ED 107 518 SE 019 207

AUTHOR	Hogerton, John F.
TITLE	Atomic Power Safety.
INSTITUTION	Atomic Energy Commission, Washington, D. C. Office of Information Services.
PUB DATE	64
NOTE	48p.
AVAILABLE FROM	USAEC Technical Information Center, P. O. Box 62, Oak Ridge, TN 37830 (cost to the general public for 1-4 copies, $0.25 ea., 5-99, $0.20 ea., 100 or more, $0.15 ea.)
EDRS PRICE	MF-$0.76 HC-$1.95 PLUS POSTAGE
DESCRIPTORS	*Energy; Environment; *Nuclear Physics; Physics; Radiation; Radioisotopes; *Safety; Scientific Research; *Utilities
IDENTIFIERS	AEC; Atomic Energy Commission; *Nuclear Energy; Power Plants

ABSTRACT

This publication is one of a series of information booklets for the general public published by The United States Atomic Energy Commission. Among the topics discussed are: What is Atomic Power?; What Does Safety Depend On?; Control of Radioactive Material During Operation; Accident Prevention; Containment in the Event of an Accident; Licensing and Regulation of Atomic Power Plants; The Experience Record; Safety Research; and Additional Information on Atomic Power. Schools and public libraries may obtain a complete set of the booklets without charge. (BT)

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Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

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Atomic Power Safety

by John F. Hogerton

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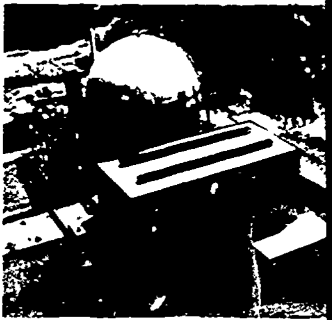
United States Atomic Energy Commission
Office of Information Services
Library of Congress Catalog Card Number: 64-62700
1964



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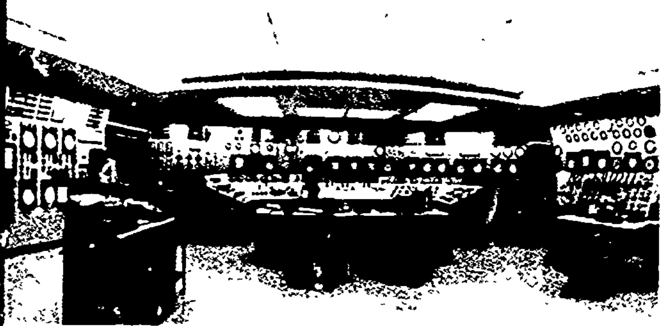
John F. Hogerton is a chemical and nuclear engineer (B. E , Yale, 1941) who has worked in the atomic industry from its beginning. Now an independent consultant, Mr. Hogerton was co-author of the final report on the secret wartime gaseous diffusion operation at Oak Ridge, Tenn., and served on the Manhattan Project Editorial Advisory Board. He has written numerous other books, including reference volumes for the AEC, for industry and for the American Society of Mechanical Engineers. He also is the author of other booklets in this series, including *Nuclear Reactors* and *Atomic Fuel*.

ABOUT THIS BOOKLET

This booklet is condensed from a larger publication, *Background Information on Atomic Power Safety*, published in January 1964, by the Atomic Industrial Forum. That publication and this abridgment were produced in recognition of the emergence of commercial atomic power as an important factor in our national economy, and of the resulting need for readily available information in nontechnical form on the characteristics of nuclear power plants and on the various measures taken during their design, construction, and operation for public safety.

This adaptation was prepared by the Atomic Energy Commission to provide increased dissemination of information on the nature and safety of atomic power operations, and to include factual treatment of the topic in the AEC "Understanding the Atom" series.

The original booklet was produced by the Public Understanding Program of the Forum, the Forum is a nonprofit membership association to promote the development and application of atomic energy for constructive purposes. Its members include industrial, financial, legal, educational, labor and government organizations



in the United States and other countries. Copies of the larger publication may be obtained by writing to: Charles B. Yulish, Project Manager, Public Understanding Program, Atomic Industrial Forum, 850 Third Ave., New York, 22, N. Y.

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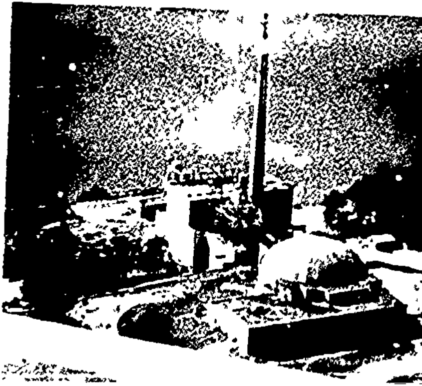

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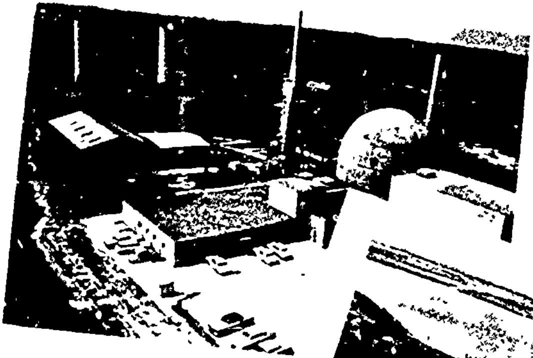

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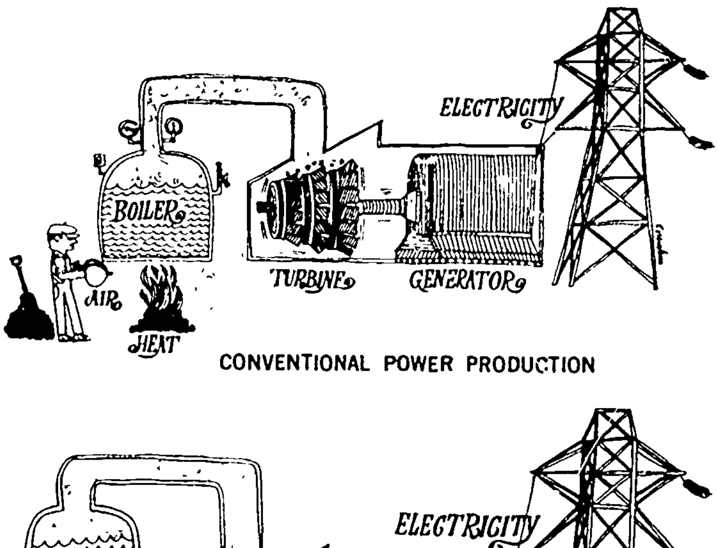
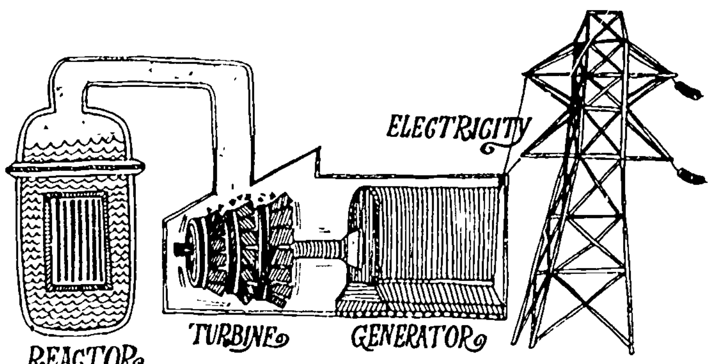


CONVENTIONAL POWER PRODUCTION



ATOMIC POWER PRODUCTION

Atomic Power Safety

By John F. Hogerton

WHAT IS ATOMIC POWER?

The subject of this booklet is the safety of central-station atomic power plants, by which is meant plants operated by utilities to supply electricity to their customers. Its purpose is to present factual information on a number of topics relating to this subject, including some of the underlying technical considerations.

By way of introduction, we will first present some general information on atomic power—what it is, why it is being developed, and where it stands today.

About 80% of the electricity used in the United States is produced in steam-electric plants. These are plants in which heat from the combustion of coal, oil or natural gas (the so-called "fossil fuels") converts water to steam. The steam is then used to drive a turbine-generator and thereby produce electric power.

An atomic power plant is a new kind of steam-electric plant in which the heat comes not from the burning of a fossil fuel, but from the fission of an atomic fuel, the basic sources of which are uranium and thorium. The turbine-generator part of an atomic plant is similar to that of an ordinary steam-electric plant; and the product, electricity, is identical.

Why is atomic power important?

There are two principal incentives for developing and using atomic power. First, it promises to help stabilize and may soon reduce the cost of generating electricity in sections of the country that are distant from coal mines or oil or gas fields and therefore bear high fuel transportation costs. Examples are the Northeast and the West Coast where fuel costs typically account for about half the total cost of power generation. Atomic power is already benefiting these sections by making a competitive energy source available to them.

The second reason is that atomic power promises ultimately to be an indispensable energy resource, country-wide. While U. S. reserves of fossil fuels (especially coal) are large, our rate of consumption is increasing rapidly. This is true not just in electric power generation, which presently accounts for about one-fifth of our fuel consumption, but also in transportation, manufacturing, heating and other activities in which fuel is consumed in large quantities. Altogether, it has been estimated that we will use as much energy from fuel over the next twenty years as we used from the American Revolution to the present day. When projected increases in our rate of energy consumption are taken into account, the indications are that we would experience some effects of depletion of our fossil fuel resources only two or three generations hence if we were to continue our present pattern of fuel utilization. The use of atomic fuels for generating electric power will help conserve fossil fuels for uses for which they are uniquely suited, and will greatly extend our energy resources for the future.

Where does atomic power stand today?

U. S. development of atomic power for central-station use began in earnest in 1954, when the Congress passed legislation permitting utilities and others besides the Federal Government to own atomic reactors. This action was taken to encourage, as well as to enable, manufacturers and utilities to develop and use atomic power. There was already in existence by then a considerable body of applicable technology, thanks to the highly successful development of reactors for submarine propulsion, and to experience gained in other major fields of reactor use.

In the short span of time since the 1954 Act became law, much has been accomplished in the direction of integrating atomic power into the U. S. electric power economy. For example,

1 A total of about 1 million kilowatts of atomic power capacity has been placed in operation; plants with an additional 1 million kilowatts of capacity are in an advanced state of construction; and an additional 2½ million kilowatts of capacity are now being designed. These numbers are small in relation to the total amount of U. S. electric power generating capacity, which is currently almost 2 hundred million kilowatts. They nonetheless represent a significant amount of power. For example, 2 million kilowatts (the amount of atomic power capacity now or soon to be in operation) are enough to supply the electrical demand of such states as Connecticut and Kansas, and of such nations as Denmark and Hungary.

2 The total capital investment made or committed to date by U. S. utilities for atomic power generation facilities has almost reached the $1 billion mark.

3 Atomic power plants can now be purchased on a firm-price basis with performance warranties.

This progress has come about as a result of a partnership effort on the part of the Atomic Energy Commission (AEC) and U. S. industry.

There exists today a sizable atomic power industry with a background of experience dating back to December 2, 1942, the day Enrico Fermi and his colleagues successfully demonstrated the world's first atomic reactor on the campus of the University of Chicago. This industry now has some 2 million man-years of experience in the United States.

WHAT DOES SAFETY DEPEND ON?

It should be understood at the outset that it is physically impossible for an atomic power plant to behave like an atomic bomb. In the latter, pieces of essentially pure fissionable material are rapidly compressed into a dense mass which is forcibly held together for an instant of time to enable the chain reaction to spread through it. These conditions do not and cannot exist in the reactors used in atomic power plants. They employ relatively dilute fuel; they are designed along different principles; and they operate differently.

The safety of atomic power plants does not depend on restraining the force of atomic energy but on containing the radioactive material it generates.

The principal radioactive materials generated are the "ashes" of fission—the so-called fission products. These are a diverse mixture of substances. Some are gases, some are solids. Some have short radioactive lifetimes,* some have long lifetimes, and some are stable (non-radioactive). The quantity of fission products formed is small in terms of mass—only a few pounds a day in a big plant—but large in terms of radioactivity. As the plant operates, the reactor's inventory of radioactive fission products builds up gradually until a point is reached at which the rate they lose radioactivity just about offsets the rate at which they are formed and the [illegible] essentially levels off. As will be brought out, all but a very small amount (less than one-thousandth of one per cent) of the material normally remains confined within the fuel.†

Small additional amounts of radioactive matter, called activation products, are formed in an atomic power plant by exposure to neutrons. This only happens in and around

* The lifetime of a radioactive substance is usually expressed in terms of its "half-life," which is the time it takes for it to lose half of its radioactivity. Half-lives of most fission products range from fractions of a second to tens of years.

† For more about nuclear fission, atomic energy and reactors, see "Our Atomic World" and "Nuclear Reactors," other booklets in this series.

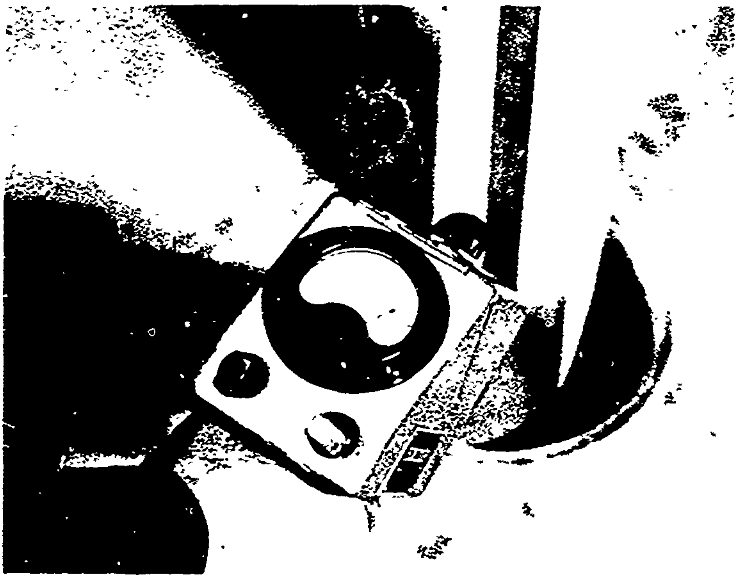
the reactor core, which is the only part of the reactor where many neutrons are present. Most activation products have very short lifetimes and are of minor importance in relation to fission products.

The basic unit for expressing amounts of radioactivity is the curie, named in honor of Marie Curie, the discoverer of radium. One curie of radioactivity is equal to a certain very large number (37 billion) of atomic disintegrations per second. But it does not help our understanding of radioactivity to be able to relate numbers of curies to numbers of disintegrations per second since the latter terminology is just as unfamiliar as the former. And what is more important, it has little absolute meaning when applied to a mixture of radioactive substances such as fission products. The reason is that different kinds and strengths radiation are given off by different radioactive materials. One kind (alpha particles) is blocked by an ordinary piece of writing paper, while another kind (gamma rays) can penetrate several feet of concrete. Also, different radioactive substances, besides having different radioactive properties, also differ in other properties that are important from the viewpoint of safety. Thus, to say that there are X curies of radioactivity in an atomic power plant is a little like lumping together the number of oranges, apples, grapes, watermelons, etc., in a grocery store; it is a number that does not tell us much.

The most meaningful way of gauging radioactivity from a safety viewpoint is by the amount of radiation to which individuals might be exposed. This topic will be discussed in a moment. First we should comment on a very important aspect of radioactivity — namely, radiation detection and measurement.

Radiation detection and measurement

The presence of atomic radiation, though not detectable by the human senses, is readily detected by several types of instruments. One of the simplest radiation detectors is ordinary photographic film, which darkens on exposure to radiation and is routinely used in the form of "film badges" as a means of measuring the cumulative amount of exposure received during a given period by workers in atomic energy installations. Other types of detectors (such as Geiger counters, proportional counters and scintillation counters) are used to detect the presence and measure the



Hand instrument used for radiation monitoring

intensity of atomic radiation. As the names of these instruments suggest, they are capable of "counting" individual particles or units of radiation. Such instruments are routinely used to monitor radiation levels in and around atomic energy installations.

The ability of radiation detection instruments to count individual particles and units of atomic radiation makes it possible to make extremely sensitive radiation measurements --or, to put it another way, to detect the presence of extremely small amounts of radioactive materials. This ability is the basis for the wide use in science and industry of small amounts of radioactive substances as a means of "tracing" events in biological, chemical or physical processes. An experiment conducted by the U. S. Geological Survey can be cited as an example. The U. S. G. S. wanted to trace the loss of water from a large reservoir. For this purpose a small amount (hundredths of a gram*) of a radioactive form of hydrogen was put in the reservoir, and ground water was later sampled at points several miles away. By measuring the concentrations of radioactive hydrogen in the samples, much was learned about the pattern of the loss from the reservoir. The sensitivity of this technique, and of radiation detection in general, is illustrated by the fact that the concentrations of radioactive hydrogen tracer in the samples were on the order of 0.00000000003 parts per million.

Radiation detection is also very sensitive in another way — namely, in its ability to identify specific radioactive substances. This is made possible by the fact that every species of radioactive atom has a characteristic pattern of radioactivity.

Thus those who operate atomic power plants can, through the use of radiation detection and measurement instruments, maintain an extremely close check at all times, not only on radiation levels in and around the plant but also on the identity and amount of any fission products present in plant effluents (see next chapter).

Background radiation

Atomic radiation is not new to the world; it is part of our natural environment. We have always lived in its presence. This "background" of natural radiation comes from two sources. One is radiation in the form of high-energy particles that come from outer space and are known collectively as cosmic rays. The other source is natural radioactivity — that is, naturally radioactive substances present in commonplace materials, such as granite, and in our very bodies. Part of the potassium and carbon in our bodies, for example, is radioactive. The following table shows a breakdown of the radiation typically received by an individual from natural sources. The values are ex-

* There are [illegible] grams in a pound. One gram roughly equals the weight of two bobby pins.

pressed in thousandths of a rem (millirem). The rem is a measure that takes into account the properties of the kinds of radiation involved. The indicated total of 125 millirems per year is an average figure. The exact figure varies from place to place mainly because of differences in the amounts

REPRESENTATIVE BREAKDOWN
OF BACKGROUND RADIATION

Source	Radiation Received* (Thousandths of a rem per year)
Cosmic rays	50
Natural radioactivity	
External sources	50
Internal sources	25
Total	125

*Dose to reproductive organs and other soft body tissue.
Source Report of United Nations Scientific Conference on the Effects of Atomic Radiation, 1962.

of natural radioactive materials present in the environs. Another reason for the variation is that cosmic rays lose strength as they pass through the earth's atmosphere so that they are stronger at high altitudes than at low altitudes. In the U. S., background radiation levels range from about 90 to just under 200 millirems per year. In some parts of the world levels as high as 12,000 millirems per year have been reported.

Incremental radiation exposure*

When we talk about radiation exposure resulting from atomic power operations, we are talking about incremental exposure to exactly the same kinds of radiation found in nature. Nor is atomic power the only source of incremental

*Defined in this case as the additional exposure received as the result of atomic power operations or other peaceful uses of atomic energy, exclusive of exposure to radiation for medical purposes.

exposure. For example, medical and dental X rays are familiar sources of radiation exposure, as are television sets and luminescent watch dials.

The biological effects of exposure to atomic radiation have been studied for many years. We now have relatively definitive knowledge about effects on the human system of exposure to large radiation doses since these have been observed. Effects that can be definitely ascribed to chronic exposure to very low radiation levels have never been observed; but, by inference from data obtained at higher levels and from our general knowledge, scientists assume that they exist. The problem of obtaining definitive information to validate this assumption is complicated by the fact that other factors in the human environment are known to produce the same changes in the human system as those assumed to result from exposure to low-level radiation.

The fact that we know less about low-level effects than high-level effects does not mean that we are without knowledge about radiation as a factor in our environment. In 1960, after reviewing what was known about radiation effects, the National Research Council commented on this point as follows:

> Despite the existing gaps in our knowledge, it is abundantly clear that radiation is by far the best understood environmental hazard. The increasing contamination of the atmosphere with potential carcinogens,* the widespread use of any new and powerful drug in medicine and chemical agents in industry, emphasize the need for vigilance over the entire environment. Only with regard to radiation has there been determination to minimize the risk at almost any cost.

In this connection, a feature that distinguishes radiation from other environmental hazards is the relative ease and remarkable sensitivity with which it can be detected and measured.

Study of the environmental aspects of radiation goes on around the clock. U. S. Public Health Service and AEC monitoring stations, supplemented by State and local facilities, routinely check air, food and water supplies at sam-

*Cancer-producing chemicals.

Instrument used for measuring radioactivity of samples

pling points throughout the country. While this surveillance network was established to monitor fallout from nuclear weapons testing, it provides an accurate and continuous check on the presence of radioactive material regardless of its source. Research on the behavior of radioactive substances in the environment is contributing to the development of new techniques for handling radiological contamination problems. Procedures have been established to mobilize teams of skilled technicians to deal with such problems should they arise. While all of this work relates primarily to the U. S. civil defense effort, the knowledge being gained and the techniques being developed contribute generally to the control of radiation in our environment.

Radiation protection standards

The problem of balancing risk against benefit is perhaps the oldest problem in human experience. In the radiation field the solution has taken the form of radiation protection standards.

Over the years, independent committees of scientists active in the radiation field have sought to define safe practice in the use of man-made radiation. There is, for example, the International Commission on Radiological Protection (ICRP), which acts in an advisory capacity to the World Health Organization. In the United States, there is the National Committee on Radiation Protection and Measurements (NCRP), which maintains its headquarters in offices of the National Bureau of Standards but is organizationally independent of that agency.

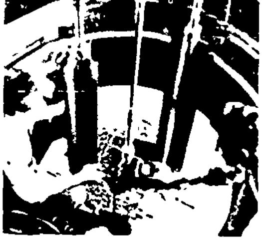
The standards which govern acceptable practice in atomic power plants are determined by the Atomic Energy Commission as part of its statutory responsibility under Federal law. In setting these standards, the AEC receives official guidance from the Federal Radiation Council (FRC), whose recommendations are subject to the approval of the President and whose membership includes the Secretaries of the Department of Health, Education and Welfare, the Department of Defense, the Department of Commerce, the Department of Labor, the Department of Agriculture, and the chairman of the AEC. Also, the AEC has the benefit of the advice of the National Committee on Radiation Protection and Measurements, and of several advisory committees which the AEC itself has established, including an Advisory Committee of State Officials.

In short, the procedures followed by the AEC in setting radiation protection standards ensure that the best scientific advice obtainable is in fact obtained.

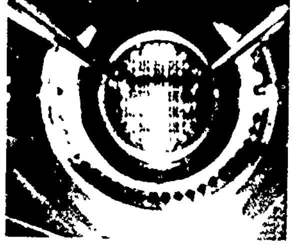
The Federal Radiation Council has recommended that incremental whole body radiation exposure of members of the general public not exceed 500 millirems per year. The AEC's radiation protection standards are designed accordingly. They include a tabulation of maximum permissible concentrations of specific radioactive substances in air, water, etc.

The AEC's basic radiation protection standards are published in the Code of Federal Regulations and have the force of law.

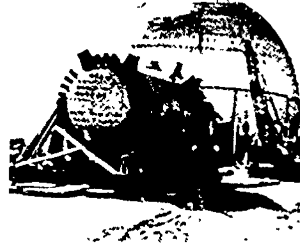
It should be mentioned before going further that the amount of incremental radiation dose estimated to have been received by communities in the vicinity of commercial atomic power plants has been kept to a very small fraction



Apparatus used for core physics measurements



Partial assembly of fuel elements in reactor core



Reactor vessel being moved into containment

of the limit recommended by the FRC. We say "estimated to have been received" because, despite the sensitivity of radiation detection instruments, the radiation levels have been generally found to be indistinguishable from natural background levels. Thus, the only way operators of these plants find it possible to estimate the exposure of neighbors is to calculate this on the basis of amounts of radioactive materials released by the plants and the dispersion characteristics of the environment.

This booklet's focus

The booklet focuses on the safety of atomic power operations within the framework of the radiation protection standards, with these points in mind:

1. Central-station atomic power development is being pursued as a matter of both national and industrial policy;

2. Radiation protection regulations have been laid down by competent authority to govern this activity;

3. Our purpose is to present factual information on safety considerations and practices and to summarize the industry's safety record to date.

The atomic power industry's "formula" for safety is as follows:

1. In designing an atomic power plant, evaluate the possible types and degrees of accidents;

2. By taking advantage of natural laws, by providing engineering safeguards, by conservative design, and by careful construction and operation, do all that can be done to prevent these accidents from occurring;

Reactor vessel being installed

Fuel rod assemblies prior to installation

Massively shielded container used to transfer "spent" fuel elements

3. Build into the plant dependable means of containing the consequences of accidents should they occur;

4. Check and double check the safety of the design, construction, and operation of the plant through licensing and compliance procedures;

5. Conduct supporting safety research and test programs.

CONTROL OF RADIOACTIVE MATERIAL DURING OPERATION

The previous chapter described the principal source of radioactivity in an atomic reactor—namely, fission products. This chapter describes how these substances are controlled during routine operation of a central-station atomic power plant. In this and subsequent chapters the discussion will be based on plants employing water-cooled reactors, which are the most widely used at the present time; however, the principles behind the plant features and operating procedures described apply to central-station atomic power plants in general.

The reactor core

A large water-cooled reactor contains 50 to 100 tons of fuel. The fuel material most commonly used today is slightly enriched uranium dioxide (UO_2) in the form of small cylindrical pellets.* The pellets are placed in thin-

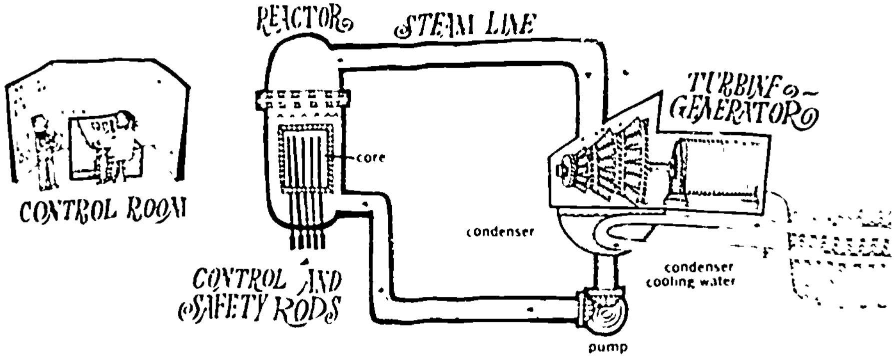
* A [illegible] fuel material is [illegible] oxide, which is used in combination with enriched uranium dioxide.

walled metal tubes to form fuel rods, a number of which are bundled together in a long metal can to make up an assembly known as a fuel element. A number of these are positioned in a grid to make up what is known as the reactor core. The core is contained in a massively constructed steel tank, known as the reactor vessel, through which cooling water flows.

The inventory of fission products in the plant, after several months of operation, amounts to several hundred pounds. The fission products are, of course, formed inside the fuel. On a weight basis, in excess of 99.99% of the fission-product inventory of the plant normally remains confined within the fuel elements. As this fact indicates, it is difficult for the fission products to escape the fuel. There are two reasons. First and most important, it is the nature of uranium dioxide to hold tenaciously onto the fission products. Second, fission products which manage to break the grip of the uranium dioxide must find a way to get past the fuel cladding (that is, the metal tubes) in order to get out. Those that do get out of the fuel enter the coolant (see below).

When it comes time to refuel the plant, which is done at intervals of a year or longer, the reactor is shut down and the top of the reactor vessel is removed. A crane is used to lift out the spent fuel elements and move them to a storage vault or pool. There they are left for several months to allow for the shorter-lived radioactivity to subside. By the end of this "cooling" period, nearly all of the gaseous fission products have lost their radioactivity. The fuel elements are then loaded into ruggedly-built lead-shielded steel containers for shipment via truck, rail, or barge, to a plant where they will be chemically processed to recover their unused fuel content for future use. It is at the processing plant that the fission products contained in the fuel elements are removed, concentrated and stored.

Thus all but an extremely small fraction of the fission products formed during the operation of an atomic power plant are normally held captive in the heart of the reactor or in spent-fuel storage, and leave the premises when the spent fuel is shipped away.

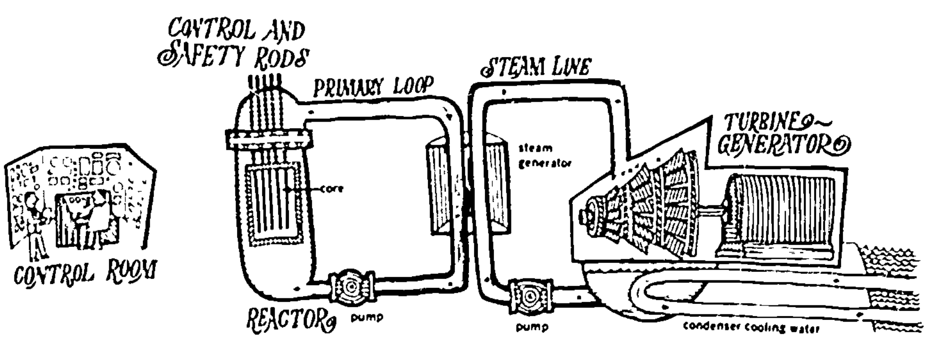


Boiling Water Plant (Direct Cycle)

The coolant system

There are two basic types of water-cooled reactors — pressurized water reactors and boiling water reactors (see figures on this page). In the former, the reactor cooling water (primary coolant) is kept under sufficient pressure to keep it from boiling in the reactor vessel. On leaving the reactor vessel it passes through a heat exchanger in which it gives up its heat to a separate stream of water (secondary coolant), thereby converting the latter to steam. Then it flows back to the reactor.

In a boiling water reactor the flow pattern is different. In this case the reactor cooling water is allowed to boil in



Pressurized Water Plant

the reactor vessel so that steam is generated in the reactor proper.* This steam goes to the turbine, is condensed, and the condensate is returned to the reactor vessel.

It is important to understand that in both systems the primary coolant circulates within a closed equipment circuit and is completely cut off from its original source (river, lake, or ocean). Indeed, in all commercial atomic power plants essentially the only water that goes from a waterway into the plant and then empties back directly into the waterway is that which is used to cool the turbine condensers. This water does not flow through the reactor. Its function is merely to carry non-usable heat away from the plant.

As the plant operates, the reactor cooling water picks up some radioactivity. One source is leakage of some fission products through minute imperfections in the fuel element cladding. These fission products, amounting to something like one-thousandth of one per cent of the fission-product inventory of the plant, are principally the gaseous and more

Assembly of a main coolant pump

Fabrication of a heat exchanger (steam generator)

*Additional steam may be generated in a separate heat exchanger similar to that in a pressurized water plant.

easily vaporized solid constituents of the fission-product mixture. Another source of radioactivity in the reactor cooling water is activation products. These include activation products formed in the water, most of which have very short lifetimes,* and activation products that are formed in reactor structural materials and enter the coolant through corrosion or erosion.

To maintain the purity of the water and to limit the amount of radioactivity in the primary cooling system, the reactor coolant is purified. This is done by drawing off a portion of the primary coolant flow, passing it through purification equipment, and then returning it to the system.

Radioactive waste handling at the plant site

In addition to processing a portion of the primary coolant flow, the coolant purification system may also handle water collected from other points in the reactor installation (for example, water that has leaked out of equipment, or that has been used to clean out equipment during maintenance operations). The purification is done by means of evaporators, demineralizers, filters and the like.

All but a small fraction of the solid or liquid radioactive substances removed during the purification process are collected as waste concentrates, which are temporarily stored. The balance, averaging a few millionths of a gram per day during routine operation, is discharged to the waterway serving the plant in a dilute waste stream generally so feebly radioactive that it meets Atomic Energy Commission standards for drinking water. Further dilution occurs as the waste stream is dispersed in the waterway.

The radioactive gases removed during the purification process average a few hundred thousandths of a gram per day during routine operation. This material is released to the atmosphere through a tall chimney on a controlled basis to assure that there is sufficient dilution and at-

*For example, species of radioactive nitrogen (formed by neutron absorption in oxygen atoms in the water) have half-lives on the order of a few seconds.

mospheric dispersion of the radioactivity to meet AEC regulations, which are based on the annual radiation exposure that might be received by persons living at the plant boundary.

The radioactive waste concentrates from the purification process, together with other miscellaneous solid wastes are encased in concrete in steel barrels. When a sufficient number of barrels accumulate, they are shipped from the plant to an AEC-approved site for burial or long-term storage.

Monitoring and regulatory control

Radiation levels inside and outside the plant are routinely monitored to ensure that proper conditions are maintained. Furthermore, all of the operations that have been described are subject to AEC inspection and compliance procedures.

ACCIDENT PREVENTION

As has been stressed, the central safety consideration in the operation of a central-station atomic power plant is control of the plant's inventory of radioactive material. Release of any of this material to the environment must satisfy the Atomic Energy Commission's radiation protection regulations. The last chapter described the procedures followed in routine plant operation. Now it is time to consider the possibility of accidents. In this chapter we will discuss the principal theoretical considerations involved, cite natural safety features which limit accident possibilities, and describe some of the precautions taken to prevent possible accidents from occurring. Another aspect of this subject—namely, containment of the consequences of accidents in the event they do occur—will be discussed in the next chapter.

Nuclear Excursions

The power level at which a reactor can operate safely is limited by the capacity of its cooling system—that is, the rate at which the primary coolant can carry away the heat generated in the reactor core. If heat were to be generated at a faster rate than it is carried away by the coolant, the fuel would overheat and could melt or even vaporize. The consequences might range from heavy radioactive contamination of the coolant (through release of fission products from molten fuel) to damage to reactor equipment and some release of radioactivity from the primary reactor system into the plant containment system.

Thus one broad category of accidents which the reactor designer takes into account is that of an accidental increase in the rate of the fission chain reaction—referred to in reactor parlance as a "nuclear excursion." And, in this connection, he also takes into account the possibility of a secondary effect—namely, that the high temperature reached in the fuel might cause chemical reactions between reactor materials that would increase the amount of energy involved.

Natural Safeguards

Most of us know someone who is contrary in the sense that the harder we try to get him to do something, the more reluctant he is to do it. We usually attribute this to a stubborn streak in his nature. Reactors designed for central-station service have a similar streak in their nature when it comes to nuclear excursions. For they are so designed that when an excursion begins, their natural tendency is to slow themselves down. Several factors contribute to this inherent stubbornness. The most important is what reactor designers refer to as the "Doppler effect." This is a complex phenomenon to describe but the gist of it is that, as the temperature of the fuel rises, the proportion of neutrons captured by non-fissioning atoms increases and the rate of fission therefore tends to slow down. The Doppler effect is not only automatic but instantaneous, and so offers immediate resistance to any increase in reactor power level.

A second factor is that as the fuel becomes hotter its density decreases slightly, which also acts to lower its reactivity.

Thirdly, in water-cooled reactors, the water that flows through the reactor core, besides carrying away the heat, serves also to "moderate" the neutrons and thereby encourage the fission chain reaction. Just as the fuel density decreases with increasing temperature, so does the density of the water and with the same effect—that is, lowering of reactivity.

In these and other ways, accidental nuclear excursions tend to be self-correcting. Thus a runaway reaction can only occur if there is an accidental addition of reactivity so large as to override the losses of reactivity which accompany the excursion. Various design safeguards are provided to prevent this from happening.

It should also be mentioned that in normal operation the temperature of the fuel cladding is kept well below its melting point. There is thus a good deal of "elbow room" for the fuel temperature to rise and fall during an excursion without affecting the integrity of the fuel elements.

Design Safeguards

We have described the natural safeguards against a nuclear excursion in some detail to correct any impression you may have had that controlling a reactor is like having a lion straining on a leash. Actually, if anything "strains its leash" in a reactor it is the reactor's control system, which is designed to shut down the reactor automatically at the first sign of an unsafe condition.

To understand how reactors are controlled it is necessary to explain what is known as "excess reactivity." If a reactor were loaded with the bare minimum of fuel needed to initiate a fission chain reaction, it could not operate for more than a split second. Why? Because as soon as the fission reaction is started, some fuel would be consumed and the reactor's fuel inventory would fall below the bare minimum needed. Also, fission products would begin to be formed and these substances would absorb some of the neutrons needed to sustain the chain reaction. For the latter reason, even if enough fuel were added to replace exactly the amount that had been consumed, the reactor still could not operate. Before the reactor could be started up again, one would have to add a little extra fuel to make up for the "drag" on the system caused by neutron losses to fission products. Because of these two factors, it is necessary in practice to load reactors with more fuel than the theoretical minimum requirement. This extra fuel furnishes excess reactivity against which the system can draw to sustain the chain reaction as the operation of the reactor proceeds.

For stable operation, there must be a means of compensating for the excess reactivity that is present in the reactor core. In other words, there must be a way of controlling the rate at which the excess fuel is consumed. Usually this is done by introducing a balancing amount of "negative reactivity" in the form of substances that are highly efficient neutron absorbers. (They can be thought of as neutron blotters.) By moving these substances into and out of the reactor core with adjustable control rods, the neutron population of the core can be decreased or increased, thereby slowing down or speeding up the chain reaction. In effect, they serve to control the rate at which neutrons are fed to the fuel.

Reactors controlled in this fashion are equipped with a number of control rods, some of which are held in reserve for emergency shutdown of the reactor. Also, in many reactors, solutions containing neutron absorbers are added to the primary coolant, either for routine control or for use during shutdown periods. In all reactors, neutron sensing instruments are used to monitor the neutron population of the reactor core. On signals from these instruments, reactivity is added to or subtracted from the system by control rod adjustments or other means. In reactors designed for central-station service, several independent neutron monitoring circuits are employed and are wired into safety mechanisms that stop the reactor automatically if the neutron readings exceed predetermined limits. This is done by rapidly inserting control rods into the reactor core. In some reactors, neutron-absorbing solutions are also injected into the core as part of the shutdown procedure.

Similarly, other instruments monitor other aspects of reactor operation, such as the level of coolant in the reactor vessel, the temperature of the coolant leaving the reactor vessel, and the pressure of the primary reactor system. These instruments are also wired into safety mechanisms that stop the reactor automatically if an abnormal condition develops.

It should be added that every effort is made to design the safety mechanisms to operate in a "fail-safe" manner, meaning that if a component were to fail, the mechanism would automatically be triggered into operation. For example, control rods are held in standby position by power operated electrical or mechanical devices. Should a power failure occur, the rods would automatically be released and enter the reactor core, thereby shutting down the reactor.

Failure of cooling system

Overheating of fuel could also be caused by an interruption in the flow of coolant through the reactor core when the reactor is otherwise operating in a stable manner. Also, once atomic fuel has seen service in a reactor it continues to give off heat when the reactor is shut down and even after it has been removed from the reactor. This "afterheat" results from the radioactivity of the fission products and, while not nearly as intense as the heat that is generated during reactor operation, it could lead to melting of the fuel elements if adequate cooling were not provided. Thus a second broad category of accident which the reactor designer takes into account is that of malfunctioning of the cooling system—either during operation or during reactor shutdown and spent-fuel storage.

The safeguards provided against cooling failures can be summed up in one phrase. ultraconservative design. Although all components are designed and fabricated to exacting standards, the designer assumes various mishaps may occur, ranging from a slow leak in auxiliary equipment to an abrupt break in the main coolant piping. Instruments are provided to monitor the system for such occurrences and, as described above, are connected into the reactor safety mechanisms so that the reactor is automatically shut down at the first sign of significant interruption in coolant flow or of outright "loss of coolant." Also, a standby system is provided to cool the reactor core during reactor shutdown in the latter event.

Failure of fuel element cladding

As was described in the previous chapter, the core of a water-cooled reactor is made up of many fuel assemblies, each containing a bundle of fuel rods. Openings at either end of the tube bundle enable the coolant to enter and leave the assembly. Thus, as the coolant circulates through the core, it flows along each individual fuel rod.

Despite rigorous fabrication standards and careful inspection procedures, it is presumed that there will occasionally be some minute flaws in the cladding tubes, or that these will develop in the course of reactor operation. Therefore, some slow leakage of fission products from the fuel into the reactor coolant is expected to occur. As the previous chapter brought out, it is a function of the coolant purification system to remove and collect fission products that find their way through the fuel cladding. Thus, within limits established by design criteria, leakage of fission products through fuel cladding into the coolant is a normal situation. There would be no interference with routine operating procedures unless these limits were to be exceeded. How could this happen? A batch of defective fuel tubes might somehow get past inspection, or perfectly good cladding tubes might be damaged as a result of local "hot spots" in the reactor core. While these things are very unlikely, the reactor designer assumes they might happen and takes them duly into account. It should be stressed that this is strictly an internal operating problem since we are only talking about fission products getting into the primary coolant system. It is the dependability of the plant, more than its safety, that is affected.

The safeguards provided in water-cooled reactors against excessive leakage of fission products into the coolant due to fuel element cladding failures include conservative design of the fuel elements themselves, and the use of monitoring instruments that indicate if design limits are approached. But there is also a more fundamental safeguard—namely, that the fuel material used in these reactors has a remarkable ability to retain fission products. Uranium dioxide and thorium oxide, the materials most commonly used today, are ceramic or porcelain-like substances. Part of their ability to retain fission products comes from the fact that they are extremely resistant to hot-water corrosion. There are other factors as well, and the result is that it is extremely difficult for any but the more volatile fission products to escape from the fuel. As an illustration of this, a case is known where multiple cladding failures occurred in some special fuel elements undergoing test in a central-station plant. Even so, the rate of leakage of fission products into the coolant was found to be well within the limits which had been set for safe operation of the plant, and it was not necessary to replace the defective fuel elements before the regular refueling took place.

Accidental criticality

Here we refer to the possibility of a fission chain reaction starting by accident. Under some circumstances, a chain reaction could start in an amount of fuel considerably less than a full reactor "core-load." Therefore, wherever atomic fuel is stored, handled or transported, care is taken to maintain safe conditions.

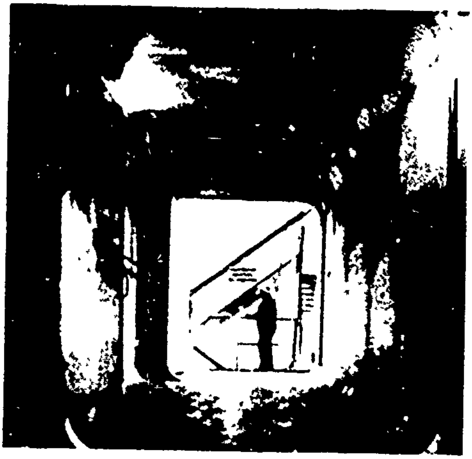
The answer to accidental criticality is "safe geometry," which means ensuring that a critical mass cannot be assembled under any circumstances. The safeguards include designing shipping containers so that it is physically impossible to load an unsafe number of fuel elements into them, and equipping fuel storage vaults with spacer devices so that safe geometry is assured.

General

We have described the major classifications of possible reactor accidents and brought out some of the safeguards, both natural and "engineered," that act to limit or prevent them. Our sole frame of reference has been safety. Before closing this chapter, the point should be made that the utilities that own and operate commercial atomic power plants have an additional frame of reference—namely, dependability of service. The need to have dependable power-generating facilities has always caused the utility industry to be extremely conservative in equipment selection and plant design. This same conservatism carries over into equipment manufacture and plant construction. The tradition of dependability of service, and the conservatism it imposes, are of themselves important safeguards.

CONTAINMENT IN THE EVENT OF ACCIDENT

As we have seen, there are multiple physical barriers in a central-station atomic power plant against the escape of radioactive substances into the environment. There is, first of all, the ability of the fuel material to retain fission products. Then there is the fuel element cladding through which fission products must pass in order to get into the reactor coolant. Then there are the walls of the reactor vessel and of other massively constructed equipment which must be breached before radioactive substances can get out of the reactor system proper. And, finally, in most of the plants being built today, there is what reactor designers call the "vapor containment system," which encloses the reactor installation and, in the event of a major accident, serves to limit the escape of radioactive substances from the plant to the environment. It is with this final barrier that this chapter will deal.



Double door entrance
to a vapor containment enclosure

The concept of vapor containment

The concept of vapor containment is best explained by describing how a containment system is designed. If you were the designer, you would begin by imagining what is usually referred to as the "maximum credible accident" — that is, the most serious reactor accident that could be expected to happen if major design safeguards failed. This would involve hypothesizing not one but a combination of several highly improbable things going wrong simultaneously. Then, taking into account the size and design characteristics of the reactor, you would make some calculations.

Let us assume, by way of example, that the "maximum credible accident" involves a sudden escape of all of the coolant contained in the primary system of a water-cooled reactor – which would happen if the walls of the high-pressure system were breached. This would mean that all of the energy normally "stored" (as heat) in the coolant might be released. Picture, in short, an event similar to a boiler rupture in which a large amount of high-pressure, high-temperature water flashes to steam.

Let us also assume that the standby core-cooling system does not function properly with the result that fuel elements overheat and cladding failures occur, releasing fission products.

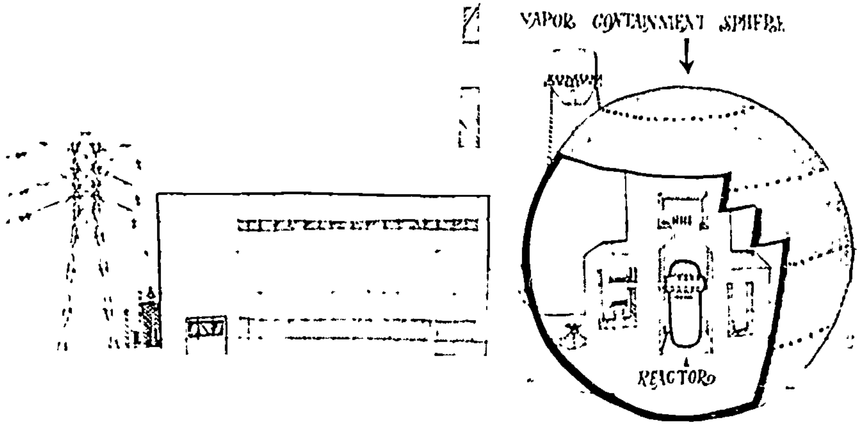
In analyzing the consequences of such an accident (or, more accurately, this combination of accidents), you would first calculate the maximum pressure that could be exerted on the walls of a vapor containment enclosure. Then, after estimating the amount of various specific radioactive substances that might be released by the overheated fuel and the possible rate of leakage of vapor out of the containment enclosure, you would calculate the maximum rate at which these substances could be expected to escape from the plant. Then, taking into account the characteristics of the proposed reactor site — in particular its meteorology (prevailing winds, etc.) and its location in relation to the surrounding population — you would estimate the maximum radiation exposure that might be received by persons at the plant boundary and at outlying distances if this hypothetical series of events actually occurred. If you found that the exposure pattern is consistent with the Atomic Energy Commission's radiation protection standards and related siting criteria, you would then be ready to proceed with the design of the containment system.

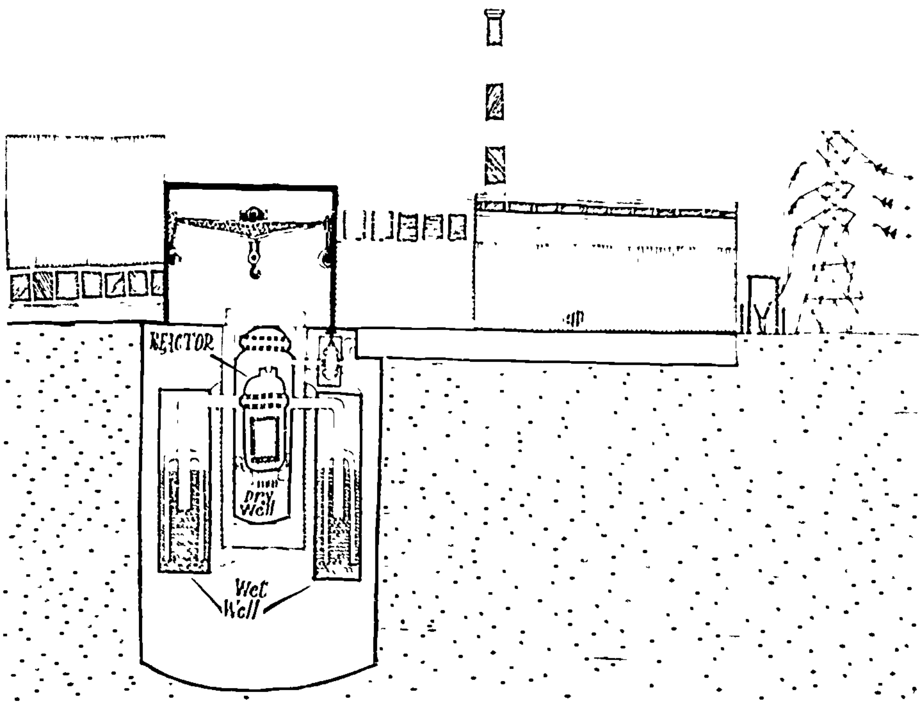
In the design and construction of the vapor containment system, the rule of conservatism applies. For example, the structural design of a containment enclosure is customarily based on a pressure higher than the calculated pressure. Wherever pipes or ventilat... ducts penetrate the enclosure, precautions are taken to ensure that they do not compromise the integrity of the containment system. The same applies to access doors for personnel. When completed, and at intervals during the life of the plant, the enclosure is carefully inspected and tested to determine that it meets the degree of leak tightness specified by the design. Beyond these and other standard safeguards, special safeguards may be provided in particular circumstances.

Types of vapor containment systems

Two principal types of vapor containment systems have been used to date in central-station plants employing water-cooled reactors.

One type makes use of a large spherical or cylindrical steel shell that encloses essentially the entire reactor installation. The shell, which in a large plant might be the height of a twenty-story building, is constructed by welding together sections of steel plate. In the plants that have been built to date, which are located at a distance from population centers, a single containment shell is used. Recent





proposals to locate plants in or near population centers are based on much more elaborate designs. These proposals have specified a double-walled, "zero"-leakage shell surrounded by a massive concrete radiation shield. The radiation level at the boundary of a plant employing such a containment system would be essentially unaffected by a major accident within the shell.

A second, basically different type of vapor containment system has come into use recently. It is known as the "pressure suppression system." In one version of this system, the reactor vessel is located in a steel containment tank surrounded by a concrete radiation shield. The containment tank, termed the dry-well, is connected by pipes to a second tank, termed the wet-well, that is partially filled with water. The entire installation is housed below ground level within a building of special construction. In the event of a vapor release from the reactor, the vapor would pass into the dry-well and from there through pipes into the wet-well. The pressure surge would be immediately relieved by vapor condensation; moreover, in bubbling through the water in the wet-well, the vapor would be scrubbed essentially free of solid radioactive particles.

LICENSING AND REGULATION OF ATOMIC POWER PLANTS

It is Federal law that no one may build or operate an atomic power plant without obtaining first a construction permit and then an operating license from the U. S. Atomic Energy Commission. The licensing procedure, outlined below, involves a searching analysis of the safety of the proposed plant, not only by the AEC's own regulatory staff, but also by expert advisors. Also, it provides opportunity for State and local authorities and the public to keep fully informed on the progress of the license applications and to participate in hearings held before action is taken to grant or deny them.

The AEC's authority and organization

The AEC is an independent agency of the Federal Government headed by a five-member commission appointed by the President. Its authority over the licensing and regulation of atomic power plants stems from the Atomic Energy Act of 1954.

Under this act, the AEC has three broad areas of responsibility. One is the production of atomic materials needed for the national defense. Another is fostering the development of atomic power and other peaceful uses of atomic energy. The third is the licensing and regulation of the peaceful uses of atomic energy.

To avoid conflict between the role of promoting the development of peaceful uses and that of regulating these same uses, the AEC has set up a separate staff for the latter function. (See Chart pages 30 and 31.)

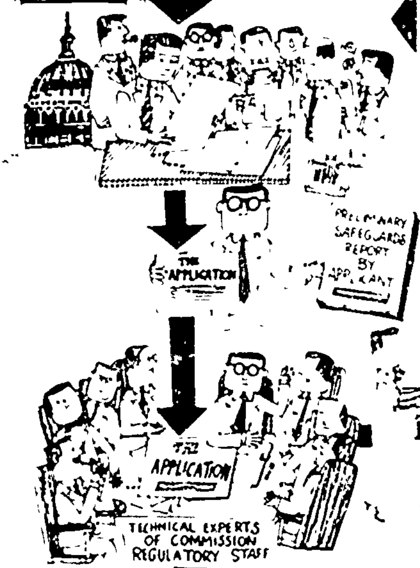
Prerequisites for a construction permit

To obtain a construction permit from the AEC, the applicant must establish his technical qualifications and

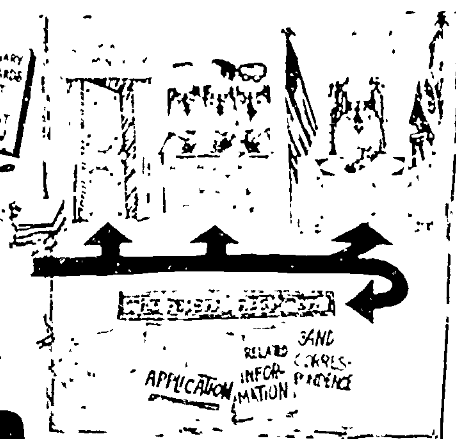
LICENSING OF POWER REACTORS

START HERE

How are central station atomic power plants licensed and regulated? The U S Atomic Energy Commission requires two separate licenses—one to build the facility and another to operate it Let's trace the steps in the process of obtaining a construction permit



1 The utility submits a formal application describing the design and location of the proposed plant and the safeguards to be provided The application also covers the utility's technical and financial qualifications



2 The AEC's Division of Reactor Licensing (DRL) makes copies of the application available to the public and ACRS DRL technical experts study the application review it with the applicant and prepare an analysis

3 The DRL analysis is submitted to the AEC's statutory Advisory Committee on Reactor Safeguards a committee of independent experts ACRS studies the application in detail and holds conferences with the applicant and DRL staff The ACRS findings are reported to the AEC and made public

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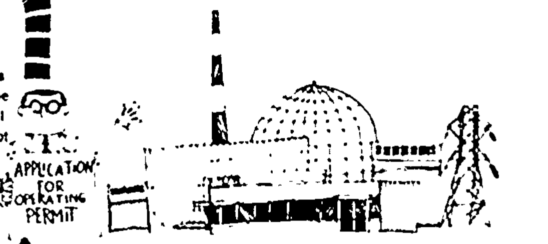
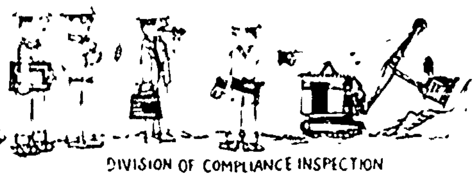
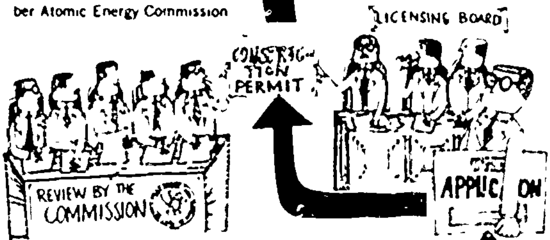
As construction progresses additional informa tion is developed and the utility applies to the C for an operating license The same careful anal s is made by the AEC in deciding whether or not ssue the operating permit



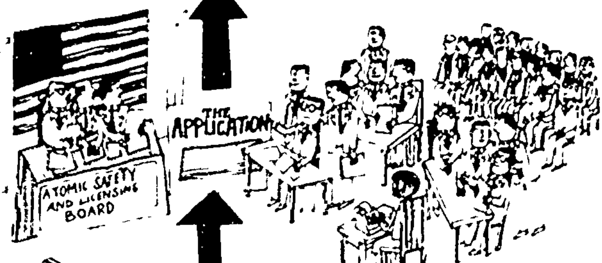
7 A construction permit is then granted or denied and public notice is given If granted con struction of the plant may begin subject to inspection by the AEC s Division of Compliance



6 The Board s decision is sub ject to review by the five mem ber Atomic Energy Commission



5 After reviewing the testi mony and the DRL and ACRS findings, the Board de cides for or against granting a construction permit



4 A public hearing is held usually near the proposed site, by an AEC appointed Atomic Safety & Licensing Board Private citizens, State & local officials, and community groups may attend and give testimony financial responsibility and must satisfy the AEC that the proposed plant will be built and operated safely.

One of the requirements of financial responsibility is that the applicant must arrange for a specified amount of insurance coverage (or equivalent financial protection) against possible public liability.

THE EXPERIENCE RECORD

Central-Station atomic power plants

The acid test of safety is experience. While the U. S. atomic power industry is still young and just beginning to grow, the amount of electricity that has been produced in central-station atomic power plants is already measured in billions of kilowatt-hours. The safety record can be summarized very briefly:

1. There has been no instance of radiation injury to any worker in a central-station atomic power plant;
2. The radiation exposure estimated to have been received by the general public as a result of central-station atomic power operations has been kept to a very small fraction of that allowed by the Atomic Energy Commission's radiation protection regulations;
3. There has been no instance of an accident in the categories described earlier (see chapter on Accident Prevention) in a central-station atomic power plant.

We do not mean to imply that reactor accidents may never happen. But, as we stressed in the discussion of accident prevention, the designers of atomic power plants postulate even very unlikely reactor accidents and the plants are designed accordingly.

In describing the operating experience of the industry, a distinction should be made between preliminary and routine operation.

Preliminary operation

When an atomic power plant is started up for the first time it is put through an extensive check-out procedure.

The period of preliminary operation may range from several months to a year or longer. During this period the power level at which the reactor is operated is gradually increased from an initially low level to that corresponding to the full rated power output of the plant. This is done in strict conformity with limitations imposed by the operating license, which may require operation at specified low power levels for an extended period.

Both during the startup procedure and trial operating period, various tests are conducted and any necessary adjustments are made. It is quite common for the reactor to experience a number of automatic shutdowns during preliminary operation, either because of over-conservative control instrument settings or because of minor malfunctioning of some components of the reactor system.

In the latter connection, the reactor components have on the whole presented fewer startup problems than the more or less standard equipment used in auxiliary systems and in the electrical generating portion of the plant.

Routine operation

Once they have entered into routine operation, central-station atomic power plants have proven to be extremely dependable producers of electricity. Utilities speak of "plant availability," meaning the percentage of time a power plant is available to supply power on demand. Atomic plants have demonstrated annual availability factors that compare favorably with those of the most modern fossil-fuel-fired steam-electric plants.

There is in fact at least one reason to expect that time may prove atomic plants to be more dependable than fossil-fuel-fired plants. The reason is that in an atomic plant the components that get the "hardest wear"—namely, the reactor fuel elements—are replaced when the plant is refueled. In fossil-fuel-fired plants, the components that get the hardest wear are the tubes in the furnace section ("firebox") of the steam boiler, which are permanent fixtures. As a general rule, these tubes present the most serious operating and maintenance problem in ordinary steam-electric power generation.

Other reactor installations

The above discussion applies to central-station atomic power plants. Such plants are designed and engineered to meet exacting utility standards of dependability over their operating life. Once in routine service, they are usually operated at fairly even power levels for sustained periods of time.*

Naval reactors

The closest parallel, at least as regards the degree of dependability required, is in the reactor propulsion systems supplied for operational Naval vessels. Here again the experience record has been excellent. At this writing something like 100 reactor-years of safe operating experience have been logged with Naval reactors.

Miscellaneous reactors

Other categories of reactor installations include:

1. Experimental or prototype power reactors operated to obtain data for the design of future central-station atomic power plants;
2. Experimental or prototype systems built in connection with the development of reactors for various specialized applications, such as supplying electricity and heat to remote military bases, furnishing auxiliary power to space vehicles, rocket propulsion, and others;
3. General- and special-purpose test reactors — reactors used to test developmental reactor materials and equipment, or to study the basic characteristics of reactor systems;
4. Production reactors — reactors used to produce plutonium and other materials for defense stockpiles;
5. Research reactors — reactors used primarily to supply neutrons and other forms of radiation for scientific research;

*Because the fuel cost of atomic power plants is low, they lend themselves to "base load" operation in a utility system — i.e., operation at 80% or more of their rated capacity over the year.

6. Training reactors — reactors used primarily as aids in teaching reactor technology;

7. Critical experiment facilities. These are not reactors in the usual sense of the term, since they operate at essentially "zero" power, but do involve the initiation of a self-sustaining fission chain reaction.

As you might expect, these diverse fields of reactor design and use represent a broad spectrum of operating conditions and circumstances. For this reason it is difficult to relate the collective experience of the reactor field to the safety of commercial atomic power plants. It can be said, however, that building and operating reactors of basically different types under widely different conditions does much to strengthen the general technology upon which the designers of commercial atomic power plants draw. Also there is at least one common denominator — namely, the opportunity for human error — so that those who design and operate reactors for one purpose can often benefit from experience gained with reactors designed and operated for quite different purposes. In this light, the fact that literally hundreds* of atomic reactors of different types have been operated under different conditions with a degree of safety almost unparalleled in industrial experience is, at the very least, a favorable omen for the commercial atomic power field.

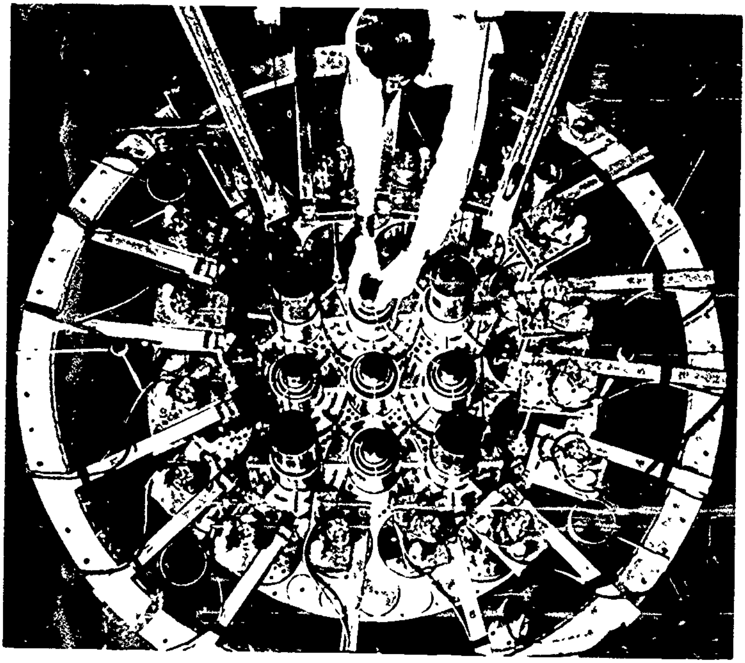
SAFETY RESEARCH

The safety of atomic power is studied as well as practiced. The U. S. Atomic Energy Commission is sponsoring a major research and test program in this field and supplementary work is done on specific problems on the initiative of reactor manufacturers or under utility sponsorship.

The AEC program is divided into two main parts — study of basic reactor accident phenomena, and testing of safety features. It also includes research and develop-

* There are approximately 400 nuclear reactors in operation in the world. Of this number, about half are located in the U. S. (These figures include reactors in all categories listed on pages 34 and 35.)

ment on all aspects of radioactive waste handling and storage. It would be beyond the scope of this booklet to describe the AEC program in detail, and therefore the following paragraphs are intended only to indicate the principal lines of effort in the field of reactor safety.



Fuel assembly in test reactor

The part of the program devoted to the study of accident phenomena has been in progress a number of years. It has involved systematic theoretical and experimental studies of the behavior of reactors under transient conditions (nuclear excursions), the performance of control devices and systems, and related activities. The emphasis has been on water-cooled reactors but other types have also been studied in considerable depth. Much of the work is conducted at the National Reactor Testing Station in Idaho where several experimental facilities are used exclusively for safety research.

The safety test portion of the AEC program is currently concentrated along four principal lines: (1) simulation of "loss-of-coolant" accidents to study the consequences of such accidents and to test related safeguards; (2) simulation of nuclear excursions in oxide fuel cores for the same purposes; (3) experiments to determine the escape pattern of fission products during fuel-meltdown accidents and to test the performance of containment safeguards; and (4) metallurgical research and engineering tests aimed at acquiring fundamental knowledge of the causes of mechanical failures in high-pressure equipment.

Through safety research and tests, the atomic power industry is continuously strengthening the most important safeguard any industry has—namely, knowledge of the causes and consequences of accidents and of the dependability of safeguards. Learning about accidents before they occur is part of the basic fabric of the safety of atomic power.

ADDITIONAL INFORMATION ON ATOMIC POWER

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