normal incidence rate.

Magnitude of Latent Health Effects Expected in a 20 Year Period for an Accident that Produces 100 Fatalities

	Chance Per Plant Per Year		
Effect	One in 17,000	One in 1,000,000	Normal* Incidence Rate
Latent Cancers	<1	450	64,000
Thyroid Illness	4	12,000	20,000
Genetic Effects	<1	450	100,000

** This is the normal incidence that would be expected for people in the vicinity of any one reactor.*

In these accidents, only the production of thyroid nodules would be observed and this only in the case of an exceedingly unlikely accident. These nodules are easily diagnosed and treatable by medical or surgical procedures. The other effects are too small to be discernable above the high normal incidence of these two diseases.

2.17 What type of property damage might a core melt accident produce?

A serious nuclear accident would cause no physical damage to property beyond the plant site but may contaminate it with radioactivity. At high levels of contamination, people would have to be moved temporarily from their homes until the radioactivity either decayed away or was removed. At levels lower than this but involving a larger area, people might take simple actions to reduce possible contamination, but would continue being able to live in the area. The principal concern in this larger area would be to monitor farm produce to keep the amount of radioactivity ingested through the food chain small. Farms in this area would have to have their produce monitored and any produce above a safe level could not be used.

The most likely core melt accident, having a likelihood of one in 17,000 per plant per year, would result in little or no contamination. The probability of an accident that requires temporary evacuation of 20 square miles is one in 170,000 per reactor per year. Ninety per cent of all core melt accidents would be expected to be less severe than this. The largest accident might require temporary evacuation from 400 square miles. In an accident such as this, agricultural products, particularly milk, would have to be monitored for a month or two over an area about 100 times as large until the iodine decayed away. After that, the area requiring monitoring would be very much less.

2.18 What would be the cost of a core melt accident?

As with the other consequences, the cost will depend upon the exact circumstances of the accident. The cost calculated by the Reactor Safety Study included the cost of moving and housing the people that were evacuated, the cost caused by denial of land use and the cost associated with the denial of use of reproducible assets such as dwellings and factories. The most likely core melt accident, having a likelihood of one in 17,000 per plant per year, would cause property damage of about $100,000. The chance of an accident causing $100,000,000 damage would be about one in 50,000 per plant per year. Such an accident would be expected on the average to occur once every 5 centuries for 100 operating reactors. The probability would be about one in 1,000,000 per plant per year of causing damage of about 2-3 billion dollars. The maximum value would be predicted to be about 4-6 billion dollars with a probability of about one in 1,000,000,000 per plant per year.

This property damage risk from nuclear accidents can be compared to other risks in several ways. The largest man-caused events that have occurred are fires. In recent years there have been an average of three fires with damage in excess of 10 million dollars every year. About once every two years there is a fire with damage in the 50 to 100 million dollar range. There have been four hurricanes in the last 10 years which caused damage in the range of .5 to 5 billion dollars. Recent earthquake estimates suggest a one billion dollar earthquake can be expected in the U.S. about once every 50 years.

A comparison of the preceding costs shows that, although a severe reactor accident would be very costly, it would not be significantly larger than a number of serious accidents which our society deals with quite often, and the probability of such a nuclear accident is of course estimated to be much smaller than the other events.

2.19 What will be the chance of a reactor melt down in the year 2000 if we have 1000 reactors operating?

One might be tempted to take the per plant probability of a particular reactor accident and multiply it by 1000 to estimate the chance of an accident in the year 2000. This is not a valid calculation however because it assumes that the reactors to be built during the next 25 years will be the same as those being built today. Experience with other technologies such as automobiles and aircraft show that as more units are built and more experience is gained the overall safety record in terms of the probability of accidents per unit decreases. There are already changes in plants now being constructed that appear to be improvements over the plants analyzed in the study.

2.20 How do we know that the Study has included all accidents in the analysis?

The Study devoted a large amount of its effort to ensuring that it covered all potential accidents important in determining the public risk. It relied heavily on over 20 years of experience that exists in the identification and analysis of potential reactor accidents. It also went considerably beyond earlier analyses that have been performed by considering a large number of potential failures that had never before been analyzed. For example, failure of reactor systems that can lead to core melt and the failure of systems that affect the consequences of core melt have been analyzed. The consequences of the failure of the massive steel reactor vessel were considered for the first time. The likelihood that various external forces such as earthquakes, floods and tornadoes could cause accidents were also analyzed.

In addition there are further factors that give a high degree of confidence that all significant accidents have been included. These are: 1) the identification of all significant sources of radioactivity located at nuclear power plants, 2) the fact that a large release of radioactivity can occur only if reactor fuel melts, and 3) knowledge of the factors that can cause fuel to melt. This type of approach led to the screening of thousands of potential accident paths to identify those that would determine the public risk.

While there is no way of proving that all possible accident sequences which contribute to public risk have been considered in the Study, the systematic approach used in identifying possible accident sequences make it very unlikely that an accident which would contribute to the overall risk was overlooked.

2.21 How do your calculations of reactor accidents compare with those of earlier studies that predicted much larger consequences?

The principal earlier Study of reactor accidents (WASH-740) was published by the AEC in 1957, before any commercial nuclear power plants were operating. Thus, this Study was necessarily vague about the engineering details of reactor accidents. The purpose of that Study was to essentially maximize the consequences that could occur in an accident. This was done because it was to serve as a basis for the Congress to use in establishing adequate indemnification of the public in the event that an accident occurred. Thus, WASH-740 served as the basis for the Price-Anderson Act which provides such indemnification.

The reactor used for the WASH-740 Study was one that generated 500 million watts (megawatts) of thermal energy as opposed to today's reactor of about 3200 megawatts. To compare the earlier estimates with the more realistic approach used in this Study, calculations were made for a 500 megawatt reactor using the Reactor Safety Study model. The results are presented in the table below.

The differences between these two sets of results can in large part be explained as follows:

1. This Study used actual population data from the census bureau for the areas in the vicinity of actual reactor sites. WASH-740 used an estimated population that was much higher.
2. WASH-740 assumed that 50 percent of all the core radioactivity would be released to the environment. This Study, using available experimental data, finds it physically impossible to attain total core releases as large as those used in WASH-740.
3. The WASH-740 calculation made no provisions for the evacuation of people. Experience shows that evacuation is highly likely and would significantly reduce the consequences of an accident should it occur.
4. The radioactivity released in a potential reactor accident would be in the form of a plume such as can be seen from smoke stacks. The radioactivity has sufficient heat associated with it to cause the plume to rise, thus reducing the concentration of radioactivity near the ground. This has some effect in reducing consequences. WASH-740's calculations did not include this effect.

2.22 What techniques were used in performing the Study?

The latest methodologies, developed over the past 10 years by Department of Defense and National Aeronautics and Space Administration, were used in the Study. These techniques are called event trees and fault trees and help to define potential accident paths and their likelihood of occurrence.

An event tree defines an initial failure within the plant. It then examines the course of events which follow as determined by the operation or failure of various systems that are provided to prevent the core from melting and to prevent the release of radioactivity to the environment. Event trees were used in this Study to define thousands of potential accident paths which were examined to determine their likelihood of occurrence and the amount of radioactivity that they might release.

Fault trees were used to determine the likelihood of failure of the various systems identified in the event tree accident paths. A fault tree starts with the definition of an undesired event, such as failure of a system to operate, and then determines, using engineering and mathematical logic, the

Comparison of Consequences from Accidents in a 500 MWt Reactor as Calculated in WASH-740 and as Predicted by WASH-1400

Parameter	WASH-740 Peak	WASH-1400 Peak	 Average
Acute Deaths	3,400	92	0.05
Acute Illness	43,000	200	0.01
Total Dollar Damage (billions)	7[1]	1.7[2]	0.51[2]
Approximate Chance per Reactor Year		One in a billion	One in ten thousand

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[1] *This is the value predicted in 1957 dollars.*

[2] *The values shown are in 1973 dollars. In 1957 dollars, these values should be about two-thirds of that shown.*

ways in which the system can fail. Using data covering 1) the failure of components such as pumps, pipes and valves, 2) the likelihood of operator errors, and 3) the likelihood of maintenance errors, it is possible to estimate the likelihood of system failure, even where no data on total system failure exists.

The likelihood and the size of radioactive releases from potential accident paths were used in combination with the likelihood of various weather conditions and population distributions in the vicinity of the reactor to calculate the consequences of the various potential accidents.

2.23 How will the results of the Study affect safety decision making?

This Study, using an overall methodology directed toward risk assessment, has developed new insights that contribute to a better understanding of reactor safety. However, many of the techniques used were developed and used only for the purpose of overall risk assessment and are not directly applicable for optimizing safety designs or evaluating the acceptability of specific designs or reactor site locations. Although the techniques developed in the Study may someday be useful for such purposes, considerable additional development is needed before they can assist effectively in safety decision making.

Decision making processes in many fields, and especially in safety, are quite complex and should not lightly be changed. This is especially true where a good safety record has already been obtained, as is so far true for nuclear power plants. The use of quantitative techniques in decision making associated with risk is still in its early stages and is highly formative. It appears that for the near future considerable additional development is needed in quantitative techniques before they can be used effectively in safety decision making processes.

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