OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

ORNL-TM-349

A SAFETY REVIEW OF THE OAK RIDGE CRITICAL EXPERIMENTS FACILITY

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A SAFETY REVIEW

of the

OAK RIDGE CRITICAL EXPERIMENTS FACILITY

Prepared by

The Facility Staff

DECEMBER 1962

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
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CONTENTS

		Page
	Abstract	1
	Introduction	1
I -	History of Critical Experiments in Oak Ridge	3
	Early Experiments	3
	Experiences at Building 9213, Y-12	4
II -	Description of the Facility	5
	Location	5
	Construction	6
	Ventilation	11
	Contaminated Waste Collection Tanks	12
	Equipment and Equipment Operation	12
	Criticality Testing Unit for Solids	13
	Criticality Testing System for Solutions	19
	Instrumentation	21
	Counting Channels	21
	Safety Channels	23
	Logarithmic Channel	23
	Scram System	23
	Building Alarm	24
	Fast Safety Channel	25
	Incident Alarm Channel	25
	Limitations on Experiments	25
III -	Facility Organization and Staff	26
IV -	Operating Procedures	26
	Program Development	26
	General Operating Rules	27
	Emergency Procedures	29
V -	Radiation Hazards	30
	Accidental Radiation Experiences	31
	Controlled Radiation Experience	32
	Accident Expectations	34
	Criticality Accident Consequence	42
	Hazards Due to Release of Radioactive Materials	43
	Consequence of Other Radiation Accidents	45

CONTENTS

Page No.

VI - Miscellany 47
Fire 47
Seismology 47
Meteorology 47

LIST OF FIGURES

1 - Y-12 Plant - West End 7

2 - Plans, Elevation, and Contours of Building 9213 . . 8

3 - West End of Building 9213 Showing the Concrete Shielding Wall Between the Roadway and the Large Doors . . 9

4 - East End of Building 9213 Viewed from Approximately 14 Feet Above the Roadway, Showing the Concrete Walls and Bunkers which Provide Shielding for the Large Doors . 10

5 - The Criticality Testing Unit 14

6 - Schematic of Criticality Testing Unit Magnetohydraulic Support Device 15

7 - Characteristic Scram Performance Curve of the Criticality Testing Unit 17

8 - Schematic of a Typical Solution System 20

9 - Minimal Instrumentation 22

10 - Radiation Exposures from February 1956 Excursion . . 33

11 - Neutron and Gamma-ray Doses and Intensities from 3.7×10^{16} Fissions 35

12 - Gamma-ray Doses Arising from Superprompt Critical Unmoderated U^{235} Assembly 36

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This memorandum was first prepared in February 1962. After perusal by the Laboratory's Reactor Operations Review Committee it was revised in April. Suggestions by the safety review committee of the Oak Ridge Operations Office were incorporated in August 1962.

A SAFETY REVIEW of the OAK RIDGE CRITICAL EXPERIMENTS FACILITY

ABSTRACT

This memorandum describes the Critical Experiments Facility located in the Y-12 Area of Oak Ridge with particular reference to the safety features of both the laboratory itself and the procedures established for the experiments constituting the specialized use for which the laboratory was constructed. Comparison of these experiments to others in which accident potentialities have been hypothesized sets an estimated 10^{18} fissions as the upper limit to the energy release to be reasonably expected as the result of the malfunction of personnel or equipment. Experimental data show the shielding incorporated in the building will adequately protect personnel from the direct radiation arising from an accident of this magnitude occurring during operations. The absence of a significant inventory of fission products in experimental materials and a simple consideration of the air-borne behavior of those produced by 10^{18} fissions show that hazards to non-facility personnel are highly unlikely.

It is concluded that the greatest potential danger to personnel is in the course of preparing fissile materials for experiments and in their storage and transport. As in many like instances, reliance for safety must be placed on the knowledge of and caution by the individuals themselves.

INTRODUCTION

The Critical Experiments Facility of the Oak Ridge National Laboratory was constructed expressly to meet the needs of various programs in Oak Ridge, and inevitably outside Oak Ridge, for data from low-energy potentially chain-reacting assemblies. The programs have required the accumulation of basic reactor physics data, the determination of the critical dimensions of material assemblies, and the study of potential nuclear reactor designs.

Only in exceptional instances is it necessary to operate critical experiments at nuclear powers sufficiently high to present radiation hazards to the individuals performing the experiments, even though the manipulation be manual as it was, indeed, in early practices. However, the ever-present probability of personnel or equipment failure, which could lead to high-level radiation emission by a supercritical array, requires a laboratory equipped for remote performance of these experiments.

A laboratory in which critical experiments are performed must also be capable of accommodating a very wide variety of activities in contrast to a reactor installation which may remain fixed in construction and operation over an extended period. The experimental equipment used for these purposes must be adaptable to many configurations of materials of interest dictated by the demands of the programs. Since the time required for the performance of a particular experiment may be only a few hours, it is not economically feasible to pattern instrumentation and controls after those conventionally prepared for long-range reactor operation. For this reason, and more importantly, because the very purpose of these exploratory experiments may truly be the evaluation of those factors upon which reactor safety will subsequently be designed, critical experiments are somewhat more vulnerable to nuclear accidents than are operating reactors. On the other hand, the over-all consequences of a nuclear accident with a critical assembly are very much less severe than are those associated with reactors because, primarily, of the absence of a significant inventory of fission products built up in the fissile material. In fact it is highly desirable to avoid such a fission-product buildup in order to allow manual adjustments of the experimental equipment and materials.

Many safety features for the successful operation of critical experiments must, therefore, be permanently built into the laboratory itself rather than be incorporated into each experimental setup. Necessary radiation shielding, for example, is made a part of the laboratory structure. Special consideration must be given to the design of ventilation systems to minimize dispersal of radioactive contamination. On the other hand, each experimental assembly must embody control and safety devices peculiar to the type of experiment under study and to the properties of the materials used.

Prior to the construction of the laboratory to be described here several critical experimental programs had been carried out at the Oak Ridge National Laboratory and at the Oak Ridge Gaseous Diffusion Plant. The inadequacy of the facilities of these two locations was recognized in 1949 in light of the expected demands for further experimentation in both the investigation of the safety of metallurgical and chemical processes and the support of reactor designs. This latter need was further emphasized by a then-active program in Oak Ridge on the development of nuclear propulsion for aircraft. At that time it was decided that a laboratory adequate for this variety and quantity of experimentation would be established, that the various programs of critical experiments in Oak Ridge would be combined, and that the work would be administered under the Oak Ridge National Laboratory. The new laboratory was occupied on August 1, 1950 and has since been the scene of an extremely wide variety of critical and near-critical experiments with fissile uranium isotopes.

It is the purpose of this report to describe this laboratory, designated locally as Building 9213, Y-12 Area, and officially as the ORNL Critical Experiments Facility, to discuss the types of experiments performed, and to describe the equipment and procedures representative of nearly twelve years of experience. Particular emphasis is placed upon the hazards to personnel which might be associated with these operations.

It is interesting to summarize, with statistics, the operating experience at the facility. Since its occupancy in 1950 through calendar year 1961 more than 9700 startup operations, representing nearly that many different configurations, have been accomplished with, perhaps, as many as 95% of the assemblies having been made critical. The average time a particular experiment was critical is recorded as 0.7 hr. Of these operations, 82 were terminated by emergency shutdown procedures and of these 82, in turn, three, or 0.03% of the total, were stopped by an unplanned high radiation field. The majority of the remaining 79 scrams occurred because of power or instrument failures.

Adherence to the fundamental operational practices outlined in this report, supported by careful reviews by internal Laboratory committees, is expected to assure continued safe and efficient operation of the Oak Ridge National Laboratory Critical Experiments Facility. Ever-present vigilance and concern for personnel protection by the experimenters in the facility must be the final safeguard in this endeavor.

I - HISTORY OF CRITICAL EXPERIMENTS IN OAK RIDGE

Early Experiments

The history of critical experiments at the Oak Ridge National Laboratory dates back to late 1945 when a series of measurements was made on assemblies of a fluorocarbon-uranium oxide mixture in which the uranium was enriched to 24% in U^{235}. The assemblies were moderated and reflected by hydrogen. A second set of experiments was performed during the spring and early summer of 1946. These consisted of tubes containing fissile material latticed in a tank filled with heavy water. The fissile material itself was a heavy water solution of uranyl oxyfluoride contained in tubes and placed within the tank. The uranium was enriched to about 95% in U^{235}.

An extended program of experiments, conducted in 1947 and 1948, had as its purpose the support of the design of the Materials Testing Reactor. The fissile material was an aqueous solution of U^{235}-enriched uranyl oxyfluoride contained in aluminum tubes which in turn were latticed in a tank which could be filled with water. Natural water, heavy water or beryllium served as a neutron reflector.

These early experiments were conducted in cells in the plutonium recovery building presently designated as 3019, X-10 Area, which were modified, at least for the latter series, to provide a 2-ft-thick shield between the controls and the assembly.

A concurrent program was planned in late 1945 at the Oak Ridge Gaseous Diffusion Plant in which measures were made of the critical masses and critical sizes of materials having nuclear properties similar to those of uranium hexafluoride. The purpose of these experiments was to provide bases for the safety of the Gaseous Diffusion Plant

operations. The first experiments in this series were performed at the Los Alamos Scientific Laboratory in the spring of 1946 for the dual purpose of training personnel and of achieving some data from fluorinated uranium compounds of high U^{235} content. Operations with fluorinated uranium compounds in solid form were inaugurated in Oak Ridge in late summer 1946 with what was probably the first equipment to be used for the remote operation of experiments with solid fissile material. This work, performed in a small laboratory near the Gaseous Diffusion Plant, was followed in 1947 by experiments with solutions of uranium salts which continued until mid-1950 when the new facility was completed.

Experience at Building 9213, Y-12

The extremely wide variety of experiments and experimental materials which have come under study in the various programs followed during the last decade at the Critical Experiments Facility cannot be described in any summary report of this kind within reasonable bounds of effort and space. Thus an attempt is made here to organize the history of Bldg. 9213 not by enumerating the individual experiments but by showing the variety of experience with fissile material that has been acquired. There are basically only two types of critical experiments: those controlled by careful additions of liquids (fissile solutions, moderator or reflector) and those controlled by the addition of solids. There are, of course, many examples of combinations of the two types.

Experiments typical of those with liquid fissile material have used uranyl oxyfluoride and uranyl nitrate solutions in a continuing program, inaugurated in 1950, in which the critical parameters of spherical, cylindrical, slab, and annular geometries have been measured. These experiments have formed the bases for many nuclear safety specifications and for special problems in the processing of enriched uranium in chemical plants. A part of this program has contributed to basic reactor physics through a better understanding of the neutron leakage and by measurement of the fission neutron yield of U^{233} and U^{235}.

Experiments typical of those with solid materials have been performed in many programs. For the Aircraft Nuclear Propulsion Project, for example, a long series of experiments was performed with heterogeneous combintations of uranium, beryllium, graphite, Teflon, and Plexiglas, of which some were reflected by graphite, beryllium or Plexiglas. Experiments with homogeneous materials have been performed in other programs using blocks of mixtures of CF_2-UF_4 and $C_{25}H_{52}$-UF_4. These have included reflected experiments as well as experiments with additional intermixed moderator.

Other solid-material experiments have been performed with unmoderated U^{235}-enriched uranium metal. Experiments of this type are characterized by an extremely short neutron lifetime and demand, therefore, more careful planning and performance than those in which the average neutron energy is lower. Included in this category have been neutron multiplication measurements on large arrays of metal billets, each containing 23 kg of

U^{235}, with and without intermixed hydrogen, to establish safe storage criteria. In addition, small rectangular assemblies of uranium metal have been made critical both unreflected and with reflectors of graphite, beryllium and Plexiglas. Preliminary experiments performed on uranium-molybdenum alloy to establish the design of the Health Physics Research Reactor also fall in this category. These experiments were followed by a complete check-out of this reactor's performance including super-prompt-critical operation with the production of energy pulses of up to 1.7×10^{17} fissions.

Several combination-type experiments have been performed for reactor projects, usually with liquid moderator and solid fissile material. Those for the Army Package Power Reactor, for example, utilized stainless steel fuel plates and were water-moderated and -reflected. The unique geometry of the Tower Shielding Reactor II was first investigated rather crudely with available materials and later, much more thoroughly, with the first reactor core fabricated from that design. The High Flux Isotope Reactor Critical Experiment No. 1 was an exploratory series of experiments with four liquid regions including a heavy water reflector. The second experiment in this series was a more accurate nuclear mockup of the reactor complete with target, fuel element, controls, water moderator and beryllium side reflector. Also included in this group are two high temperature (1300°F) molten salt (ZrF_4-UF_4-NaF) reactor experiments. These had internal and external beryllium reflectors.

There have also been a number of experiments with uranium solutions poisoned with boron in glass and with copper to establish the safety of certain operations. Other water-moderated and -reflected experiments with fuel elements from pool-type reactors, from Savannah River Reactors, and from Hanford Reactors have aided in a variety of nuclear safety problems.

All these experiments have been performed in this facility on a variety of combinations of equipment, many of which were of a temporary nature because of the limited duration of the individual programs. Although the basic controls of this equipment are permanent parts of the facility they may be supplemented by more flexible components for the individual experiments. Typical equipment for performing these experiments will be described in the next section.

II - DESCRIPTION OF THE FACILITY

Location

The Critical Experiments Facility is located at a remote site in the southwest portion of the Y-12 Area. It is situated in a pocket in the terrain formed by surrounding hills several hundred feet higher than the building itself. The projected distance to nearest work areas is more than 2000 ft and to the nearest public highway is 4200 ft. The facility is enclosed in an area to which access is restricted by a chain

link fence. Gates in the fence, except the one at the entrance to the facility, are kept locked. Many of these features are shown in Fig. 1, a plan of the area including contours. Figure 2 shows the immediate building environment in greater detail.

Construction

The facility is a two-story concrete and concrete block structure about 200 ft long and 80 ft wide. The west and east ends of the building are shown in Figs. 3 and 4, respectively. Floor plans of the building are included in Fig. 2.

The three* assembly areas or test cells extend the full height of the building, i.e., about 35 ft, and each has a floor area between 900 and 1520 ft^2. A control room is associated with each cell and is separated from it by a 5-ft-thick ordinary concrete wall having a specific gravity of about 2.5. Visual communication between the control and test areas is provided by water-filled windows; verbal communication by an intercom. Necessary office, laboratory, and other supporting space is located in the central portion of the building.

Radiation shielding on the south side of the building is provided by concrete walls for the protection of the guard stationed at the area portal and of travelers on the roadway.

Although the 12- to 18-in. wall thicknesses on the east, west and north sides of the building were established by structural needs, they provide significant radiation shielding at the boundary of the area defined, on these sides, by the perimeter fence located at least 50 ft from those parts of the building where no material shielding is purposely installed. Openings through these walls are closed by wooden doors which reduce significantly the protection afforded by the walls. The effect of the leakage through these openings in the ends of the building has been minimized by the addition of concrete walls and bunkers, as shown in Fig. 2.** The other openings lead into limited access areas.

Many other features were incorporated in the design to improve the over-all personnel protection. In some places, for example, windows were substituted for solid walls where the latter may have back-scattered radiation into normally occupied areas.

The scattering of radiation by air was underestimated at the time of the design of the building and, as a consequence, the original roof met structural requirements only. The need for shielding against air scattering was later recognized and at the present time, either by

* The original construction included only two test cells, on the east and west sides. The third, separated from the east cell by a 5-ft-thick wall, was added in 1957.

** The photographs, Figs. 3 and 4, show more of the openings than are visible from the roadway.

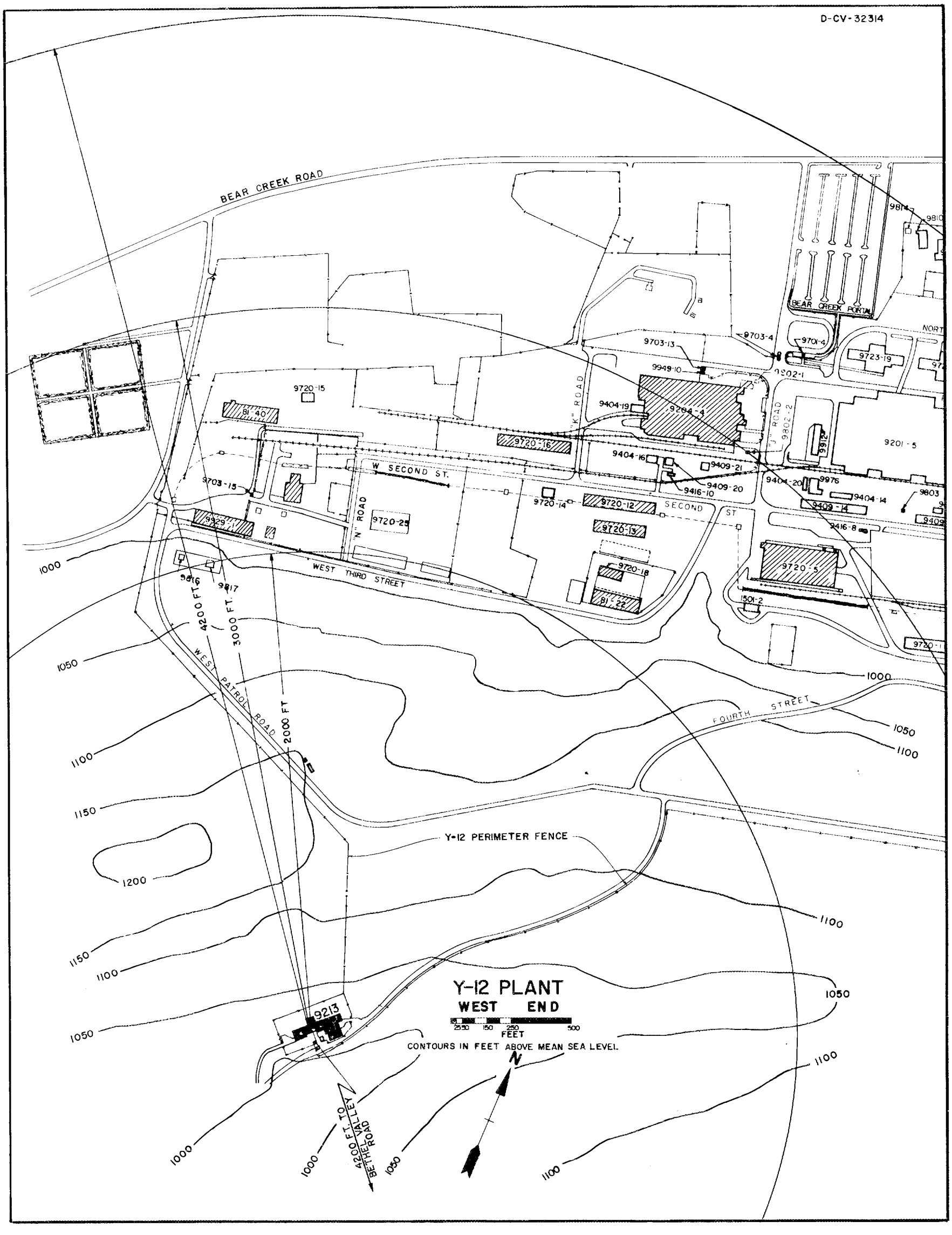
D-CV-32314
BEAR CREEK ROAD
BEAR CREEK PORTAL
W SECOND ST.
SECOND ST
WEST THIRD STREET
FOURTH STREET
WEST PATROL ROAD
"K" ROAD
"J" ROAD
"N" ROAD
4200 FT.
3000 FT.
2000 FT
4200 FT. TO BETHEL VALLEY ROAD
Y-12 PERIMETER FENCE
Y-12 PLANT
WEST END
FEET
CONTOURS IN FEET ABOVE MEAN SEA LEVEL
N
9213
9204-4
9703-4
9703-13
9949-10
9701-4
9723-19
9802-1
9802-2
9404-19
9404-16
9409-21
9409-20
9416-10
9404-20
9976
9404-14
9409-14
9803
9416-8
9720-5
9720-15
9720-16
9720-14
9720-12
9720-13
9720-18
9720-25
9703-15
9929
9816
9817
9812
9201-5
1501-2
1000
1050
1100
1150
1200

FIG. 1

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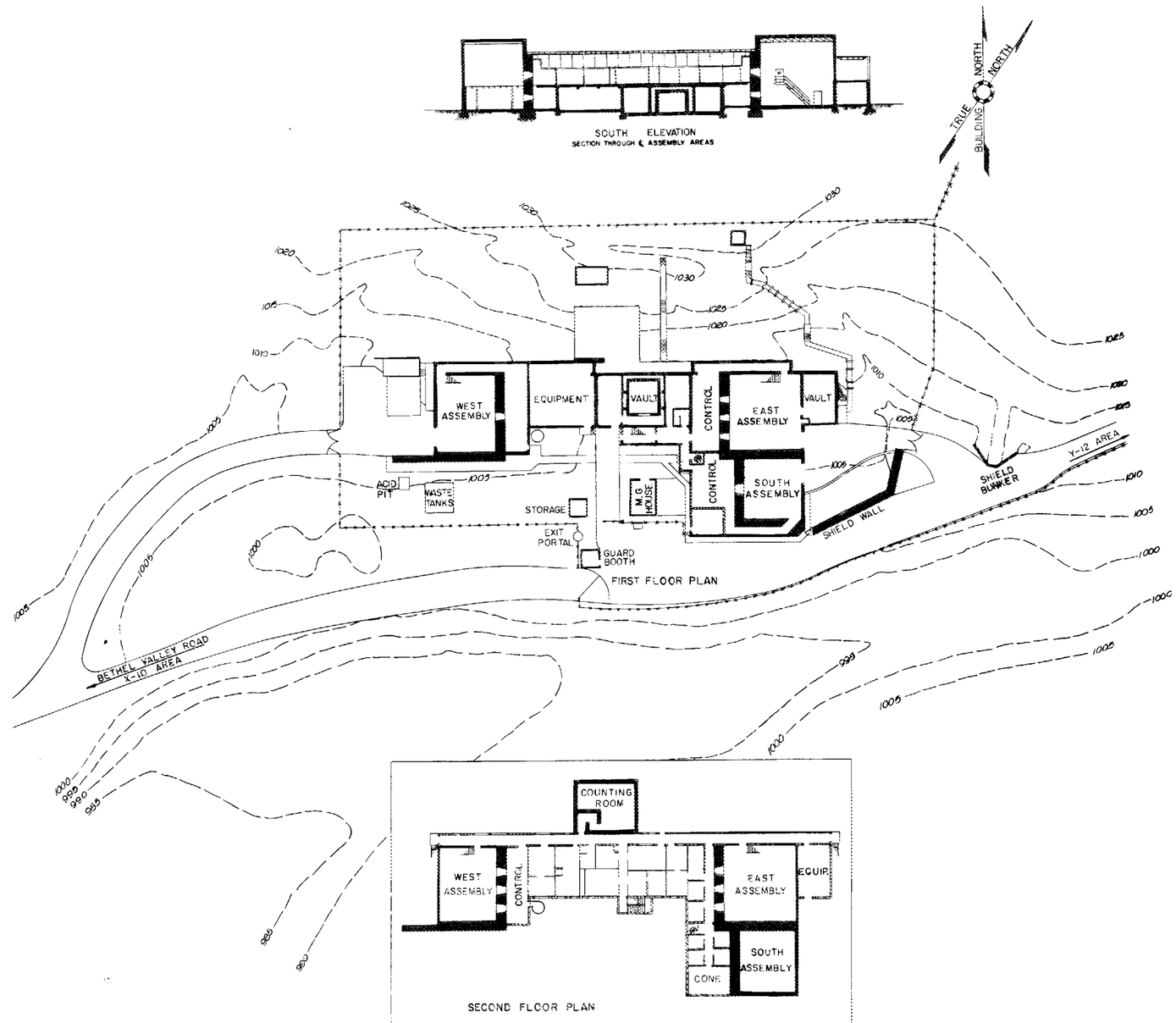

PLANS, ELEVATION AND CONTOURS, BUILDING 9213

FIG. 2

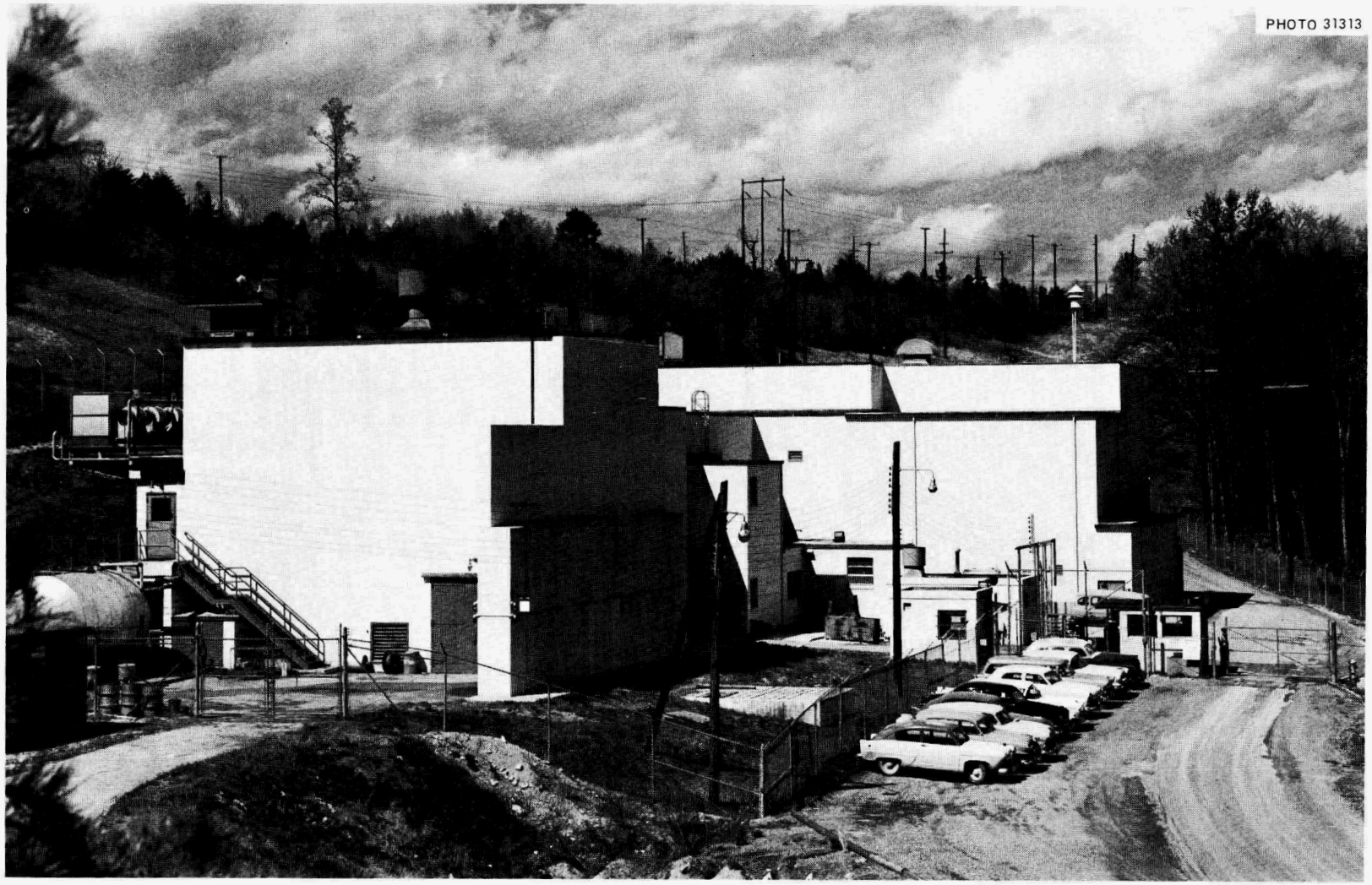

Fig. 3. West End of Building 9213 Showing the Concrete Shielding Wall Between the Roadway and the Large Doors.

PHOTO 38049

Fig. 4. East End of Building 9213 Viewed from Approximately 14 Feet Above the Roadway, Showing the Concrete Walls and Bunkers Which Provide Shielding for the Large Doors.

addition to the old structure or by inclusion in the design of the new area, each test cell is covered by a 1-ft-thick concrete slab. The intermediate general-purpose area and the guard shelter are covered by concrete at least 3 in. thick. In practice, of course, the effective thickness of these roof shields is somewhat greater because of the angle at which the radiation must traverse them in order to be scattered into the central area or onto the road.

Reference is made to the drawings and specifications of the architect-engineer for structural details.[1]

Many data have been amassed over the ensuing years from both accidental supercritical excursions and planned experiments which yield an evaluation of the protection of personnel afforded by these structures. More detailed reference to these supporting data will be presented in the discussion of potential accidents. In summary, however, it may be said that very adequate shielding is provided against damage to personnel from radiation sources of the maximum expected intensity, described in Section V, below, in the three cells if these personnel are within designated areas during the course of experiments. Control of personnel in nominally unshielded areas is by the perimeter fence and by rigid administrative practices.

Ventilation

The entire building is air conditioned. Each of the three cells is heated and ventilated by air circulated and conditioned in a system serving that cell exclusively. By this means, therefore, contamination arising in one area is not directly carried by an air stream into another area of the building. It is further provided that all air handling equipment in the building is automatically stopped upon signal from high level radiation detectors in each cell so that contaminated air, which might accompany the high level radiation, remains stagnant until such time as it is deemed appropriate to reactivate the air handling equipment. This reactivation must be done manually. In addition to the usual air conditioning system, each cell is equipped with a 1000 cfm fan which normally runs continuously and discharges to the atmosphere. This outflow of air maintains the pressure within the cell slightly below that in adjacent areas of the building and also below that of the ambient atmosphere. Thus, at least in the short interval required for air pressures to equilibrate after stoppage of the fans upon emergency signal, the flow of air is into the potentially contaminated area. Subsequently, any contamination can be discharged to the atmosphere either by the small fans or by the large exhaust blowers, each having a capacity of at least 10,000 cfm, with which each cell is equipped. Appropriate louvers open

1. Giffels and Vallet, Inc., Detroit 26, Mich. Job 48-148A, completed 1950. Barber and McMurray, Knoxville, Tenn. Contract 81Y-34807, completed 1957. UCNC Dwgs. E-CV-24227, E-S-24228, E-S-24229, E-S-24230, E-S-24420, E-HV-23275, completed 1958.
These drawings and specifications are available from Union Carbide Nuclear Company, Engineering Services, Y-12 Plant, Oak Ridge, Tenn.

as the blowers start in order to provide free and rapid exhaust of any air-borne material. Filters are not installed in these exhaust systems since personnel can be readily controlled in the remote area in which the facility is located. Little, if any, inconvenience would be forced on activities in other areas by such a procedure.

Beyond that which has already been described, there is no provision for containment of air-borne activity. The facility is inadequate for the hazards which might arise in experimentation with highly toxic materials, such as plutonium, without sufficient containment. This inadequacy does, indeed, impose the principal limitation on the types of experiments which can be performed.

Contaminated Waste Collection Tanks

To guard against loss of fissile materials, the drains from laboratory areas lead first to an acid-neutralizing pit thence to hold tanks which are emptied only after analyses have shown permissive quantities present. Incidentally, no concentration even approaching that economically salvable has ever been collected in these tanks. Possibility of accidental criticality in the tanks is precluded by location of the entrances to the drains above floor level or by fitting them with gasketed pipe caps.

Equipment and Equipment Operation

The Critical Experiments Facility is equipped for experiments of all kinds with both liquids and solids. These may range from test vessels containing aqueous solutions of enriched uranium, with or without an aqueous reflector, to tests of massive pieces of unreflected uranium metal. In all cases, of course, the approach to critical is by the addition of reactivity through the remote operation of some device from the shielded control area. This device may be a pump for liquids or it may be a motor drive to bring sections of a solid assembly together. The action by which reactivity is added is reversible and the rate at which reactivity is removed exceeds the rate at which it is added. In general, reactivity may also be removed by some entirely independent means. This may be appropriate pipes and valves whereby a liquid is drained through large ports by gravity from the test vessel into its storage reservoir; or may be the insertion of a neutron absorbing material into a solid array - or the reverse, the removal of fissile material, reflector or moderator - by gravity or by the action of a spring.

There are experiments, however, which are safely and more satisfactorily performed with the decrease in reactivity effected by only one method, usually the reversal of that by which reactivity is added but, of course, at a greater rate. These are experiments in which the critical parameters are well established and the available excess reactivity, even in the event of most unusual occurrences, is known to be small. An example of this type of assembly is an array of tightly fitting pieces of solid material mounted in two parts, one being movable by remote control.

A neutron source of strength appropriate to the experiment is always proximate to the fissile material during its initial assembly. The source is a driver for the neutron multiplication. It may be an encapsulated mixture of plutonium and beryllium or of polonium and beryllium, the spontaneous fission of U^{238}, or a nuclear reaction within the test materials. In assemblies expected to become critical provision is made for removal of the source capsule into a shielded region in order to truly establish criticality.

Two sets of equipment presently in use are described as typical illustrations of the above design criteria. The first, designated as the Criticality Testing Unit, is used for assemblies of solids of relatively small volume. The second apparatus is for solutions of fissile materials.

Criticality Testing Unit for Solids. The equipment used for assembling solid materials is typified by the Criticality Testing Unit (CTU) which was designed primarily for critical experiments on unmoderated metal systems. The separation of components is the only safety operation available for the systems to be studied. The equipment and its use are discussed here as an example of one type of experiment.

The CTU, shown in Fig. 5, consists primarily of two tables: a fixed table which is manually adjustable in elevation, and a vertically movable platform powered, through a magnetic coupling, by a pneumatic-hydraulic system to bring the parts of an assembly together. The fixed table, which constitutes the upper section of the unit, is a circular stainless steel membrane, 24 in. in diameter, clamped in an aluminum tension ring and set in an aluminum frame supported by vertical legs at the corners of a 4-ft square. Several membranes having thicknesses ranging from 0.005 to 0.025 in. are available. The table elevation may be varied from 6 to 8 ft above floor level.

The movable platform support device is shown schematically in Fig. 6. The platform itself is an 18-in.-dia by 1-in.-thick circular stainless steel plate attached to the magnet housing. In some experiments the lower section of the critical assembly will rest upon a low-density structure, mounted on this platform, in order to reduce neutron reflection.

During normal operation the magnet is energized and the platform follows the motion of the hydraulic-cylinder piston. Full travel is 24 in. at a maximum lift rate of 20 in./min without load. As the table nears its upper limit this rate is decreased by throttling the hydraulic flow in the following manner. At a preset position in its travel the moving member operates a switch which diverts the flow through a system consisting of two orifices in parallel each with its own manual shutoff valve. Prior to starting an experiment, selection is made of the desired closure rate and the appropriate valve setting is made. At present, flow through one of the two orifices allows a rate of 0.15 in./min and through the other 0.25 in./min. Flow through both orifices permits a rate of 0.40 in./min. The minimum lowering rate of the platform for normal shutdown exceeds the maximum rise rate and is 40 in./min. Present magnet characteristics

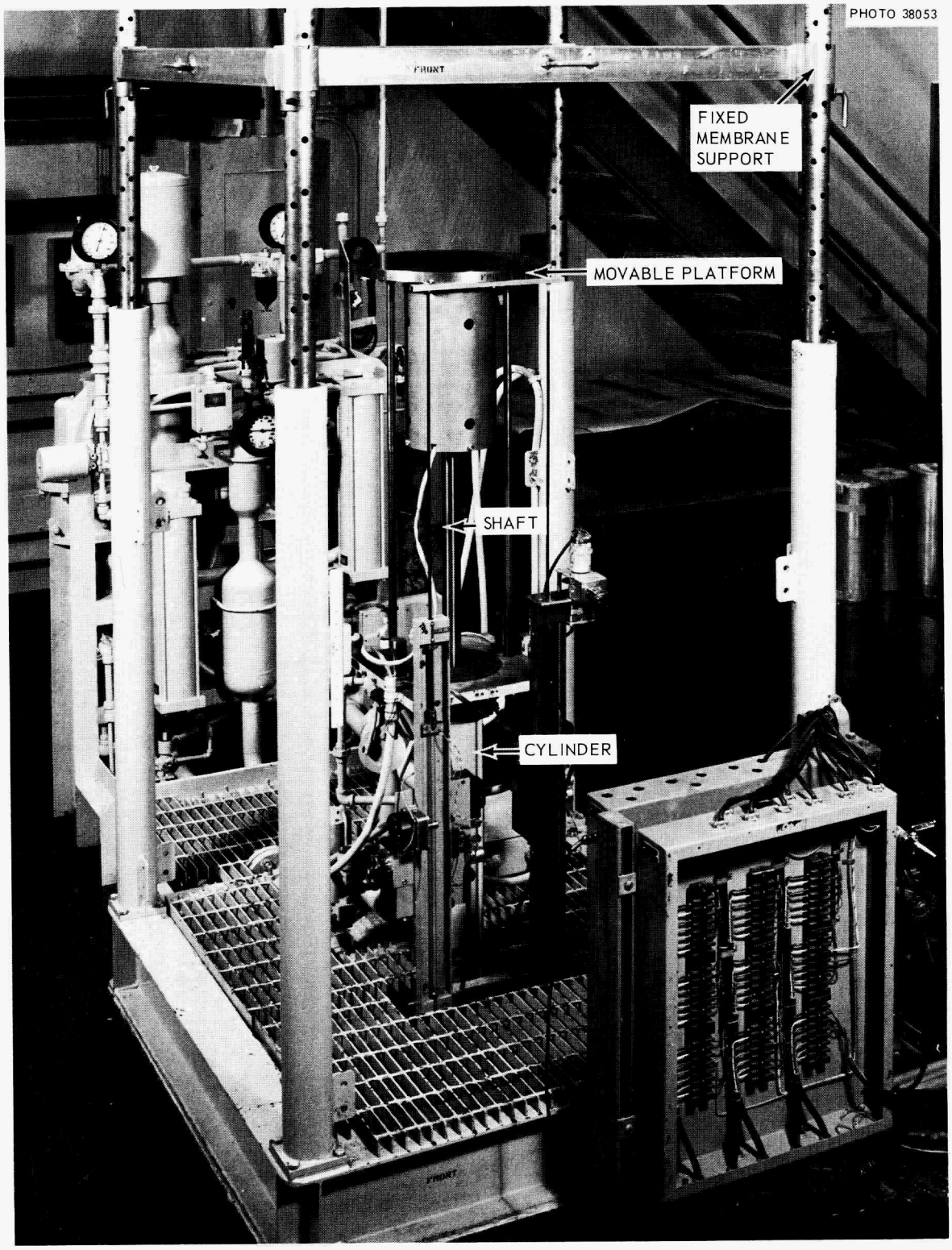

Fig. 5. The Criticality Testing Unit.

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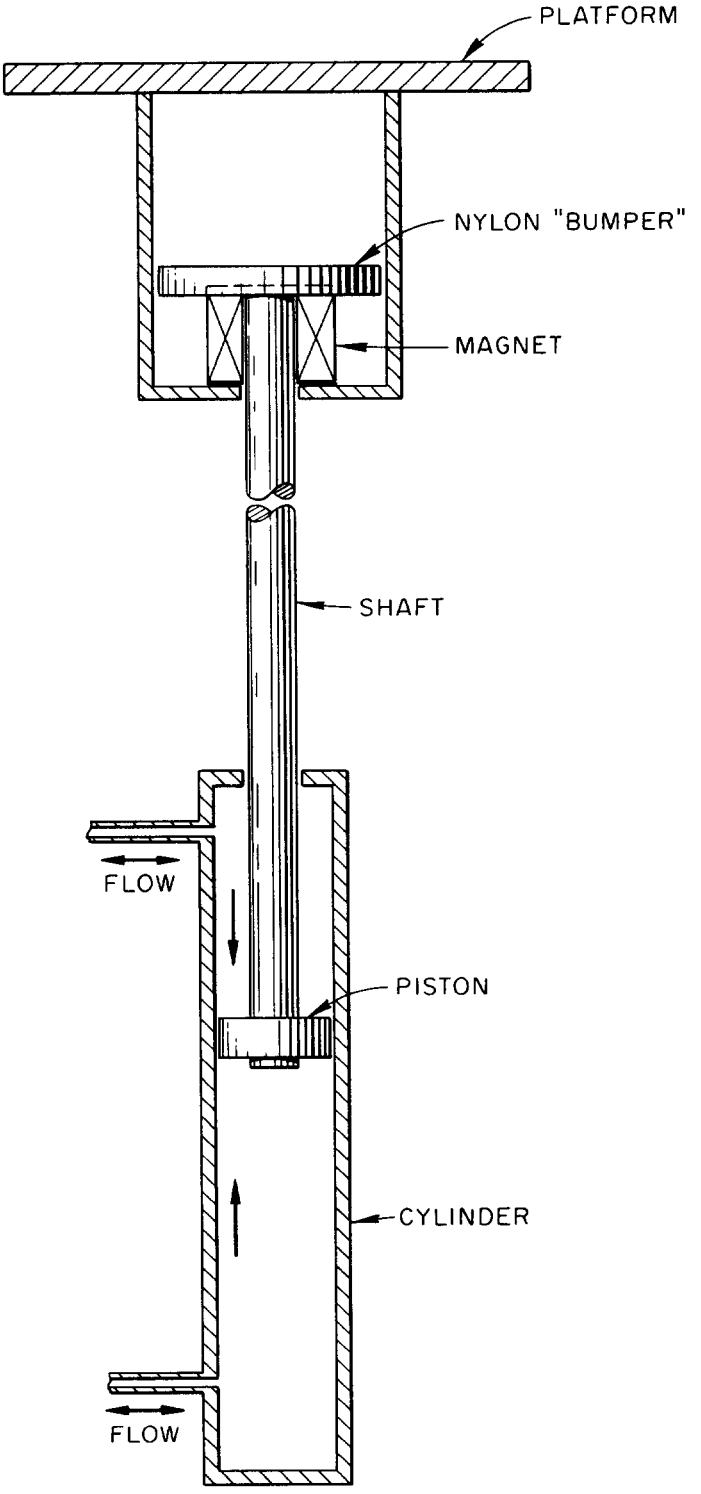

Fig. 6. Schematic of Criticality Testing Unit Magnetohydraulic Support Device.

limit the permissible load on the movable platform to 500 lb. With this load the maximum rise rate is ~ 10 in./min and the lowering rate is 58 in./min.

The safety feature of the CTU, the separation of the components of the assembly, is effected in two ways. When an emergency condition occurs, the magnet is de-energized and the platform drops at least 6 in. under gravity. Separation of the sections of the assembly is also brought about by a reversed hydraulic force on the piston, provided by oil under high pressure, which moves the piston through its total downward displacement in less than 2 sec. A characteristic emergency performance curve is shown in Fig. 7. The platform moves under gravity over the first 9 in. of travel at which time contact is made between the platform and the nylon bumper attached to the top of the piston rod, so that the ensuing motion is governed by the hydraulic system. The downward motion begins about 35 msec after initiation of the signal to the electrical circuits. This delay depends, of course, upon the load and the magnet current. Minimal release time can be achieved for a particular load by adjusting the magnet current; a value as low as 18 msec has been measured. The rate of component separation, upon emergency signal, is about 12 in./sec over the first inch of travel, 60 in./sec for the next 9 in., and 10 in./sec for the remainder of the downward stroke. Initial accelerations greater than 1 g are possible through the hydraulic action, although in experiments in which the assembly consists of simply stacked components such rapid motion undesirably disturbs the assembly, particularly during test of the safety system at the beginning of each operating day.

The safety features are adjusted to conditions for maximum safety commensurate with the experiment under study.

Provision is also made in the CTU whereby an assembly can be prepared in three sections. The center section will be fixed on the diaphragm and the lower one movable as described above. In addition an upper section can be raised and lowered by an air operated piston.

The time rates of reactivity change, derivable from the above speeds, are, of course, strong functions of the characteristics of particular assemblies. In one assembly of U^{235}-enriched uranium metal, for example, the sensitivity near closure was the order of \$10/in., which is equivalent to a time rate of reactivity increase of 1.6 cents/sec at the slowest speed of approach. Advance from delayed to prompt critical under these conditions required 1 min. In normal shutdown the initial rate of reactivity decrease was about \$6/sec. In emergency shutdown the average rate of reactivity decrease over the first inch of travel was \$120/sec. A reactivity decrease of ~\$7.5 had occurred 100 msec after the high-level signal.

An experiment performed with the CTU follows somewhat the following procedure. The fissile material is in regularly shaped units sized to be not only individually subcritical but judged, by experience, to constitute less than one half of a critical mass under the conditions

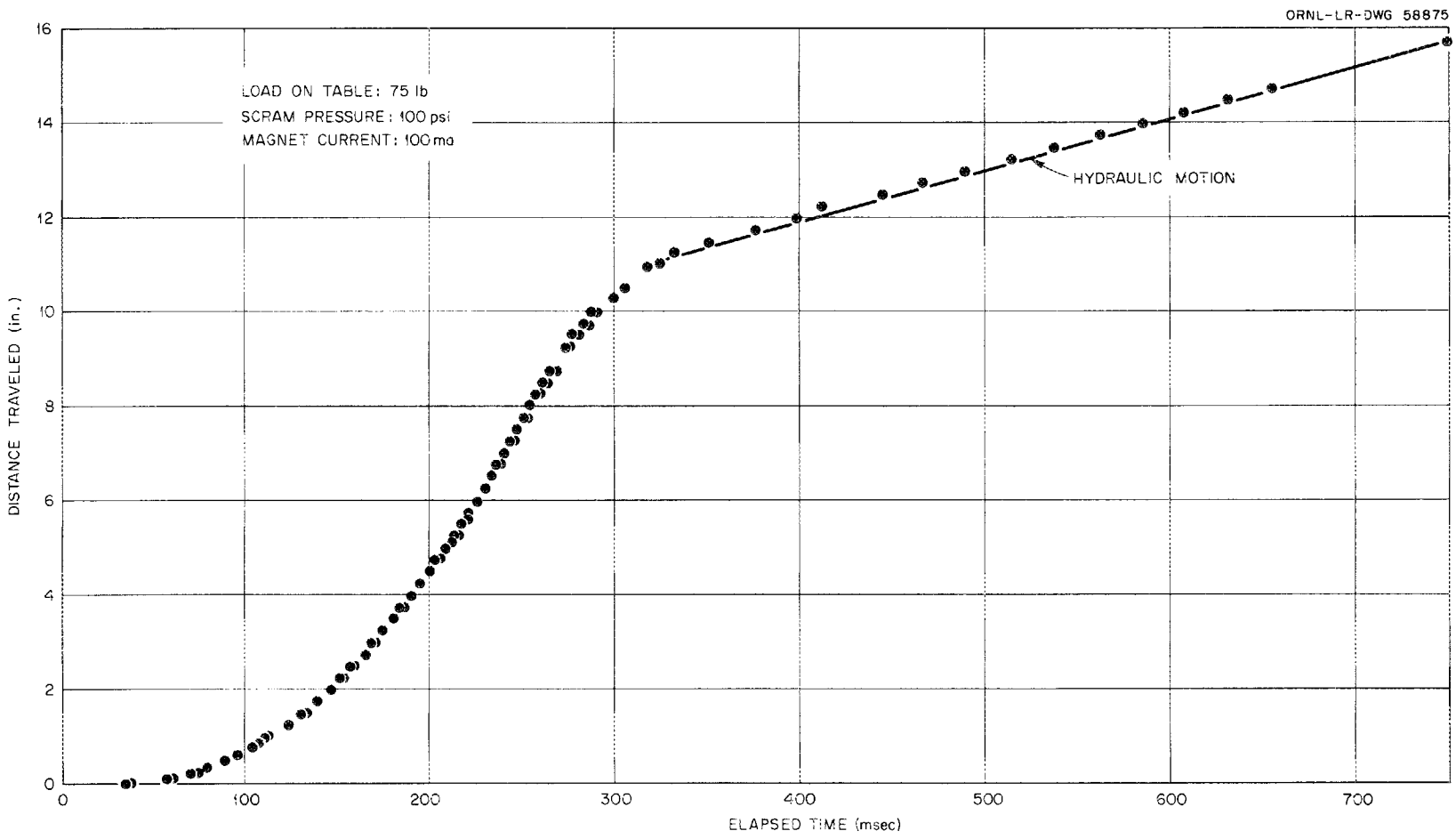

Fig. 7. Characteristic Scram Performance Curve of the Criticality Testing Unit.

of the experiment. After verification that the behavior of operational instrumentation and safety systems is satisfactory and that a neutron source is appropriately located, one of the units of fissile material is located on the movable platform and another, well aligned vertically with the first, is placed on the diaphragm. The platform is raised, to bring the lower unit in contact with the bottom of the diaphragm, by operation of the drive mechanisms from the control room. This operation is in a careful and reversible manner even though there is little expectation that the two pieces in contact will become critical. The neutron count rate is measured with the components in contact and compared to that with one fissile unit present. The rate with the two units in contact may be less than the rate for a single unit because absorption effects may possibly override the neutron multiplication by the combined units.

Having established that two unreflected units are subcritical, a small piece of solid hydrogenous material, simulating the neutron reflecting properties of a pair of hands, is added to the assembly and the above measurement repeated. If this combination is subcritical, a second unit can be safely added to, say, the platform and the procedure repeated. The reciprocal of the neutron multiplication will eventually be a decreasing function of some system parameter, such as the mass, height, or number of pieces, and the intersection of the extrapolation of this function with the coordinate is an estimate of the critical value of that parameter. Assuredly the function will not be linear; hopefully the curvature will be convex towards the origin; at best it is a guide toward terminal conditions. Continuation of this step-by-step process leads to a near delayed critical configuration, perhaps a little subcritical, perhaps a little supercritical, by amounts depending upon the size of increments of reactivity which are available.

The test of the reactivity of the assembly is, of course, the observation of the time behavior of the neutron population upon removal of the startup neutron source.

The initial assembly may be satisfactorily made in an alternate manner. In this method it is known that the initial loading in each section is subcritical and that the combination of the two may be critical. The neutron intensity in this procedure is measured as a function of the component separation. Extrapolation of these data will indicate the critical separation.

With the critical condition as a point of departure there are many possible subsequent operations depending upon the purpose of the experiment. If the desired information has been ascertained, the sections of the assembly are separated and the next experiment is begun. If power or flux distributions are desired, the assembly is made supercritical in some manner, for example by the remotely controlled addition of a neutron reflector, and allowed to reach the power necessary for activation of appropriate detectors. Then the reactivity is returned to zero, the irradiation proceeds to the necessary exposure and the unit is disassembled. If it be desired to observe the kinetic behavior of

the material, a perturbation is made in the buckling and the resulting reactor period is measured.

Criticality Testing System for Solutions. The most common aqueous solutions used in experiments have been those of uranyl nitrate and uranyl fluoride. These corrosive solutions must be used in systems and vessels which are protected against corrosion in order to minimize the buildup of foreign materials. The time in storage far exceeds the time the material is used in a critical experiment; consequently, storage systems are constructed of compatible materials. The west assembly cell of the Critical Experiments Facility contains two such systems, both capable of remote operation after the necessary manual settings have been made as required by operating procedures. The system described in the following is typical.

The schematic shown in Fig. 8 is an experimental system constructed almost entirely of polyvinylchloride. The storage manifold consists of several 6-in.-ID cylinders ~20 ft long, slightly inclined to facilitate draining. Solution from these cylinders is directed to a centrifugal pump, thence to the test vessel always located, in height, above the storage system in order that solution is returned by gravity. The system is vented at appropriate points through an air filter.

Referring to Fig. 8, A and D are remotely operable normally closed valves and B and C are remotely operable normally open valves. Valves A and B cannot be open simultaneously. All other valves shown are manually operated and must be adjusted before an experiment is begun. The emergency "dump" system consists of an ~10-ft length of 5-in. pipe connected directly to the test vessel by valve C and short nipples. The minimum constriction in this line is 3 in. in diameter. A manually or instrument initiated scram signal opens valves B and C providing the maximum drain rate. Valve E, in a bypass, and F or G, which are not remotely adjustable, control the rate of solution flow through the 1/2-in. feed pipe. The maximum feed rate during operation does not exceed the drain rate through valve B. That the desired flow has been established may be observed in two ways; by use of the flow meter or by measuring the time rate of solution addition to the test vessel. The latter, being both more accurate and more convenient, is usually used.

Increments of solution as small as desired may be added to a test vessel by the manual adjustment of valves E, F and G and the remote operation of A. The procedure for an approach to critical is similar to that discussed for solid systems. Typical ratios of drain to feed rates are 5.6 for valve C and 2.5 for valve B for particular settings of valves E, F and G. As an illustration of the reactivity addition rates, as practiced, two examples are cited. The flow of UO_2F_2 solution having a uranium concentration of 350 g/liter into a 10-in.-ID aluminum vessel corresponded to a maximum rate of reactivity addition of 0.8¢/sec; the rate of removal of reactivity was 4.5¢/sec through the dump system and 2¢/sec through normal drain. In the second example, the critical parameters of an array of 5-liter plastic cylindrical containers were tested with a $UO_2(NO_3)_2$ solution having a uranium concentration of

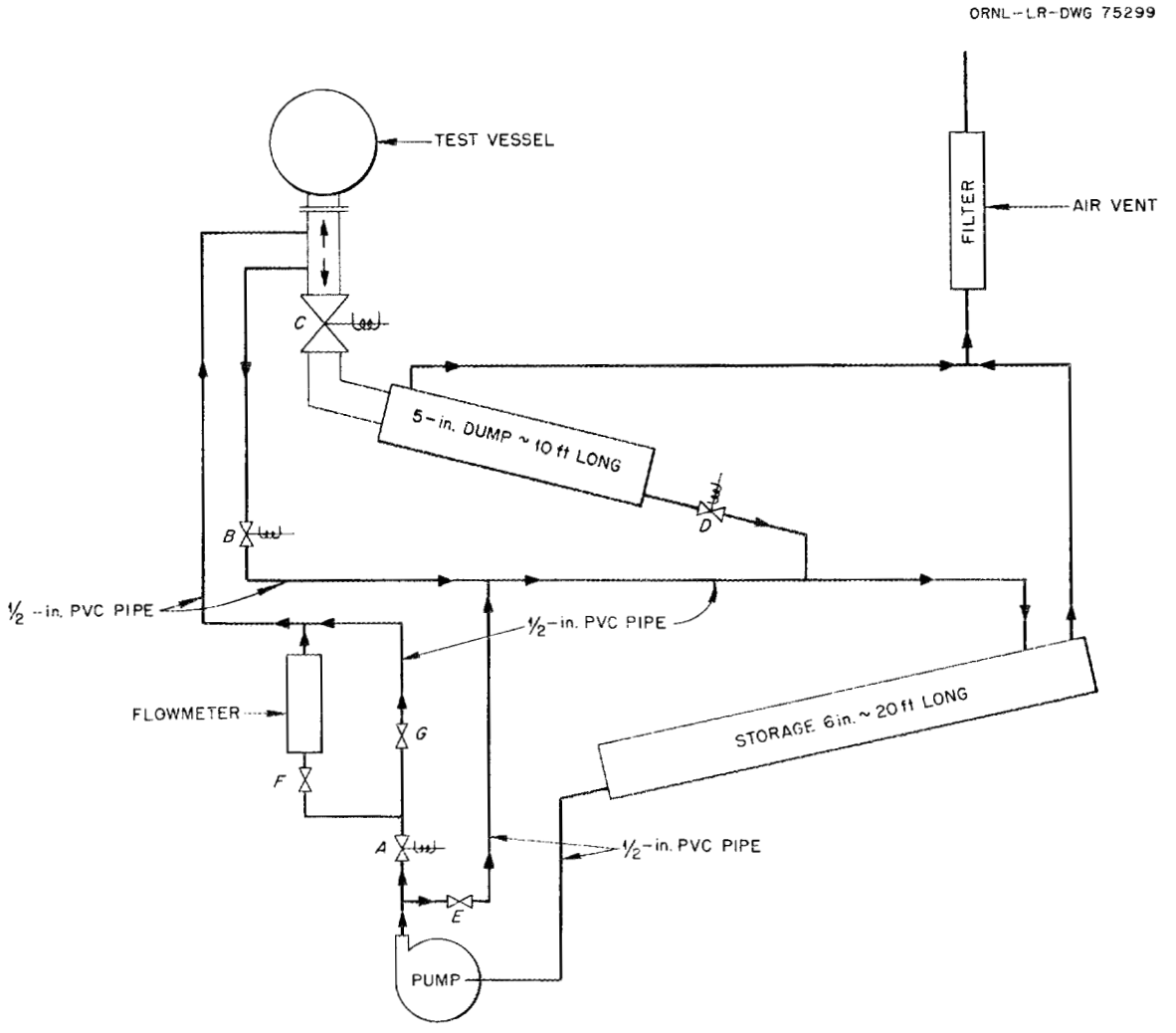

Fig. 8. Schematic of a Typical Solution System.

410 g/liter. The flow of solution was remotely controlled to the five central units of the array. The maximum rate of addition of reactivity was 7.3¢/sec, with corresponding drain rates of 41¢/sec through the dump system and 18¢/sec through the normal drain.

Other means of reactivity control are available depending upon the experiment and its purpose. In each case, a suitable ratio of reactivity addition to drain rate is determined and evaluated prior to achieving critical.

Instrumentation

Because of the diversity of operations in the three experimental areas instrumentation requirements vary and each location is provided with more than the minimum amount of electronic equipment necessary for performance of critical experiments. Generally, an experiment is performed with all working channels in use; however, operation is permitted if some are removed, as a result of instrument failure or saturation due to excess radiation at the detector, provided the minimum number of units is still functioning. Most experiments are conducted at power levels of less than 10 mw, although some measurements may be carried out at levels up to the order of 1 watt. Extraordinary situations sometimes arise involving levels of the order of 100 watts, and occasionally controlled radiation excursions are generated. The numerous instrument channels, having different input sensitivities and ranges of operation, are capable of providing adequate monitoring at all operating levels.

Minimum instrumentation for initial operations includes two neutron-sensitive counting channels, one linear neutron level safety channel, one dual-output gamma-ray sensitive photomultiplier safety channel, one logarithmic neutron level channel, and suitable shutdown and building alarm devices. When the 10 mw level is exceeded, the counting channels are no longer required and, too, they may become inoperable owing to range limitations. Safety channels are necessary throughout an experiment since they provide scram protection in the event of an unexpected abnormal rise in power. A block diagram of typical instrumentation is shown in Fig. 9 and the components are described below.

Counting Channels. Counting channels provide visual and aural indication of the neutron level during both startup and low power operations provided the counting rate does not exceed the order of 10^5 counts per minute. Highly sensitive BF_3-filled proportional counters* are usually used as detectors for startup and operational purposes and miniature fission counters and BF_3-filled counters (1/4 in. in diameter) for experiments where space limitations are imposed, such as for flux distribution studies. Standard linear amplifiers** transform

* Model 10500, Radiation Counter Laboratories, Inc., Skokie, Ill.
** Types A-1, A1D, and DD-2 are used.

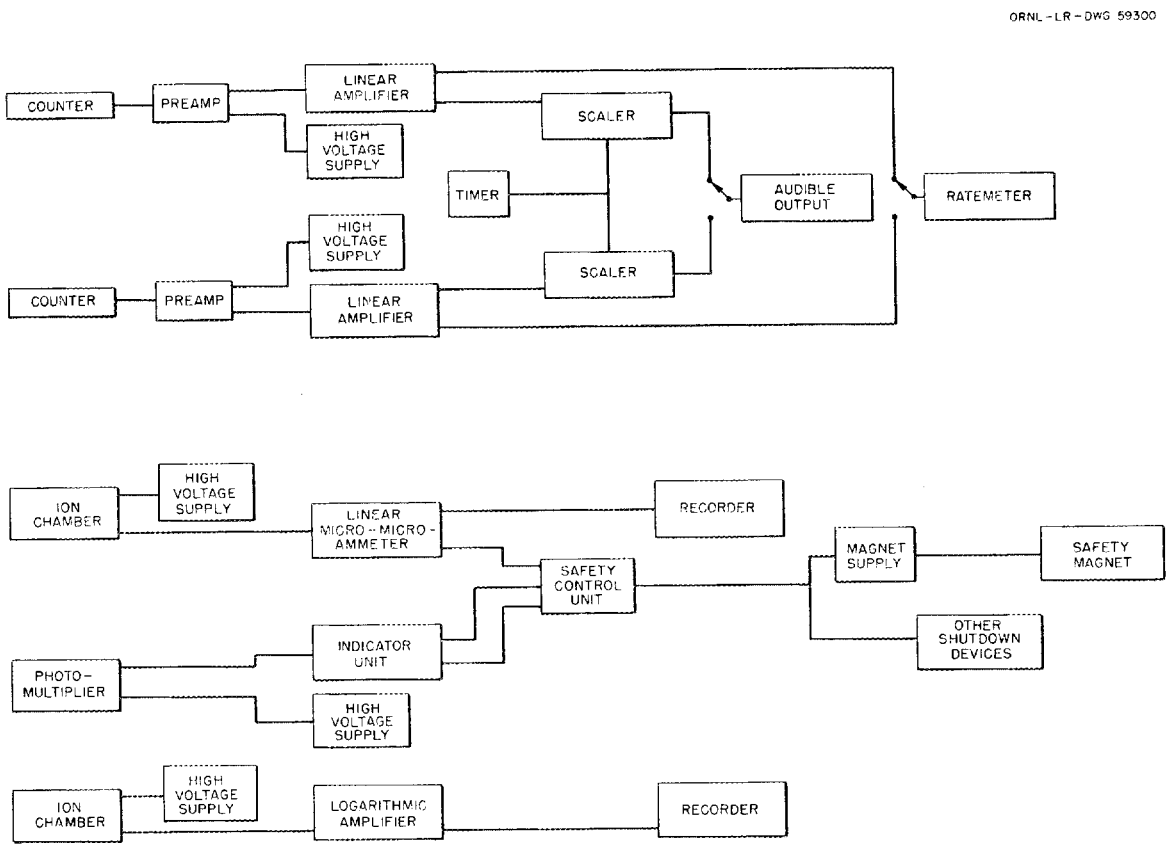

Fig. 9. Minimal Instrumentation.

the output of the detectors to pulses large enough to drive scalers and ratemeters. An audible count is provided by a mechanical register in the scaler output. This signal is transmitted to the test cell, over the intercom, during loading operations.

Safety Channels. The neutron sensitive safety channel provides both visual indication of neutron level throughout an experiment and a voltage signal to the safety control unit to activate the scram system. In a typical channel, integrated current from an uncompensated BF_3-filled ion chamber is fed to a linear micro-microammeter in which the signal is amplified and displayed on a panel meter and on a strip-chart recorder. Full-scale range of the readout devices is adjustable in decade steps by a range selector switch. The output voltage of the instrument is proportional to the meter reading.

The dual-output photomultiplier safety channel, generally insensitive to startup level signal but responsive to levels greater than about 1 mw, provides both on-off signals to the safety control unit (to initiate emergency shutdown) and visual indication of the gamma-ray level. A typical detector consists of a sodium iodide phosphor mounted on the face of a ten-stage multiplier phototube. The integrated output signal, proportional to the gamma-ray flux level, is introduced on the grids of a twin-triode vacuum tube circuit as a negative-going voltage. Sensitive relays in the plate circuits operate the scram system through the safety control unit described below. Visual indication of the gamma-ray level is provided by output meters or strip-chart recorders.

Logarithmic Channel. This channel provides visual indication of the neutron level with a single range covering up to six decades. The integrated current from an uncompensated BF_3-filled ion chamber is fed to a logarithmic diode and the amplifier which follows develops an output which is proportional to the logarithm of the neutron flux. This output is displayed on a panel meter and on a strip-chart recorder.

Scram System. The requirements of a scram system include a triggering signal, which may originate in safety instrumentation or in a manually operated switch, and appropriate circuitry, designated as the safety control unit, which upon receipt of the signals initiates a series of events resulting in the operation of mechanical and electromagnetic devices that reduce the reactivity of the assembly. The safety instrumentation has been discussed above; therefore only the response of the safety control unit to triggering sources will be described here.

The voltage signal from the linear safety channel feeds a trip circuit consisting of a vacuum tube with a current-sensitive plate relay. This signal increases in proportion to the neutron flux until at a preset level the relay is de-energized. This level is about 150 per cent of the signal required to give a full-scale deflection of the output meter for that particular instrument range. This feature insures rapid response to signals arising from abnormal conditions at all levels of operation. It follows, a priori, that the scram point is also off the chart-recorder

scale, reducing the frequency of false scrams. Some instrumentation includes a meter relay which does provide an on-scale scram point. It is emphasized that meter relays are only secondary scram devices.

The on-off signal from the photomultiplier safety channel serves the same function as the linear channel trip circuit output. Adjustment of two preset trip points are made in the indicator unit of the channel so that the first activates the scram system at a level slightly greater than the operating range, and the second, operating two orders of magnitude higher, serves as a backup.

When a trip occurs in either channel, an ac-operated relay is de-energized and its contacts are so connected that a red warning light is illuminated, indicating an instrument trip, and power to the magnet supply and other shutdown devices is interrupted. In addition, an auxiliary relay opens the dc supply to the magnet. Collapse of the magnet current initiates an action which rapidly reduces the reactivity of the assembly in an effort to quench an excursion. This may be the insertion of a safety rod, the opening of a valve to drain fissile solutions or moderator water, or, as in the case of the CTU, the separation of the assembly components. Other shutdown devices operate somewhat more slowly to produce the same effect.

The response time of the scram system, i.e., the time required for a step-function impressed on the input of an instrument channel to de-energize the shutdown devices, is the order of 10 msec. For most types of experiments this is adequate, being commensurate with the time behavior of the mechanical and electromagnetic components of the scram system. In the case of the CTU, in which rapid response is of primary importance, special instrumentation provides a response time of 1 msec.

The scram system is designed to be fail-safe to the extent that loss of building power, burnout of safety circuit relays, and commonly experienced trip circuit failures create a scram condition, shutting down the experiment until such failures are corrected and it is safe to proceed with normal operations.

Building Alarm. The building alarm is a system of horns, bells, and sirens situated about the building which serve, when actuated, as warning to personnel that an accidental radiation excursion has occurred. The radiation monitors which provide the signal to the system are scintillation sensors located, in groups of three, in each of five sensitive areas within the building. The alarm is automatically sounded when the radiation at two of the three monitors constituting a group reaches a preset value. The location of the monitors initiating an alarm is identified as a room number by the illumination of the appropriate block on each of five annunciator panels. The initiation of an alarm stops all air-moving equipment in the building, turns on the flashing red light on the roadway from the main Y-12 area (warning traffic not to proceed onto the road which passes the building), and indicates in the office of the Y-12 Plant Shift Superintendent. (This paragraph revised and minor changes

made elsewhere Aug. 23, 1965 to conform with recent modification to the alarm system.)

Fast Safety Channel. A somewhat faster response time is incorporated in the instrumentation for control of experiments with materials where neutron lifetimes are short, such as in U^{235}-enriched unmoderated uranium. The fast response is obtained by feeding an amplified photomultiplier output signal directly to the input of a specially designed magnet power supply which provides full magnet current from a vacuum tube circuit until the predetermined trip point is reached. When the input voltage reaches this level, an electronic switch operates, cutting off the magnet current 1 msec following the incidence of a sharply rising signal on the scintillator. Additional circuitry is included in this channel to trigger the scram system in the manner described in the section entitled Safety Channels.

Incident Alarm Channel. This channel embodies a gamma-ray sensitive photomultiplier, similar to that used in the safety channels, which responds to radiation in its immediate area but does not respond to radiation released from the order of 10^{17} fissions in other test cells. The instrument provides a visual indication of its operation and also initiates a building alarm only when an excursion occurs in the immediate test cell. It performed satisfactorily during recent planned radiation-pulse experiments.

Limitations on Experiments

As has been stated previously, the versatility of the facility has been demonstrated by the successful performance of experiments with both fissile isotopes of uranium in almost every conceivable configuration with and without other materials of interest. It has also been pointed out that the facility is not equipped to cope with the contamination problems which might arise upon the dispersal of large quantities of toxic materials since the structure has no unique built-in gas-containment features. It is deemed inadvisable, therefore, to enter upon an experimental program with plutonium without providing measures required to assure containment of the possible contamination.

There have been occasions in the past, and there probably will be others in the future, where, in the judgement of senior experimenter, it was not expedient to achieve criticality. These decisions have been governed by the nature of the material, by the expected consequence of an accident, and by deficiencies in the experimental equipment. So a second limitation on experiments or experimental programs at the facility is that which may arise from evaluation of the hazards associated with a particular operation. In most cases, of course, assemblies are made critical in order to unequivocally establish the desired information.

Beyond these limitations there are no restrictions on the kind or type of critical experiment which can be performed at this facility; on the other hand, all experiments proposed for the facility are subject to these limitations and to others which may be imposed by Laboratory

management in the procedures described below.

III - FACILITY ORGANIZATION AND STAFF

The Critical Experiments Facility is organized as a part of the Neutron Physics Division of ORNL, the responsibility for the operation of the facility being vested in a supervisor. For guidance in matters of safety the Neutron Physics Division has established a Reactor Safety Review Committee, which reviews each experimental activity within the division at least annually. The committee consists of the division director, the supervisors of the various facilities operated within the division and other experienced technical personnel. The operations within the facility are reviewed by the Laboratory's Reactor Operations Review Committee.

The facility is staffed by a number of technically qualified individuals to some of whom is delegated the responsibility for the experimental programs. At the time of this writing (February, 1962) the facility technical staff comprises 10 scientists, three technicians, and a part-time health physicist.

By academic training the 10 scientists may be classed as four with Ph.D degrees or the equivalent, four with master's degrees, and two with bachelor's degrees. Of the three technicians, two have college training, not necessarily, however, in technical fields. Five scientists qualify as senior experimenters, defined below, and three members of the staff as experimenters. The average experience of the former group is nine years and that of the latter is five years. These statistics are believed significant because they indicate the background and caliber of the persons to whom the operations are assigned.

Additional personnel include a secretary, a janitor, a security guard located adjacent to the facility during regularly scheduled hours, and personnel from maintenance and other supporting services assigned to the facility from time to time as need demands. In this manner the number of personnel regularly within the area is minimized.

IV - OPERATING PROCEDURES

Program Development

The need for and desirability of a particular experimental program at the Critical Experiments Facility is first established at the division level after, in some cases, consultation with others from both ORNL and outside groups to whom the information to be derived will be useful. If, in the opinion of the facility staff, the experiment is significantly different from other which have been performed at the

facility, the proposed program must be reviewed in detail by the division's review committee. After the feasibility of the program has been established, the responsibility for its organization and performance is assigned to one of the senior experimenters, defined below. He, in collaboration with the supervisor of the facility, other members of the staff, and outside specialists, develops the details of materials, equipment, instrumentation and procedures required to carry out the program.

After agreement on the experimental materials and methods, operations follow generally accepted procedures, modified and amended to conform to the demands and unique features of the particular experiment in question. Necessary changes arising during the experiment are developed in consultation with other senior experimenters. As indicated above, changes of sufficient importance are reviewed by the division committee.

General Operating Rules

The following terms used in these rules are intended to convey the meanings given here.

Senior Experimenter shall designate a person having a working knowledge of reactor theory and at least one year of operational experience at this facility and who preferably, but not necessarily, has past experience with experiments in which the form of the fissile material was similar to that of a proposed experiment.

Experimenter shall designate a person with the above qualifications except he is not required to be versed in reactor theory.

Neutron multiplication measurement refers to the monitoring of a subcritical assemblage of fissile material. Such measurements require the presence of a neutron source and neutron-sensitive counting equipment which is used to observe the change in the neutron counting rate as reactivity is added.

Exclusion areas are portions of the facility having insufficient shielding to permit free access to personnel during operations. These are delimited by posted signs, gates, audible alarms or by red and green lights. When the red light is on, traffic into that exclusion area is prohibited.

Fail-safe describes the characteristics of systems and mechanisms used in critical experiments which, in the event of any loss of building power or of commonly expected electronic circuit failures, automatically scram the assembly.

Administrative control connotes nuclear safety practices dependent upon the adherence to specified conditions or restrictions during handling or storing of fissile material.

1. The safety and operational procedures of all experimental programs involving fissile materials shall be established jointly by the supervisor of the facility and at least one other Senior Experimenter.

2. One Senior Experimenter shall be in charge of all operations concerning a particular experiment. A minimum of two persons, one of whom is an Experimenter, shall be present during any experiment involving fissile materials.

3. The primary concern of the person in charge of operations shall be the evaluation of personnel safety.

4. Any deviation from an established experimental program, however insignificant, shall be reviewed by at least two Senior Experimenters.

5. All experimental plans must be understood and approved by each participant prior to the performance of an experiment. If anyone has doubt of the safety of a particular action or step, the experiment shall be suspended until every one concerned is satisfied that to continue involves no undue risk.

6. No experiment shall be performed under duress of time.

7. The satisfactory performance of equipment used for new critical assemblies, including verification of fail-safe features and the adequacy of the safety devices in effecting the required shutdown function, shall be established prior to achieving initial criticality.

8. Reliability and function of all parts of the safety system shall be established by a series of pre-experiment tests conducted at the beginning of each operating day. These tests shall include observing and recording on appropriate check lists the response of detectors and their associated circuits to the motion of a neutron or gamma-ray source at the beginning of each operating period (day) except that the audible building alarm shall be tested at monthly intervals.

9. During operating periods red signal lights shall designate inadequately shielded areas within the perimeter fence from which all unauthorized personnel shall be cleared before the commencement of operations. Persons are warned against entry into these areas by the red signals and by appropriate signs and alarms.

10. Each experiment shall be monitored by several mutually independent radiation sensing devices. At least two of these devices, individually, shall automatically initiate a scram of the assembly when a preset radiation level is exceeded. One of these devices may also respond to a stronger signal and actuate the building alarm. In some instances this latter function may be accomplished by a circuit entirely independent of the low-level safety.

11. Means shall be provided for the manual activation of scram circuits and building alarms.

12. Visual and/or audible indication of neutron multiplication shall be provided to personnel making manual loading of potentially critical configurations.

13. All initial approaches to critical shall be made with a neutron source present.

14. Neutron multiplication measurements shall be made and used in all initial attempts to achieve criticality. Thereafter visual indication of the effect of reactivity changes will be adequate.

15. Increases in reactivity shall be made in a controlled and reversible manner. Controls shall be such that reactivity may be removed during any operation at a rate greater than the maximum rate of addition of reactivity. Further reactivity additions shall not be made until the effects of previous additions have been manifested.

16. The number of persons, including visitors, present in the control room during an experiment shall be at the discretion of and subject to the direction of the Senior Experimenter in charge.

17. All members of the technical staff shall be acquainted with the operation and location of radiation-survey instruments and emergency equipment. Adequate operable radiation detecting instrumentation shall be provided in each control room.

18. All fissile material in the facility is subject to administrative control. Senior Experimenters shall be responsible for the safe transfer and storage of fissile materials. All storage arrangements shall be based on experimental results or shall be in accord with practices established or approved by the Laboratory's Criticality Review Committee.

19. A permanent record of experiments shall be made and kept.

Emergency Procedures

Procedures have been developed for the protection of personnel in the event of a radiation emergency. A local emergency crew is organized under a local director and is coordinated with the Y-12 area emergency organization. The occurrence of a radiation energency is signaled by the simultaneous sounding of bells and horns located throughout the building. This signal is initiated either manually or by one or more radiation-detection instruments in the event of a radiation emergency.

When the emergency signal is sounded all personnel, including visitors and security guards in and around the area, immediately assemble at a central well-shielded location within the building.

Subsequent procedures will be determined by the local director on the basis of the immediately determinable consequences of the excursion. Personnel exposures will be determined from ion-chamber type pocket dosimeters and from activities induced in security-badge components. The presence of air-borne contamination will be ascertained from a constantly operating air monitor which may extract samples from any area of the facility. Contaminated areas and those to which access is restricted by direct radiation will be delimited by the local emergency crew.

In the unlikely occurrence of widespread air-borne contamination, egress from the facility will be along one of the two available routes, the one selected to be established by the prevailing wind. An anemograph, located at the assembly point and actuated from a station adjacent to the facility, and an anemometer, mounted at the portal, supply information useful in establishing the route to be followed. Medical and more complete radiation-survey facilities are available in both the Y-12 and the X-10 areas, each being at the terminus of one of the egress routes.

Emergency equipment, including a portable two-way radio and additional radiation-detection instruments, is located at the Y-12 portal adjacent to the facility.

V - RADIATION HAZARDS

The potential radiation hazards attendant to the activities in the Critical Experiments Facility may be classed as those associated with normal operations and those resulting from some malfunction of equipment or personnel. In the former class may be, for example, exposure to neutrons and gamma-rays used regularly for various necessary operations, exposures to fission-product and natural radiation from experimental materials, and exposures to the prompt radiation generated in nuclear chain reactions. Knowledge of and adherence to prescribed shielding, provided both by distance and by appropriate materials, will ensure the resulting exposure to be within maximum permissible values.

Of a much higher order of importance are the hazards associated with unusual operations and occurrences. Among these are contamination and exposure resulting from the dispersal of natural (Po, U^{234}) and artificial (U^{233}, Pu, fission products) radioactive materials. There is also the possibility of exposure to prompt and delayed radiation arising in fissions occurring in chain reactions of greater intensity than scheduled. The principal concern in this discussion is with hazardous conditions generated by these unplanned occurrences.

Any discussion of the expected magnitude and consequences of accidents, be they nuclear or otherwise, is highly speculative because of uncertainties in the assumed cause of the accident and in its progress, It is possible,

however, to support considerations of the consequences of many accidental occurrences in this facility by experience gleaned from a rather wide variety of mishaps. Although it is obvious that these occurrences are credible, it is not postulated that they are of maximum possible severity. In addition, radiation from extended operations of critical assemblies at relatively high power and from very intense radiation pulses of short duration, characteristic of those expected from accidents in certain critical experiments, purposely generated in a recent program provide valuable information for criticality accident evaluation. This discussion of potential hazards is, perhaps, made unique by these pertinent experiences.

Throughout the following discussion of hazards' potential at the Critical Experiments Facility it should be recognized that the staff is augumented by a member of the ORNL Applied Health Physics Group who is capable in specialized techniques of radiation detection and protection. The services for which health physicists are responsible are delineated by ORNL management in the Health Physics Manual.[2] The satisfactory manner in which these responsibilities are implemented reduces significantly the possibility of exposures to personnel active in potentially hazardous areas.

Accidental Radiation Experiences

The most severe accident in the history of the facility occurred in the spring of 1951 and is reported by Callihan and Ross.[3] It was caused, basically, by security-imposed restrictions on communications between the fabricator and the user of a polonium-beryllium neutron source. Misinterpretation by the fabricator of the specifications resulted in a capsule of extremely impractical design of which the user was not made aware and was not able to observe by inspection at the necessary safe-exposure distance. The capsule, containing about 7 curies of polonium at the time of the accident, became opened, allowing wide dispersal of the polonium throughout one of the test cells and significant internal and external contamination of an employee. Medical and clinical findings indicated no detectable damage incurred from the radioactivity. The quantity of beryllium associated with the inhaled polonium was considered too small to be toxic. Many small items were disposed by burial; others, including the cell itself, were decontaminated in a long and laborious process.

Next in order of severity are noted several instances of contamination principally by U^{233} and U^{234}, resulting from dispersal of aqueous solutions of enriched uranium through the failure of welded joints and the rupture of vessels. In some of these, personnel have experienced an intake of significant but permissible body burdens of uranium. Many

2. "Procedures and Practices for Health Physics Protection," Oak Ridge National Laboratory (1961).
3. D. Callihan and D. Ross, "A Review of a Polonium Contamination Problem," ORNL-1381 (Aug. 12, 1952).

entailed arduous labor for decontamination of plant, personnel and equipment.

Three unplanned supercritical quantities of U^{235}-enriched uranium have been assembled. Two of these accidents, reported by Thomas and Callihan,[4] occurred with aqueous solutions. In the first of these, which occurred in May 1954, a reactivity addition of \$2.8 to a volume of solution generated 0.9×10^{17} fissions; in the second, in February 1956, the yield was measured to be 1.6×10^{17} fissions but the reactivity is not known. Although both volumes were in open vessels, in only one was any solution expelled. In both cases the safety devices operated within a few hundred milliseconds, and the systems were returned to below delayed critical in the order of a second. The power-time patterns probably consisted of an initial spike terminated by temperature and gas-evolution effects followed by an essentially constant-power interval, during which the solution was near delayed critical, until the safety devices became effective. The total personnel exposure to neutrons and gamma-rays incurred in the second of the above accidents are recorded in Fig. 10. Exposures in the first accident were comparable. It is pointed out that since the occurrence of these two accidents both the heavy shielding on the south side of the building and the additional roof shielding described earlier have been added to the facility.

The third criticality accident, reported by Callihan,[5] occurred in November 1961 as U^{235}-enriched uranium, neutron-moderated and -reflected by hydrogen, was being assembled. The yield was estimated to be 10^{15} to 10^{16} fissions. There was no exposure to occupants of the building or dispersal of air-borne activity beyond the immediate area in which the accident occurred.

Controlled Radiation Experience

Measurements have been made at a number of locations in and adjacent to the building of both the intensity of the radiation field and the integrated exposure resulting from extended critical operations at relatively high power. Typical results are presented here.

A volume of solution, located in the west test cell, was operated in January 1960 at an average power of 7×10^{12} fissions/sec, yielding

4. J. T. Thomas and D. Callihan, "Radiation Excursions at the ORNL Critical Experiments Laboratory," ORNL-2452 (May 5, 1958).
A survey of criticality accidents has been prepared by W. R. Stratton, in "A Review of Criticality Accidents," Progress in Nuclear Energy, Series IV, Vol. 3, London, Pergamon Press 1960 and in Proceedings of the Karlsruhe Symposium on Criticality Control in Chemical and Metallurgical Plant, European Nuclear Energy Agency, 1961.
5. D. Callihan, "Criticality Excursion of November 10, 1961," ORNL-TM-139, (Feb. 13, 1962)

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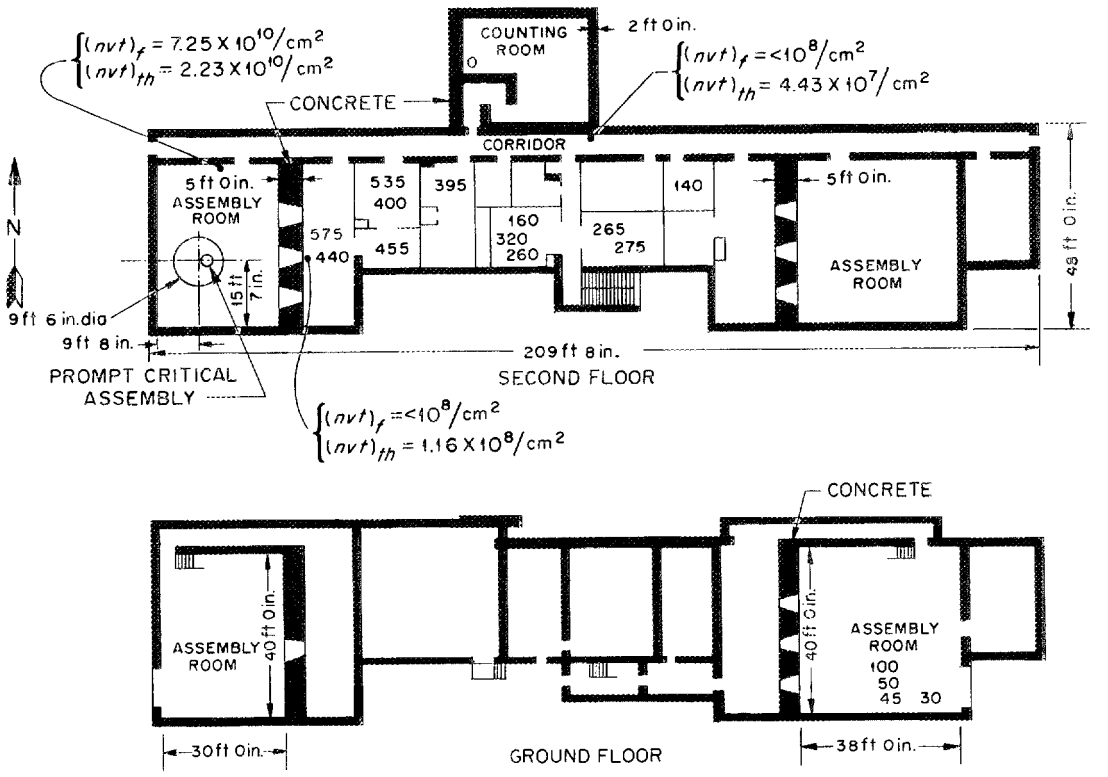

1. TOTAL EXPOSURES (mrem) RECEIVED BY INDIVIDUALS RECORDED AT THEIR POSITIONS
2. NEUTRON EXPOSURES INCURRED BY FOILS AT THREE FIXED POINTS ARE SHOWN.

Fig. 10. Radiation Exposures from February 1956 Excursion.

a total of 3.7×10^{16} fissions. The purpose of the experiment was to provide radiation for dosimetric studies close to the source. Additional dosimeter measurements, of interest to this discussion, were made at a number of points outside the test cell and are recorded on Fig. 11. The gamma-ray and neutron intensities were measured by portable survey meters* and the exposures were determined by film.

The measures given in Fig. 11 were made after the shield additions described previously had been completed. From a comparison of these data with those from an identical experiment prior to the addition of the extra roof shield (not reported here), it is interesting to note that many of the exposures at locations outside the building were actually greater with the increased shielding present. This increase is attributed to radiation scattered by the more massive roof.

Of greatest interest and value in this consideration of shield effectiveness are observations of the radiation dose incurred at a number of locations from a series of sharp, intense energy pulses produced in a superprompt critical assembly of unmoderated and unreflected U^{235}-enriched uranium-molybdenum alloy. These data are a byproduct of a program which had the primary intent of establishing the operation of a device for producing such pulses called the Oak Ridge Health Physics Research Reactor which has been reported by Mihalczo.[6] Gamma-ray sensitive film and, in some instances, neutron-sensitive film, was exposed at a number of locations to two series of radiation pulses having integrated yields of up to 1.7×10^{18} fissions. The data are given on the area plan in Fig. 12.

Accident Expectations

The intensity of potential accidents in the Critical Experiments Facility can be expected to be distributed over a wide range since the energy spectrum of the peak-population neutrons is in wide variety.

The strong negative temperature coefficient of reactivity of well-moderated, homogeneous uranium materials, the evolution of radiolytic gas in aqueous solutions of enriched uranium salts, and the relatively long neutron lifetime in media where fissions are produced predominantly by thermal neutrons are expected to place accidents with liquid assemblies in the lower bracket of the severity range. In fact, the two accidents that occurred with solutions at this facility yielded only about 10^{17} fissions prior to their termination by safety devices. The intensity of the radiation from this type accident, even though it be assumed that the two or more safety devices do not operate, would not be significantly greater than that in the above instance. Although the energy and fission product release may be much greater, since energy release would endure

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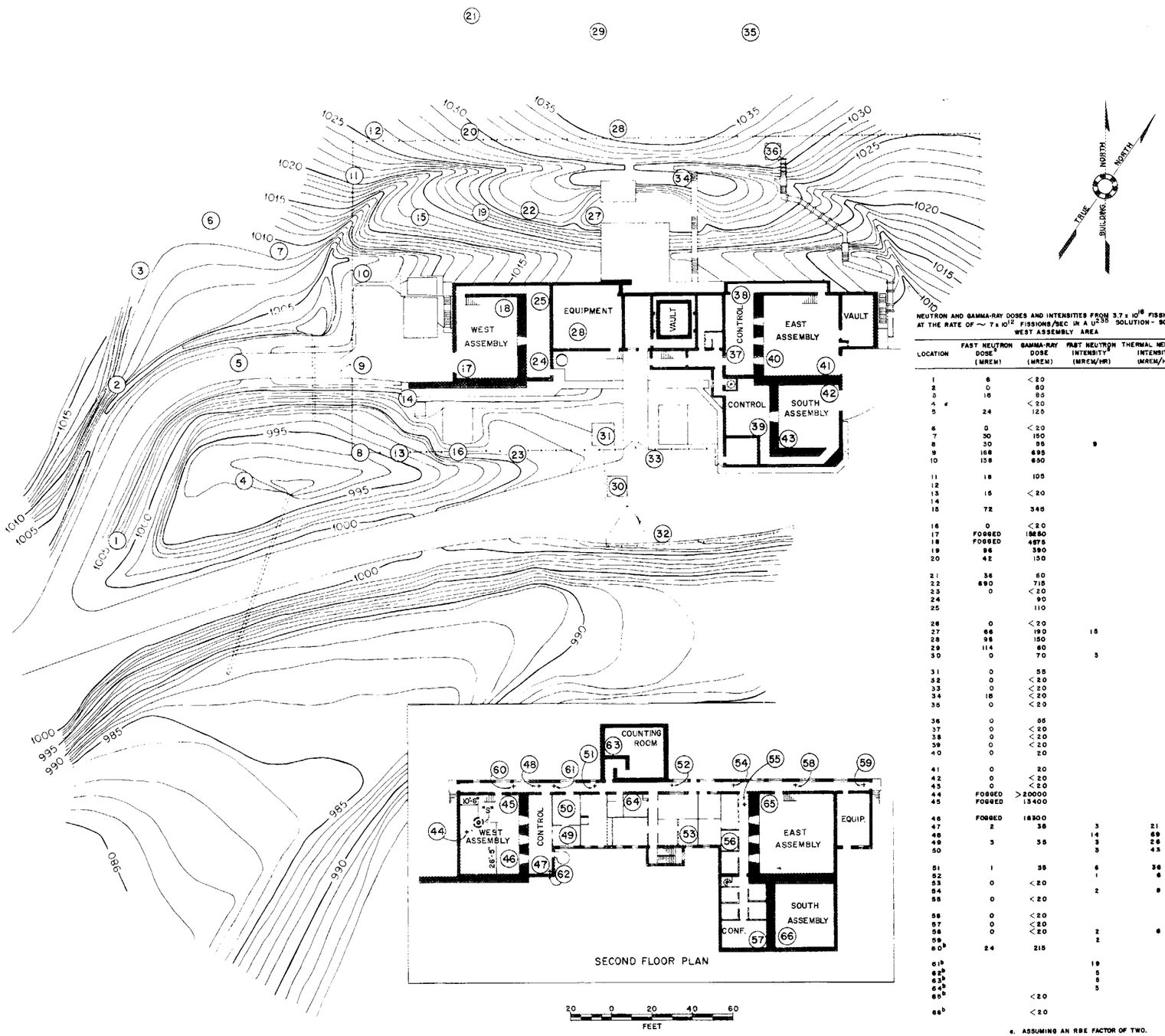
* Appreciation is expressed to L. C. Johnson and R. D. Parten of the ORNL Health Physics Division for these data.

6. J. T. Mihalczo, "Super-Prompt-Critical Behavior of an Unmoderated, Unreflected Uranium-Molybdenum Alloy Assembly," ORNL-TM-230 (May 10, 1962)

E-CV-44216



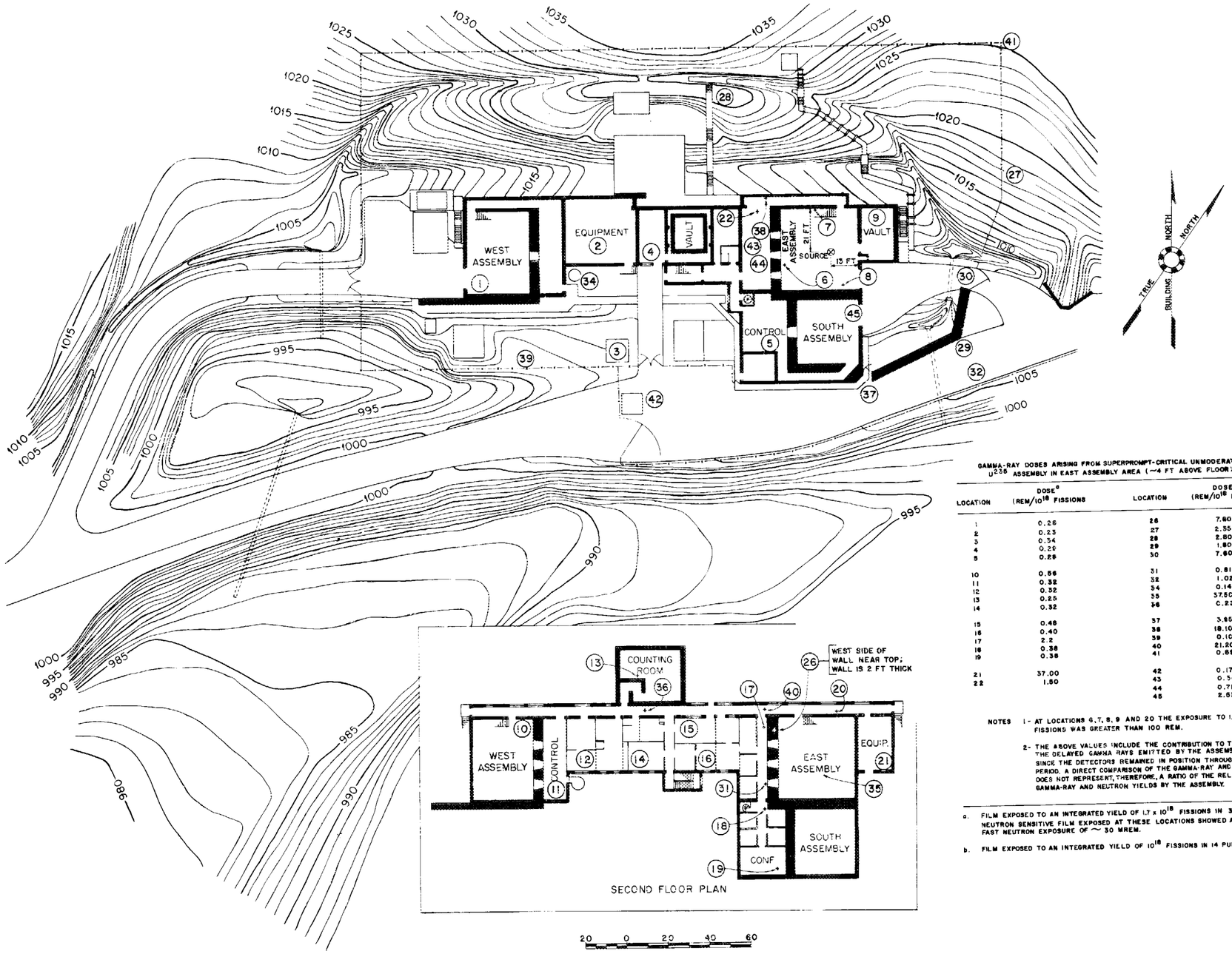
NEUTRON AND GAMMA-RAY DOSES AND INTENSITIES FROM 3.7×10^{16} FISSIONS PRODUCED AT THE RATE OF $\sim 7 \times 10^{12}$ FISSIONS/SEC IN A U^{235} SOLUTION - SOURCE AT "S"
WEST ASSEMBLY AREA

LOCATION	FAST NEUTRON DOSE[a] (MREM)	GAMMA-RAY DOSE (MREM)	FAST NEUTRON INTENSITY[a] (MREM/HR)	THERMAL NEUTRON INTENSITY (MREM/HR)	GAMMA-RAY INTENSITY (MREM/HR)
1	6	< 20			
2	0	60			
3	16	95			
4		< 20			20
5	24	125			
6	0	< 20			
7	30	150			25
8	30	95	9		24
9	168	695			
10	135	650			40
11	15	105			35
12					150
13	15	< 20			
14					20
15	72	345			
16	0	< 20			
17	FOGGED	15250			
18	FOGGED	4575			
19	96	390			
20	42	150			
21	36	60			
22	690	715			
23	0	< 20			
24		90			
25		110			
26	0	< 20			
27	66	190	15		54
28	96	150			
29	114	60			
30	0	70	3		15
31	0	55			5
32	0	< 20			
33	0	< 20			
34	15	< 20			
35	0	< 20			
36	0	55			
37	0	< 20			
38	0	< 20			
39	0	< 20			
40	0	20			
41	0	20			
42	0	< 20			
43	0	< 20			
44	FOGGED	> 20000			
45	FOGGED	13400			
46	FOGGED	16300			
47	2	35	3	21	35
48			14	69	100
49	3	35	3	26	25
50			3	43	32
51	1	35	6	36	30
52			1	6	5
53	0	< 20			
54			2	8	8
55	0	< 20			
56	0	< 20			
57	0	< 20			
58	0	< 20	2	6	5
59			2		4
60[b]	24	215			
61[b]			19		170
62[b]			5		60
63[b]			5		30
64[b]			5		20
65[b]		< 20			
66[b]		< 20			

a. ASSUMING AN RBE FACTOR OF TWO.
b. OBSERVATION MADE ON ROOF.

FIG. 11

E-CV-44217



GAMMA-RAY DOSES ARISING FROM SUPERPROMPT-CRITICAL UNMODERATED U^{235} ASSEMBLY IN EAST ASSEMBLY AREA (~4 FT ABOVE FLOOR):

LOCATION	DOSE[a] (REM/10^{18} FISSIONS	LOCATION	DOSE[b] (REM/10^{18} FISSIONS
1	0.26	26	7.60
2	0.23	27	2.55
3	0.34	28	2.80
4	0.29	29	1.80
5	0.29	30	7.60
10	0.56	31	0.81
11	0.32	32	1.02
12	0.32	34	0.14
13	0.25	35	37.50
14	0.32	36	0.22
15	0.48	37	3.85
16	0.40	38	18.10
17	2.2	39	0.10
18	0.36	40	21.20
19	0.38	41	0.69
21	37.00	42	0.17
22	1.50	43	0.54
		44	0.71
		45	2.63

NOTES 1- AT LOCATIONS 6, 7, 8, 9 AND 20 THE EXPOSURE TO 1.7×10^{18} FISSIONS WAS GREATER THAN 100 REM.

2- THE ABOVE VALUES INCLUDE THE CONTRIBUTION TO THE DOSES BY THE DELAYED GAMMA RAYS EMITTED BY THE ASSEMBLY AFTER SHUTDOWN SINCE THE DETECTORS REMAINED IN POSITION THROUGHOUT THE TEST PERIOD. A DIRECT COMPARISON OF THE GAMMA-RAY AND NEUTRON DOSES DOES NOT REPRESENT, THEREFORE, A RATIO OF THE RELATIVE PROMPT GAMMA-RAY AND NEUTRON YIELDS BY THE ASSEMBLY.

a. FILM EXPOSED TO AN INTEGRATED YIELD OF 1.7×10^{18} FISSIONS IN 30 PULSES; NEUTRON SENSITIVE FILM EXPOSED AT THESE LOCATIONS SHOWED A MAXIMUM FAST NEUTRON EXPOSURE OF ~ 30 MREM.

b. FILM EXPOSED TO AN INTEGRATED YIELD OF 10^{18} FISSIONS IN 14 PULSES.

FIG. 12

until some self-destructive operation terminated the reaction, personnel damage is expected to be negligible because of shielding and of orderly evacuation opportunities. An example of this reactivity behavior is the accident in the Y-12 Plant at Oak Ridge reported by Callihan and Thomas,[7] in which 10^{18} fissions were generated in a series of power spikes lasting about 3 min followed by a 17-min constant low-power emission until the "safety device," in this case the slow inflow of water, diluted the solution to a subcritical concentration.

The reduced intrinsic shutdown characteristics and the shorter lifetime of the fission-producing neutrons in unmoderated, high-density assemblies place the accident consequences with these materials at the other extreme of potential severity.

It is believed sufficient for present purposes to adopt the speculations of others who have predicted accident behavior rather than to again prophesy extremes in accident potential. The methods and materials of experiments with solids performed in the critical facility of the Lawrence Radiation Laboratory, for example, are basically similar to those employed in Oak Ridge. Carothers[8] has recently reviewed the practices at that laboratory with assemblies of unmoderated, beryllium-reflected U^{235}-enriched uranium metal and of unreflected graphite-moderated enriched uranium and has predicted the magnitude and consequences of a severe accident having a reasonable probability of occurrence. To accomplish this analysis, it was necessary to assume the inadvertent achievement of some degree of superprompt criticality, the failure of external shutdown devices, a distribution of the energy, and the dispersion of fission products. These assumptions must be related to the facility structure, the distribution of personnel and other physical characteristics of the environment to yield a measure of the accident consequences. There are uncertainties in many of these assumptions and in the way they are treated.

The detailed analyses of Reference 8 are summarized here.

The assembly considered is a heterogeneous stack of graphite plates and thin enriched uranium foils. It is a system where the only obvious inherent shutdown mechanism is the vaporization of the foils and consequent blowing apart of the core. Other mechanisms not involving foil vaporization might be conjectured, but all depend on so many imponderables that it is difficult to treat them in any but a qualitative manner. The foils are typically one or two mils thick and they rest in ten-mil-deep slots in the graphite plates. The thermal contact between the plates and foils is poor, since they touch only lightly at a few points of their surface. This keeps almost all of the energy in

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7. D. Callihan and J. T. Thomas, Health Physics 1, 363 (1959).
8. James Carothers, "Hazards Summary Report for the LRL Critical Facility," UCRL-6220 (March 3, 1960).

the foils, at least until the foils have melted. Heating of the air in the slots by the foils will occur at a rapid rate, since many of the fission fragments formed in the foils can escape. This quantity of air, however, cannot expand to appreciably decrease the reactivity until temperatures above the melting point of uranium are reached. Such effects will aid the shutdown, but they will be ignored in the analysis below. They thus act to make the final yield figure a pessimistic upper limit.

The behavior of the system was investigated for the case of a 2% step increase of reactivity above delayed critical with complete failure of all scrams. The sequence of events is considered to be the following:

a) A 2% step increase of reactivity, above delayed critical, is added;
b) A prompt period is generated, and at least some of the central foils vaporize;
c) Following vaporization of the foils, the core is disassembled by the pressure of the uranium vapor.

The assembly is assumed to be a 48-1/2- x 48-1/2- x 42-1/2-in. rectangular parallelepiped having a C/U ratio equal to 1200. The core has a volume of 58 ft^3 and a mass of 2680 kg; the fuel mass is 43 kg of uranium.

If the reactor period is given by $T = \ell^*/k_{ex}$ and ℓ^* is taken as 1.1×10^{-4} sec, the resulting period will be 8.5 msec. No reactivity loss is assumed for any increase in fuel temperature. When the fuel vaporizes, the self-shielding of the foils will be decreased as the fuel mixes with the moderator. As a pessimistic assumption, all of the 5% effect of the self-shielding is assumed lost even though mixing is negligible in short times. This corresponds to a 5% addition to fuel which will increase the reactivity by less than 0.5%. The period will now be $1.1 \times 10^{-4}/0.018 = 6 \times 10^{-3}$ sec.

Consider now the central one-eighth of the core volume enclosed by a cube 23 in. on a side. Due to the flux distribution, 35% of the power will be generated in this volume. It will, therefore, heat most rapidly and will determine the time scale of the disassembly. This region contains 7.1 ft^3 of graphite and 23 moles of uranium.

As the fuel foils commence to vaporize, the pressure in the 0.10-in.-deep fuel slots also commences to increase. This pressure will be the vapor pressure of the uranium at the temperature of the fuel foils. If it is assumed that the vaporized uranium acts as a perfect gas, the fractional amount of fuel that has vaporized is given by n_{vp}/n_u where

$$n_u = \frac{P_{pg}V}{RT}$$

$$n_{vp} = \frac{P_{vp}V}{RT}$$

and where P_{pg} and P_{vp} are, respectively, the pressure in volume V at temperature T when all the uranium is vaporized and when n_{vp} moles are vaporized.

The vapor pressure of uranium is taken as

$$\log P_{vp} = -\frac{2.3 \times 10^4}{T} + 5.7 \text{ (atmospheres)}$$

Each foil is in a slot 6 x 6 x 0.010 in. The perfect gas pressure if all of the uranium vaporizes is then

$$P_{pg} = 0.43\ T \text{ (atmospheres)}.$$

Since the fractional quantity of uranium that has vaporized is P_{vp}/P_{pg}, less than ten per cent of the uranium is vaporized until the temperature exceeds 7000°C. The pressure, however, is substantial long before this. At 6000°C, for example, the pressure is 65 atmospheres. Since the only constraint on the system is the weight of the graphite, which is approximately 100 g/cm^2 or 0.1 atmosphere at the central plane, disassembly of the system will begin as soon as temperatures sufficient for vaporization are reached.

For the purpose of estimating the time required for disassembly, assume that the only force acting is that at the central plane. This is clearly a very conservative assumption, because each foil will act independently to force up the graphite above it, and there are some 85 foils in one 6 x 6 in. vertical stack. However, the flux distribution will produce a variable heating along the vertical axis, and the central foils will produce the largest effect. Since 1 in. of core height is worth about 1% in reactivity, removal of 2-1/2 in. is required to remove 2-1/2% reactivity. A 2-1/2% reactivity increase corresponds to a 6% mass increase, (2.5 in./42 in.). The density decrease necessary to require a 6% increase is 3% ($M_c \propto 1/d^2$). If this is caused by expansion only in the vertical direction, it corresponds to 1.25 in. Since disassembly in the vertical direction will be greatest in the center, decreasing to the edges, motion of 2-1/2 in. in the center will be considered sufficient to stop the reaction.

The time required to move the graphite 2-1/2 in. will depend on the pressure at the central plane. If the driving pressure is assumed to remain constant during the motion, then the time to move 2-1/2 in. is

Pressure (atm)	Time (sec)
1	3.5×10^{-2}
10^2	3.5×10^{-3}
10^3	1.1×10^{-3}
10^4	3.5×10^{-4}.

Thus, at temperatures which correspond to appreciable foil vaporization (6000 - 12000°C) the vapor pressure of the uranium is sufficient to disassemble the reactor in less than one generation (6×10^{-3}) seconds. As the foil gaps enlarge, the uranium which had not vaporized will do so and the material will then act as a perfect gas. The pressure behavior with time will be quite complex, but the assumption of constant pressure furnishes a reasonable approximation to the disassembly time. It is only necessary to observe that less than one generation is necessary for shut down, from the time that a temperature of 6000°C is reached.

The magnitude of the energy release is really fixed by the stipulation that the foils vaporize. This can be best appreciated by a consideration of the energy required to heat the foils, melt them, heat the molten metal, vaporize it and heat the vapor. No direct figures are available for the enthalpies of liquid or vaporous uranium, but the heat capacity for the liquid and vapor can be assumed to be equal to the solid. Then:

$$\text{to heat the metal, } H = (1100^\circ - 300^\circ) \times 9 \frac{\text{cal}}{\text{mole}} = 7.2 \frac{\text{k cal}}{\text{mole}}$$

$$H_{fusion} = 2.5 \frac{\text{k cal}}{\text{mole}}$$

$$H_{vaporization} = 116.0 \frac{\text{k cal}}{\text{mole}}$$

$$\text{Total energy required to form vapor at } 1100^\circ\text{C} = 125.7 \frac{\text{k cal}}{\text{mole}}$$

$$\text{To heat the vapor to } 12000^\circ\text{C, } H = (12000 - 1100) \times 9 \frac{\text{cal}}{\text{mole}} = 98.1 \frac{\text{k cal}}{\text{mole}}$$

Thus, the total energy only varies between 126 k cal/mole and 224 k cal/mole whether the pressure in the foil gap is one

atmosphere or 5000 atmospheres.

A release of 224 kcal/mole throughout the central 23 in. cube will be sufficient, on the basis of the disassembly times, to terminate the excursion. This is approximately 5 megacalories. The remaining 7/8 of the reactor will have 65% of the total fissions or about 9 megacalories. The total excursion is thus certainly less than 14 megacalories or 1.7×10^{18} fissions. A number of pessimistic assumptions have been made in the estimate. These are, that the air in the gap does not heat and contribute to the disassembly, that no uranium vapor leaves the reactor when it is formed, that all disassembly is accomplished by the foils in the central plane instead of all 85 in one vertical stack, and that only vertical disassembly takes place. Thus, 1.7×10^{18} fissions is regarded as a very pessimistic upper limit to an excursion which is terminated by physical disassembly of the reactor.

Two other points should be mentioned here. First, shocks are not assumed to develop in the graphite during disassembly. Sound speed in the graphite is 2.8×10^5 cm/sec, using 4.3×10^9 gm/cm^2 as the elastic modulus of graphite. The assembly is roughly a sphere with a 60 cm radius, so 2.1×10^{-4} sec are required for a signal to reach the outer surface. The pressure signal was assumed to occur in the order of one generation (6×10^{-3} sec) so no shocks should develop. The second point is that the thermal diffusivity of graphite is too small to absorb appreciable energy from the vapor during the assembly time. This is important in preventing cooling and condensation of the vapor on the graphite. The diffusivity is $k/d\ C_p$ and if $k = 0.05$ cal/sec/cm/$^\circ$C, the heat can penetrate only about 0.04 sec in one generation.

Another accident is assumed to occur in a metal system characterized by small size, small heat capacity and very fast generation time. These properties mean, in general, a more violent physical reaction to a large excursion, but a smaller total quantity of radiation than in the system of greater dimensions.

The type of accident investigated for this system is one where a double failure has taken place. The core is composed of nesting enriched uranium shells. The assumption is made that a core having a multiplication of 75 has been constructed and disassembled on a vertical assembly machine which brings the two sections of an assembly together. The operator now erroneously adds 5 kg of metal. Assembly is started, and the scram mechanism does not operate.

The addition of 5 kg of enriched uranium to a system which is at a multiplication of 75 will make it super prompt critical. At a multiplication of 75 a bare enriched uranium system has 96.5%

of the delayed critical mass. The bare spherical critical mass is 52 kg, so the 3.5% required to bring the M = 75 system to delayed critical is 1.8 kg. Thus, the addition of 5 kg produces a system which is 3.2 kg above delayed critical. The surface mass increment between delayed and prompt critical is 1.04 kg. The addition of 3.2 kg beyond delayed critical, which is 6.2% of the delayed critical mass, should therefore yield a reactivity of \$3.10 above delayed critical for the fully assembled system.

The reactivity change per second must now be estimated in order to calculate the behavior of the system during assembly. If we assume that a one mil separation of the two halves of the assembly is equivalent to removal of enriched uranium from the assembly and that uranium at the center is six times as effective as at the surface:

$$\Delta m/\Delta s = 11.5 \text{ g/mil and}$$

$$d\rho/ds = 0.066 \text{ \$/mil.}$$

For a closure speed of 0.5 in./min., $d\rho/dt$ = 55¢/sec. On the other hand, if the effect of a one mil diametral gap is assumed to be equivalent to a uniform decrease in density, the rate of change of reactivity is found to be 37¢/sec.

A machine calculation of the assumed accident, with a pessimistic 70¢/sec ramp increase of reactivity to a final reactivity of \$3.10 above delayed critical gave an integrated yield of 2.2×10^{17} fissions. The analytical method was applied to the last Godiva I accident with a favorable comparison between calculations and observations.

It is believed that the uncertainty in the treatment of the accident causality is at least as great as the uncertainty in the causality itself, even if the accident occurs under somewhat different circumstances. Since it is shown by Carothers that the energy yield from accidents, which are no more or less credible than might be postulated in Oak Ridge, is no greater than 10^{18} fissions, that value is assumed to be the maximum for this discussion and equally uncertain, duplicative analyses are avoided.

Criticality Accident Consequences

Reference to the data from radiation surveys summarized in Figs. 10, 11 and 12 shows that the direct personnel exposure to be expected in normally occupied areas to radiation arising from the assumed 10^{18}-fission accident is well below maximum permissible tolerances. Experience has also shown that, in the absence of destructive forces which would violate the integrity of the structure, air-borne contamination would be sufficiently contained to make unnecessary evacuation of personnel. If the structure were violated and fission products were quickly dispersed outside the building, evacuation procedures are established to preserve safety against exposure.

Hazards Due to Release of Radioactive Materials

Having established the magnitude and location of a source of airborne radiation it is possible to predict, on the bases of assumed wind patterns and terrain characteristics, a measure of the exposure at locations beyond the immediate locale of the facility. Estimates of the dilution occurring over these distances may be obtained by one of Sutton's[9] diffusion equations. It has been recommended by Gifford[10] and by Burnett[11] that an appropriate form of the relation is

$$\frac{X}{Q} = \frac{2}{\pi u C^2 d^{2-n}} \qquad (1)$$

where X/Q, the dilution factor, is the concentration at the point of exposure expressed in curie-sec/m^3 per curie released at the source, u is the average wind speed in m/sec, d is the distance from the source to the exposure point in meters, and C and n are constants whose values depend upon local conditions. Typical values suggested for this locale are: n = 0.25, C = 0.1, and u = 2.5 m/sec.

The hazards to personnel are an external dose arising from the radioactive cloud and an internal dose resulting from inhalation of activity. The external dose, in rem, is given by Burnett[12,13] to be

$$Z = 0.26 \frac{X}{Q} ES, \qquad (2)$$

where E is the effective energy of the radioactive material, assumed to be 1.5 Mev/disintegration, and S is the activity release in curies. The internal dose, in rem, to a body organ is given by

$$D = 73.8\ fI\ \Sigma E(RBE)N\ T/m, \qquad (3)$$

where I = inhaled activity, μc,
f = fraction of inhaled activity retained in a body organ,
T = effective half life of the retained fraction, days,
m = mass of organ, g,
E = energy absorbed by organ, Mev,
(RBE)N = product of relative biological effectiveness and local disposition factor.

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9. "Meteorology and Atomic Energy" July 1955, U. S. Dept. of Commerce, Weather Bureau, Chapter 4, "An Outline of Atmospheric Diffusion Theories."
10. F. A. Gifford, U. S. Weather Bureau, Oak Ridge, Tenn., personal communication.
11. T. J. H. Burnett, ORNL Health Physics Division, personal communication
12. T. J. H. Burnett, Nuc. Sci. Eng. 2, 382 (1957).
13. T. J. H. Burnett in an appendix to a report by M. I. Lundin, "Health Physics Research Reactor Hazards Summary Report," ORNL-3248 (June 27, 1962).

The fission products most readily released from a melted reactor core are iodine and the noble gases. It has been shown that the internal exposure resulting from inhalation of iodine is more severe than all other exposures, both internal and external, even if all the fission products were released.[12,13] Using Eq. 3, Burnett[13] has determined the internal dose to a thyroid with a mass of 20 g to be 1.5 rem per uc of inhaled I^{131}, where T = 7.6 days, f = 0.23, and $\Sigma E(RBE)N = 0.23$ Mev. The total internal dose then would be

$$D_I = 1.5 \frac{X}{Q} BS \qquad (4)$$

where B is the breathing rate, assumed to be 5×10^{-4} m^3/sec, and X/Q and S are as defined previously.

On the basis of the above, estimates can be made of the external and internal doses resulting from a maximum credible accident at the Critical Experiments Facility. The accident is postulated as a superprompt critical assembly of metal yielding 10^{18} fissions, a situation similar to that proposed by Carothers.[8]

Each test cell at the facility has an air capacity of about 3×10^4 ft^3 and is normally continuously exhausted by a 1000 cfm fan. If the shutdown devices fail to deactivate this fan, about 30 min will be required to discharge the air-borne fission products outside the building.

It is shown in Fig. 1 that the facility is almost surrounded by 200-ft-high hills, which are partially wooded. The nearest area continuously staffed is 650 m distant and regions of relatively high population density are about 1000 m distant. These sites are in the western section of the Y-12 Plant north of Bldg. 9213. The nearest public highway is 1400 m to the south of the building. This location of the facility provides moderate shelter from the winds aloft and it can be expected that the drift of air-borne material down the winding valley would provide considerable opportunity for impingement and deposition on the foliage as well as entrapment and delay in the wooded slopes. These conditions are characterized by the values assumed for the constants in Eq. 1.

For the external exposure it is assumed that 10% of all the products generated in 10^{18} fissions are released to the room atmosphere and that they, on the average, decay for 15 min before discharge from the building. These conditions establish a release of 1.2×10^3 curies and would give, from Eq. 2, the following external doses at several distances.

Distance (meters)	External Dose (rem)
300	0.50
500	0.19
1000	0.05
1500	0.02

For evaluation of the internal exposures, it is assumed, as a conservative estimate, that all of the iodine isotopes, expressed in an equivalent quantity of I^{131}, are discharged from the building. This amount is ~5.5 curies produced in 10^{18} fissions and will increase to ~6 curies during the first hour owing to the decay of tellurium. The resulting internal doses at various distances, obtained from Eq. 4, are:

Distance (meters)	Internal Dose (rem)
300	5.2
500	2.2
1000	0.6
1500	0.3

These internal doses are to be compared to the accepted quarterly tolerance to the thyroid, 8 rem, specified by the International Committee on Radiation Protection.

The above considerations assume the presence of personnel in areas designated for occupancy during the performance of critical experiments, a condition enforced by strict administrative practices. If there were, simultaneously, a supercritical assembly and a violation of these practices the consequence to personnel could be severe as evidenced by the first two critical experiment accidents at the Los Alamos Scientific Laboratory which were fatal to two employees even though the yields were only 10^{16} and 3×10^{15} fissions.[14] Some of the survivors of these exposures were within a few feet of the source.

The nuclear accident of most serious consequence is, therefore, the one which could happen during preparations for critical experiments. It could, for example, occur in the transport or storage of the fissile materials. These operations, like those in production circles, are governed by strongly enforced acceptable practices defined, for example, by the Nuclear Safety Guide.[15] The initial stages in the assembly of a critical experiment, of necessity often done manually, are monitored.

Consequences of Other Radiation Accidents

Certain naturally radioactive materials and generators of other nuclear reactions are used within the facility and present potential hazards. Included in this category at the present time are plutonium in radiation detecting devices, plutonium and polonium in neutron sources, radium as a source of gamma rays, the decay products of U^{232} (a contaminant in U^{233}) which are gamma-ray emitters, U^{234} (an impurity in U^{235}) which is a relatively strong alpha-particle emitter, and fast neutrons arising from high-energy particles impinging on an appropriate target.

14. J. G. Hoffman, "Radiation Doses in the Pajarito Accident of May 21, 1946," LA-687 (May 26, 1948).
15. Nuclear Safety Guide, TID-7016, prepared by Project 8 of the American Nuclear Society Standards Committee.

The plutonium foils used as neutron detectors are contained in an ORNL-approved manner. The only conceivable hazard is the contamination which might result from dispersal of the plutonium as a result of a fire.

The plutonium and polonium used in neutron sources are encapsulated with beryllium. The plutonium sources are used as received from the vendor and are doubly enclosed in welded containers, the inner one of tantalum and the outer of stainless steel. A study by Kaufman[16] of the containment capabilities of this construction indicates its adequacy. Although the Po-Be neutron sources are welded in stainless steel by the vendor, it has been the practice to further enclose them in either brass or stainless steel outer containers. In addition to the extra protection, this practice allows facility in methods of attachment to equipment and to handling tools. The radium sources are sealed in small needle-like cylinders which, in turn, are enclosed in metal cylinders. It is necessary, of course, to provide adequate shielding to avoid exposure to the radiation emitted by these sources.

Although the hazards associated with the rupture of any one of the above containers and the attendant inconvenience and cost of the necessary decontamination have, in the experience of this facility, far exceeded those incurred in the accidental prompt critical arrays, it is believed that regular and frequent tests for leaks minimize the possibility of severe contamination.

The uranium isotopes, used as experimental materials, are potential sources of personnel and area contamination because of their alpha-particle activity and their gamma-ray emitting characteristics.

These contamination potentialities are best countered by good housekeeping, by frequent radiation surveys, and by adherence to shielding requirements for gamma-ray protection.

Some experiments require an intense source of fast neutrons produced in nuclear reactions arising when high-energy deuterons impinge upon tritium or upon deuterium. Associated personnel hazards are exposure to the neutrons and contact with the high electrical potential necessary for the acceleration of the particles. Operators are routinely protected against the former by the shielding provided in the facility construction since the neutrons are usually produced in one of the test cells and their control is from a shielded control room. Against electrical shock and inadvertent exposure during set-up or adjustment operations there is strict self-disciplined control by the experimenters supplemented, in the latter case, by neutron monitors. The tritium itself must be recognized as a potential contaminant.

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16. J. L. Kaufman, "Hazards Summary and Safety Procedures for Reactor Controls Plutonium-Beryllium Neutron Source," ORNL-CF-60-6-20 (June 8, 1960).

VI - MISCELLANY

Fire

Although the building is almost entirely of fire resistant construction, there is finite possibility of the ignition of some structural component or, more likely, of uranium metal, the latter spontaneously. The major consequence of a uranium metal fire will be, of course, a dispersal of alpha particle contamination. Sensitive areas are equipped with extinguishers recommended by knowledgeable authorities for combatting metal fires. In case of failure of immediate control, an affected area would be abandoned, the ventilation system deactivated and reentry made with suitable protective equipment.

Seismology

The infrequency and low intensity of seismological disturbances in the area under discussion has been reviewed and documented in earlier reports of this kind.[17] It is impossible to certify that every disorder of a storage or experimental assembly of fissile material would decrease its reactivity. Reasonable recognition is made of the adverse possibility in the design of storage facilities and experimental equipment.

Meteorology

In the opinion of the local office of the U. S. Weather Bureau, the meteorology immediate to the Critical Experiments Facility is too complex for meaningful generalization.[18] Simple and pessimistic considerations of the extent of wind borne radioactive contamination, discussed earlier in this report, show that, in the absence of an inventory of long-lived fission products, the usual condition in this remotely located facility, the problem is insignificant.

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17. See, for example, F. T. Binford, et al., "The ORNL Research Reactor Safeguards Report," ORNL-1794, Vol. 1, Oct. 7, 1954.
18. F. A. Gifford, U. S. Weather Bureau, Oak Ridge, Tennessee, private communication.

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