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CRITICAL EXPERIMENTS AND NUCLEAR SAFETY AT OAK RIDGE NATIONAL LABORATORY

A. D. Callihan

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CRITICAL EXPERIMENTS AND NUCLEAR SAFETY AT OAK RIDGE NATIONAL LABORATORY

A. D. Callihan

ABSTRACT

This paper considers two somewhat separate aspects of potential hazards in the nuclear reactor program. The first section describes the safety features of the critical-experiments program at Oak Ridge National Laboratory and reviews its operational experience. In these experiments, reactor prototypes are studied and the problems of fuel processing are examined. The second section of the paper presents some design bases for fuel processing equipment and discusses the administration of nuclear safety at the Laboratory.

INTRODUCTION

Potential hazards, of a kind unique in the atomic energy field, are present in several parts of the reactor development programs. There are, of course, those hazards associated with operating reactors where the immediate environs are subject to direct radiation and where quantities of fission products may be released into the area surrounding the reactor site. Unscheduled power excursions have occurred in critical experiments, and such excursions jeopardize the safety of personnel performing the experiments. In the operations in which fissionable materials are prepared and are fabricated into reactor fuel and in which residues are recovered, extreme caution must be exercised to prevent a chain-reacting accumulation.

It is the purpose of this paper to discuss the manner in which the last two of these three problems are treated at Oak Ridge National Laboratory. The topics are somewhat independent and divide the paper into two sections. The first outlines some of the safety features and operational practices of the experiments; in the second part some criteria which have been established for safely handling fissionable materials are presented, and the administration of nuclear safety is briefly discussed.

CRITICAL EXPERIMENTS

Included in the program of critical experiments have been studies of reactor prototypes, the empirical evaluations of bases for the nuclear safety of chemical and metallurgical processes, and some research in reactor physics. Although the details of the experiments in this program differ significantly, much of the equipment and many of the practices are equally applicable to all three.

Laboratory

It is appropriate to consider briefly the unique features of the laboratory which was designed, in 1949, expressly for these experiments. It is a two-story building (Fig. 1) about 200 ft long and 40 ft wide, located approximately 1 mile from the nearest working areas and separated from them by natural earth barriers. At each end of the building is a test cell, about 30 × 40 × 35 ft high, separated from the central section of the building by a wall of ordinary concrete 5 ft thick. The three remaining walls and the roof of each cell are at present of usual structural dimensions, reliance being placed upon the isolation of the building and upon strict visitor control for the protection of personnel from radiation exposure in unshielded areas. It is important that each test cell has a ventilating system entirely independent of those supplying other parts of the building and that each has a manually controlled air exhaust, which can be used to disperse air-borne contamination. These exhausts contain no filters, since their infrequent use can be scheduled when meteorological conditions are proper in this essentially unpopulated area. The test cells are maintained at pressures somewhat lower than those in the adjacent areas of the building. There is little direct radiation from these low-power critical experiments and no significant buildup of fission-product contamination during their normal operation; so the principal need for these safety

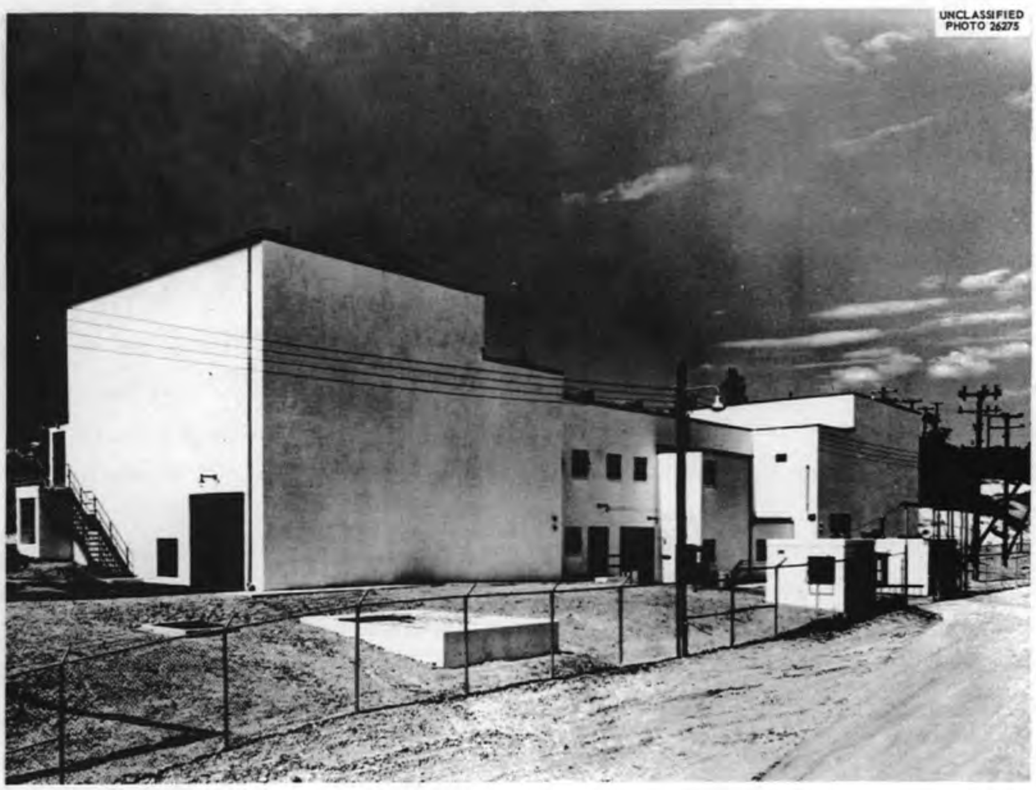

Fig. 1. Critical Experiments Facility at Oak Ridge National Laboratory.

features has resulted from short-lived, unscheduled power excursions. The building is equipped with audible alarms actuated by radiation detectors.

Design of Equipment

Although the design bases for the apparatus of all critical experiments are fundamentally the same, the details of control and safety features often depend upon the component materials. All equipment used in these programs is designed on a "fail-safe" philosophy whereby the experiment is stopped by a power outage or by an electronic-equipment failure. In each apparatus there are at least two safety devices; one is quick acting and controls, therefore, a relatively small amount of reactivity, and another, a "last-ditch" type, controls a large amount of reactivity at a somewhat slower rate. The former is exemplified by the rapid insertion of a solid neutron absorber into a solid or liquid fuel array, or by the ejection of a section of the core or reflector of an all-solid assembly, producing reactivity changes at a rate of the order of 10%/sec, with a total value of a few per cent in k. The larger reactivity changes are brought about by the mechanical separation of essentially equal parts of an array of solids or by the removal, usually by gravity, of the fuel solution or the aqueous reflector and moderator in a liquid system. The usual effect of these changes is the reduction of the reactivity to zero at an initial rate which is the order of 0.1%/sec. The control of the reactivity in the approach to critical and in subsequent reactivity changes is by fine adjustment of the position of a neutron absorber or of the quantity of fuel, moderator, or reflector in the array. A change in the level of the liquid fuel or reflector, for example, is a very satisfactory and sensitive control. Although the maximum rates of increase, limited by mechanical or hydrodynamical means, are usually in the range of 0.01 to 0.1%/sec, the actual rates, under the control of the operator, are very much lower. The reactivity is monitored by a number of neutron and gamma-ray sensing instruments, including a logarithmic amplifier. Signals from these instruments actuate the safety devices and alarms when preset reactivity levels and their rates of change are exceeded.

In general, interlocks have not been used in these experiments, although in some equipment the neutron source and the safety mechanism must be in position before the first large addition of reactivity can be made. It has not been the practice, for example, to prohibit access to the test cells during operation by shutdown switches in doors, because in many instances it is necessary and safe to inspect the equipment after assembly has begun. No changes which will increase the reactivity are made during these inspections. The greatest reliance for safe operations has been placed on careful and experienced personnel. It is their practice to satisfactorily test, with a source of neutrons, the operation of all instruments and safety devices immediately before beginning an experiment. Basic safety rules and procedures have been prepared, and copies are supplied to all members of the staff.

Operating Experience

Two prompt-critical excursions have occurred in this program over a ten-year period. In both instances there was no significant personnel exposure and no property damage. Each incident involved an aqueous solution of enriched uranium in an unreflected vertical cylinder and produced the order of 10^{17} fissions in an undetermined time – the experiments were not instrumented for such rapid transients. In one experiment, in May 1954, a very effective neutron absorber which also displaced solution, normally located on the axis of the cylinder, was accidentally tilted so that its upper end rested against the rim at the top of the cylinder, thereby introducing 2.1% excess reactivity. In the second excursion, which occurred in February 1956, a transient period, resulting from the addition of a small increment of U^{235} to a very slightly subcritical system, actuated the safety circuits and thus released a sheet of cadmium which fell into the large, shallow volume of solution. It is believed that the solution was displaced first from the center of the cylinder and then, upon reflection of the disturbance by the wall, back to the center, forming a prompt-critical configuration. An analysis of the first of these excursions, based on the method of Fuchs[1] and measurements of the time constants of the system, showed that a number of oscillations in the power probably occurred before the system finally became subcritical, since otherwise it would have remained supercritical for 1 or 2 sec, a time inconsistent with the observed energy release.

Neutron monitors within the test area during the more recent excursion recorded an exposure of about 10^{11} fast neutrons/cm^2 and a third as many thermal neutrons at a point 20 ft from the source. Personnel exposures in the control room immediately adjacent to the concrete shield wall separating it from the site of the excursion were 0.5 rep, including both neutrons and gamma rays, with only slightly lower values noted in the remainder of the building. The apparent attenuation of thermal neutrons by the shield wall, obtained from the activations of resonance absorbers, was several orders of magnitude less than the attenuation expected from the properties of the concrete. This difference and the higher-than-expected exposures in more distantly located areas in the building have pointed up the importance of air-scattering of the radiation. Steps are being taken to provide shielding against this potential future source of radiation.

NUCLEAR SAFETY

Design Bases

Of the experiments referred to in the above discussion, those of great importance to safety in reactor programs have established bases for the design and operation of

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[1]K. Fuchs, *Efficiency for Very Slow Assembly*, LA-596; see also, G. E. Hansen, *Burst Characteristics Associated with the Slow Assembly of Fissionable Materials*, LA-1441 (July 1952).

processes for the production and fabrication of fuel elements and for the subsequent recovery of residual fissionable materials. Values of several parameters which determine the nuclear reactivity of aqueous solutions of the fissionable isotopes are given below. These values have been established as guides in process designs. In some instances the values are conservative, because of uncertainties in the present knowledge of the limiting critical conditions, and will be revised as more data become available. In these examples it is assumed that only those materials usually found in chemical processing plants – ordinary water, concrete, and stainless steel – are present and that the density of the fissionable element is less than $1/cm^3$. The solutions are considered to be homogeneous and sufficiently dilute to thermalize the neutrons. No reference is made here to the conditions which must apply in handling enriched uranium and plutonium metal, where quite different regulations must be imposed.

Critical Mass and Volume. – These parameters of a critical system are minimal in spherical geometry, and the values given below for the three isotopes describe spheres which can be made critical with all other factors optimized. The uncertainty in the values is estimated at ±5%. The chemical concentration at which the critical mass of a particular isotope is a minimum is different from that at which its critical volume is a minimum.

	Mass (g)	Volume (liters)
U^{235} (~90% enrichment)	800	6.3
U^{233}	588	3.5
Pu^{239}*	509	5.0**

*The specifications for plutonium are based on experiments performed at the Hanford Works of the General Electric Company and have been made available through the courtesy of W. J. Ozeroff.

**The minimum critical volume of plutonium solutions is probably somewhat greater than 5.0 liters, the value used as a limit in safety control.

No significant safety factors are included in these values of critical masses and volumes, except as noted in the case of solutions of plutonium. In practice, a factor of at least 2 has usually been applied in those procedures which have been mass-limited and in others, described below, where safety is based on the chemical concentration of the solution. Through this factor one guards against inadvertent double-batching and against errors in sampling and in analysis. A factor somewhat less than 2 is applied to the critical volumes in setting limits on vessel capacities.

Process Specifications. – Solutions of the three isotopes may be safely processed and stored in vessels having the dimensions listed below, which have been conservatively derived from experimental results. Since safety is imposed by these dimensions, all other factors, including a hydrogenous reflector, may be optimized. In solutions of sufficiently low concentration, the neutron absorption by hydrogen prevents the establishment of a chain reaction. Values of the limiting concentrations, calculated from cross sections, are included in the list.

	Cylinder Diameter (in.)	Slab Thickness (in.)	Maximum Concentration (g/liter)
U^{235}	5.0	1.4	11.6
U^{233}	4.0	~0.5	10.9
Pu^{239}	5.4	1.9	7.8

Other variables which determine critical conditions are, of course, the density of the fissionable isotope, the presence of neutron-moderating and -reflecting materials, and the proximity of other process vessels which may contribute to the over-all reactivity. In the practical approach to a problem, a combination of limitations may be applied in such a manner that the required safe condition is achieved without severely impairing the economy of the process. If, for example, it is assured that neutron reflectors, such as water in cooling jackets, concrete walls, and personnel, will always be separated from a vessel by at least several diameters, the mass, capacity, and dimensional limits given above can be increased by about 50%. These relaxations in the specifications must be used with caution because even the vessel walls themselves provide some reflection. Although experiments have shown that probably no solution of U^{235} contained in a thin-wall vessel 8 in. in diameter will be critical, it is suggested that the outside diameter of the cylinder not exceed 8 in., on the premise that substitution of the wall material for solution will not increase the reactivity. A conservative mass limitation of 25 kg of high-purity U^{235} can be placed on a process where a uranium salt is free from hydrogen or other moderating elements. As other examples, with uranium enriched in U^{235} to only 5%, the diameter of a cylinder may be 10 in. with all parameters optimized, including a hydrogenous neutron reflector effectively infinitely thick, and the minimum critical mass and volume are about 1.8 kg of U^{235} and 30 liters. In a like manner consideration can be given to any number of combinations of conditions characteristic of a process to yield a workable and safe procedure. The particular problem of pipes intersecting at 90 deg has been examined experimentally by using a solution of high-purity U^{235} at an optimum concentration with a water neutron reflector. These experiments have shown that the pipe diameters given above should be reduced by 30% when a "cross" is formed and by 20% when a "tee" is formed, in order to preserve the factor of safety inherent in the straight-pipe diameters.

Administration

The use of fissionable materials within the Laboratory is divided between two broad programs. One of these includes the operation of nuclear reactors, critical experiments, and preliminary reactor assemblies under the direction of personnel experienced in, and having as their prime responsibility, the control of nuclear chain reactions. These systems are equipped with radiation monitoring instruments and control devices such as safety rods containing neutron poisons. The design and prescribed operation of the reactors at the Laboratory are reviewed by the Advisory Committee on Reactor Safeguards of the AEC. In the second program, the fissionable materials are processed in various fabrication, purification, and separation procedures. Attendant to both programs are problems of storing and shipping fissionable materials.

The responsibility for nuclear safety within the Laboratory has been placed upon line organization. Individuals directing activities which are of such a nature as to involve nuclear hazards are responsible for control in these activities to the same extent that they are responsible for research, design, maintenance, and operations. A staff group, reporting to the Laboratory Director and composed of personnel familiar with the potential hazards, has been formed to give approval of the procedure and equipment to be used in the second of the above programs, the nonreactor operations, and in storage and shipment procedures. These approvals are based primarily upon results from experiments which have provided both specific design criteria and more general information as background material. As additional data become available, these bases may be revised.

In the administration of the safety practice, line supervision responsible for any design or operations obtains approval of those parts which involve or which may involve nuclear safety. Necessary information is furnished to the approvals committee, including the type, quantity, and chemical composition of the material, its concentrations and density, the dimensions and geometric shapes of the containers, and a flowsheet of the process. The committee investigates each problem, advises the originating group on the hazards which may be incurred, and approves the final design and procedure. In general, such approval specifies necessary operating restrictions.

The nuclear safety of any process will be assured, wherever possible, by the dimensions of the components – such as pipe sizes and container capacities – including spacing between individual components of the same or adjacent systems. Where safety based on geometry alone is precluded, designs may be predicated on batch sizes and/or chemical concentrations, or combinations of them with geometry, and such designs will be considered satisfactory only if two or more simultaneous and independent contingencies must occur to promote a chain reaction. The use of these nongeometric safety criteria places upon operational supervision the responsibility for accuracy in sampling and analytical procedures. No significant use has been made of neutron absorbers, such as boron and cadmium, in processing equipment, since, to be effective, they must be distributed with the process material.

The programs of the Laboratory, being primarily research and development, necessitate an individual review of most of the proposed processes in which fissionable materials are handled, thereby permitting the application of those safety criteria especially adaptable. This method is in contrast to one in which more general criteria can be routinely applied.