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HAZARDS SUMMARY REPORTS
FOR THE
BATTELLE PLASTIC REACTOR FACILITY

by

David A. Dingee
Joel W. Chastain, Jr.

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BATTELLE MEMORIAL INSTITUTE
505 King Avenue
Columbus 1, Ohio

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David A. Dingee and Joel W. Chastain, Jr.

Experiments using a plastic-moderated assembly as a radiation source are described and the hazards attendant to these experiments are evaluated.

The critical assembly, designated Battelle's Plastic Reactor Facility is constructed in the form of a cube. A portion of the plastic and fuel will be removed from the center of this reactor to provide a radiation environment for exposing fission-chamber devices. This central void region will approximate a flux trap in which a high neutron-to-gamma ratio is expected.

The fuel-element assemblies are composed of strips of aluminum and Teflon-coated uranium sandwiched with plastic and encased in aluminum boxes. One portion of the core is on a movable table, while the other part is on a fixed table. The core is assembled remotely by driving the movable table against the fixed table.

Primary control and safety of the assembly is achieved by inserting or withdrawing regulating and safety elements and by increasing or decreasing the distance between the two core halves. For safety, the maximum normal rate of reactivity addition has been limited to 0.04 per cent $\Delta k/k$ per sec for control-element withdrawal, and table closure. The system is interlocked so that only one control element can be withdrawn at a time and so that the movable table and elements cannot be moved simultaneously. In addition, criticality cannot be reached by only moving the tables together.

No experiments with the Plastic Reactor Facility are planned since it will serve only as a source of radiation operating at a constant power level. Consequently, the hazards of a nuclear excursion are minimized. However, the safety aspects of the operations and possible power excursions have been analyzed. The analysis indicates that these operations present no significant hazard to the public persons or operating staff.

We request that our Facility License (CX-9) be amended to permit operation as outlined in this report.

INTRODUCTION

This report reviews experimental details and safety aspects associated with operating Battelle's Plastic Reactor Facility as a radiation source in a program to develop and optimize the performance of new fission-chamber devices. This program will be conducted at the Battelle Critical Assembly Laboratory.

The Laboratory and site were evaluated in a report submitted to the Advisory Committee on Reactor Safeguards in October, 1954. A Construction Permit was issued on December 28, 1955 and converted to a Facility License (CX-9) on January 15, 1958.

Reports summarizing hazards associated with five critical assembly studies have been submitted and approved. These studies include a beryllium-moderated critical assembly described in BMI-ACRS-611; a plastic-moderated critical assembly described in BMI-1166; two gas-cooled, water-moderated critical assemblies described in BMI-1240 (Rev.) and BMI-1379 (Rev.); and a uranium dioxide-fueled, organic-and-water-moderated reactor described in BMI-1445.

The present critical-assembly core will be composed of 225 or 256 aluminum fuel-element cans containing Teflon-coated highly enriched uranium, foil, and polyethelene, and aluminum strips. These cans are square in cross section and will be loaded so as to form a cubical reactor approximately 2 ft on a side.

The core is assembled in two sections: one section on a fixed table and the other on a movable table. The section on the movable table can be driven remotely to assemble the core. The assembly will be controlled by vertical-acting fuel-element cans with poisoned upper regions and fueled lower regions. Additional safety is provided by separating the core into two regions.

Either nine or sixteen fuel cans will be removed from the center of the core to form an axial void region in which the fission chambers may be exposed to neutron and gamma radiation.

In the following sections the Battelle site is described, and design and safety features of the Plastic Reactor Facility are given in detail. As indicated in the report, this assembly has been used for an extended period in a previous experiment. A summary of these former experiments is presented to aid in evaluating the present operations.

CRITICAL-ASSEMBLY SITE

Site Location and Description

The site of the Critical-Assembly Laboratory is in Madison County, Ohio, 15 miles west from downtown Columbus. The property is located on the Georgesville-Plain City Road, an improved county highway which is not heavily traveled. The Battelle-owned land extends slightly beyond the Pennsylvania Railroad to the south and is bounded on the east by Big Darby Creek, which is the boundary between Franklin and Madison Counties. The tract contains a total of 694 acres. Figure 1 is a topographic map showing the site in relation to Columbus and the surrounding area.

The Critical-Assembly Laboratory is one of four buildings at the Battelle Nuclear Research Center, which is located at the northern end of this property. The location of these buildings with respect to each other and the details of the immediate vicinity are shown in Figure 2. Figure 3 is an aerial photograph of the area and shows a portion of the Battelle land.* The nearest boundary of the property is over 1200 ft from the building.

The surrounding area is a farming community and is sparsely populated. The closest town is West Jefferson, population 2500, which is about 2 miles southwest of the laboratory location. The closest building is a barn, 2000 ft northwest of the site, and the closest dwelling is 3100 ft to the southwest. During the summer months, a Girl Scout

*This photograph was taken in 1955 and does not show recent additions which appear in Figure 2.

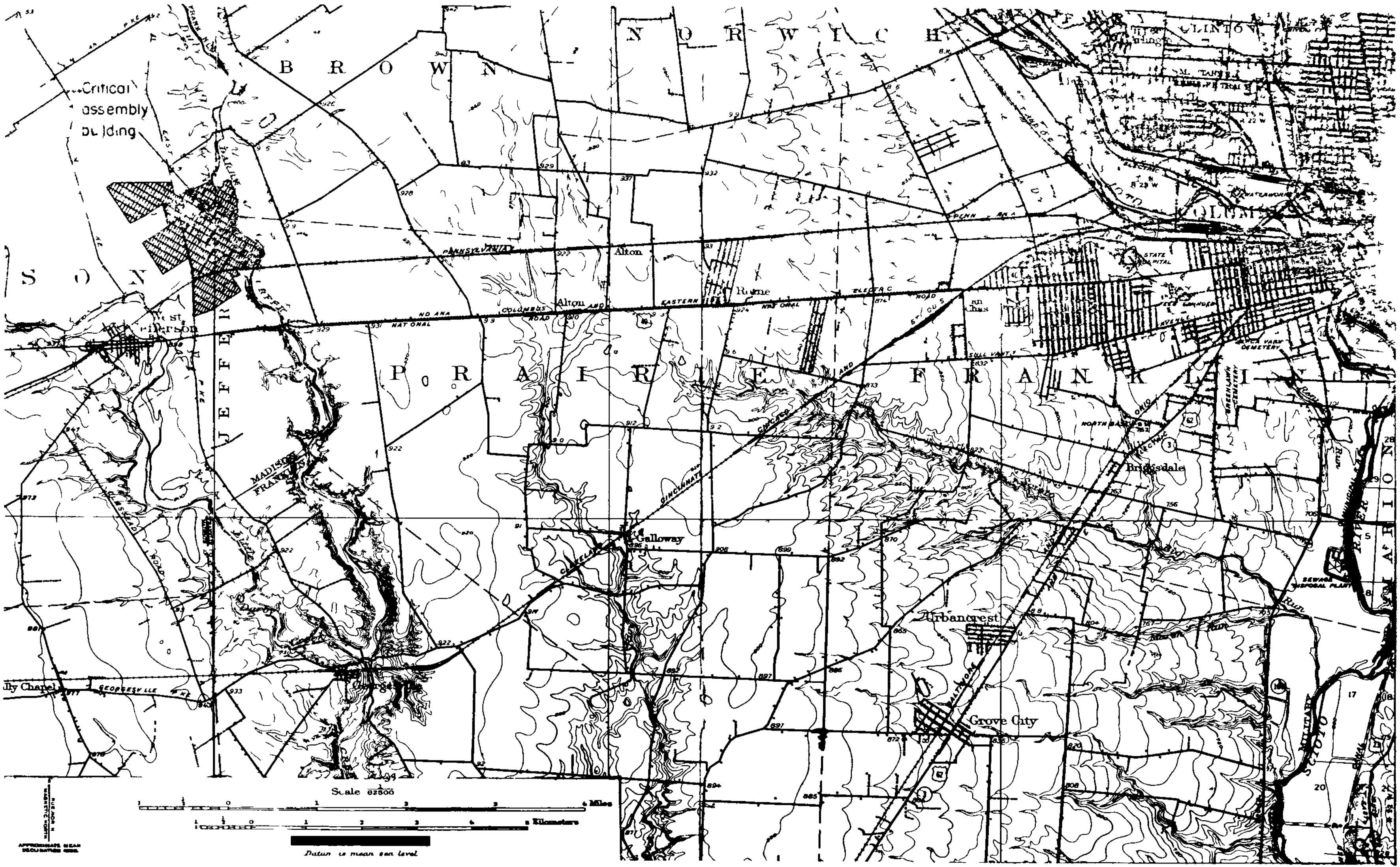

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FIGURE 1. TOPOGRAPHICAL MAP

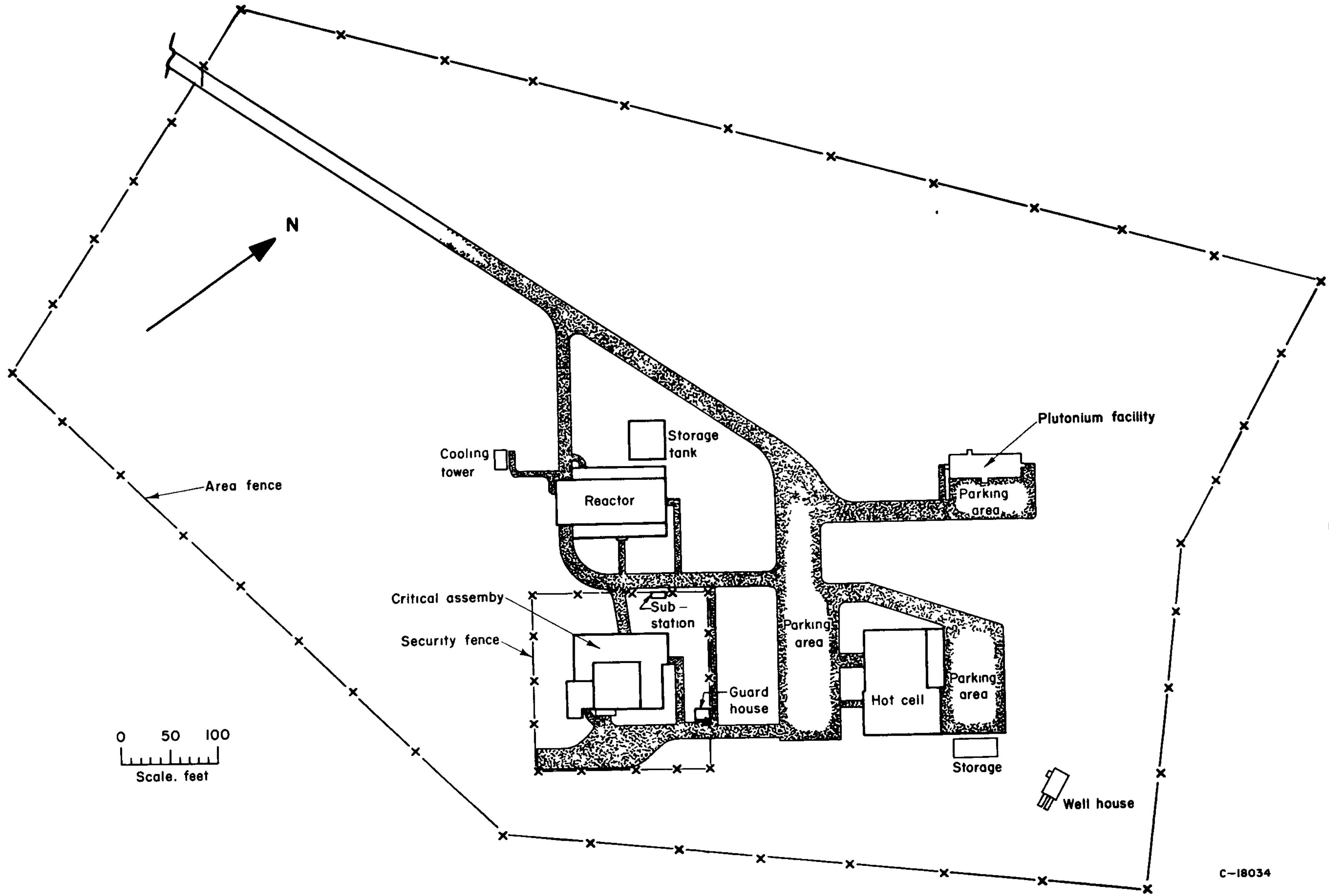

FIGURE 2. BATTELLE NUCLEAR RESEARCH CENTER

FIGURE 3. AERIAL PHOTOGRAPH OF BATTELLE NUCLEAR RESEARCH CENTER N33942

camp located across the Big Darby is inhabited. The site is about 2000 ft from the camp. The estimated total number of residents within 1 mile of the site is 60.

The site is located on level ground having an average elevation of 900 ft above sea level. The average elevation of downtown Columbus is approximately 750 ft. The change in elevation from the site to downtown Columbus takes place by a gradual fall over the 15-mile interval. A flat-bottom ravine about 40 ft deep crosses the plot from east to west and is the bed of a small intermittent stream. The Big Darby Creek flows in a broad valley along the eastern boundary of the property and is approximately 50 ft below the elevation of the site.

Critical-Assembly Building

The Critical-Assembly Laboratory is a building having 11,430 ft^2 of floor space. The building contains the reactor-assembly room, a control room, a vault, a counting room, an instrument laboratory, a shop, a radiation-instrument calibration facility, and rooms which may be used as offices or laboratory space. The first- and second-floor plans are shown in Figure 4. The building is constructed of concrete block faced with brick, with a structural-steel frame, except for the storage vault and assembly room. The storage vault is constructed entirely of reinforced poured concrete. The assembly-room walls are 2 ft thick up to a height of 26 ft. The wall above this and the roof are Q-panel aluminum siding. All of this is supported by a heavy structural-steel frame.

The arrangement of the assembly room, control room, and vault, and the associated stairwell, forms an area which can be shut off from the rest of the building.

The power provided for the installation is 300 kva. Other utilities are compressed air, demineralized water, natural gas, and a 3-in. water-supply main.

The building is heated by forced-hot-water heat. The temperature is controlled by thermostats in the assembly room and by valves on the individual heaters in other locations. The control room, the instrument laboratory, and the counting room are air conditioned.

Assembly Room

The reactor assembly room is approximately 40-ft square and 50 ft high. The three walls facing into the building are of reinforced poured concrete 2 ft thick. The other wall is 1-ft-thick poured concrete. This concrete extends to a height of 26 ft, which is enough to shield personnel in the inhabited portion of the building. Above this height, the walls are constructed of Q-panel aluminum metal siding on the outside and steel sheets on the inside. The Q-panels have caulking material between them. The steel plates have lead tapes sealing the seams. This type of construction furnishes a tight enclosure. The siding above the solid concrete wall is supported by structural-steel framework, which also supports a 10-ton crane. The roof is built up of asphalt and gravel over heavy building paper and is supported by a Q-panel metal deck.

A large exhaust fan located in a penthouse above the office area supplies fresh air to the room. The exhaust is through the ceiling. Both the air inlet and the exhaust opening are equipped with louvers and a solenoid-operated sheet-metal plate to make the openings tight when the fan is not in operation.

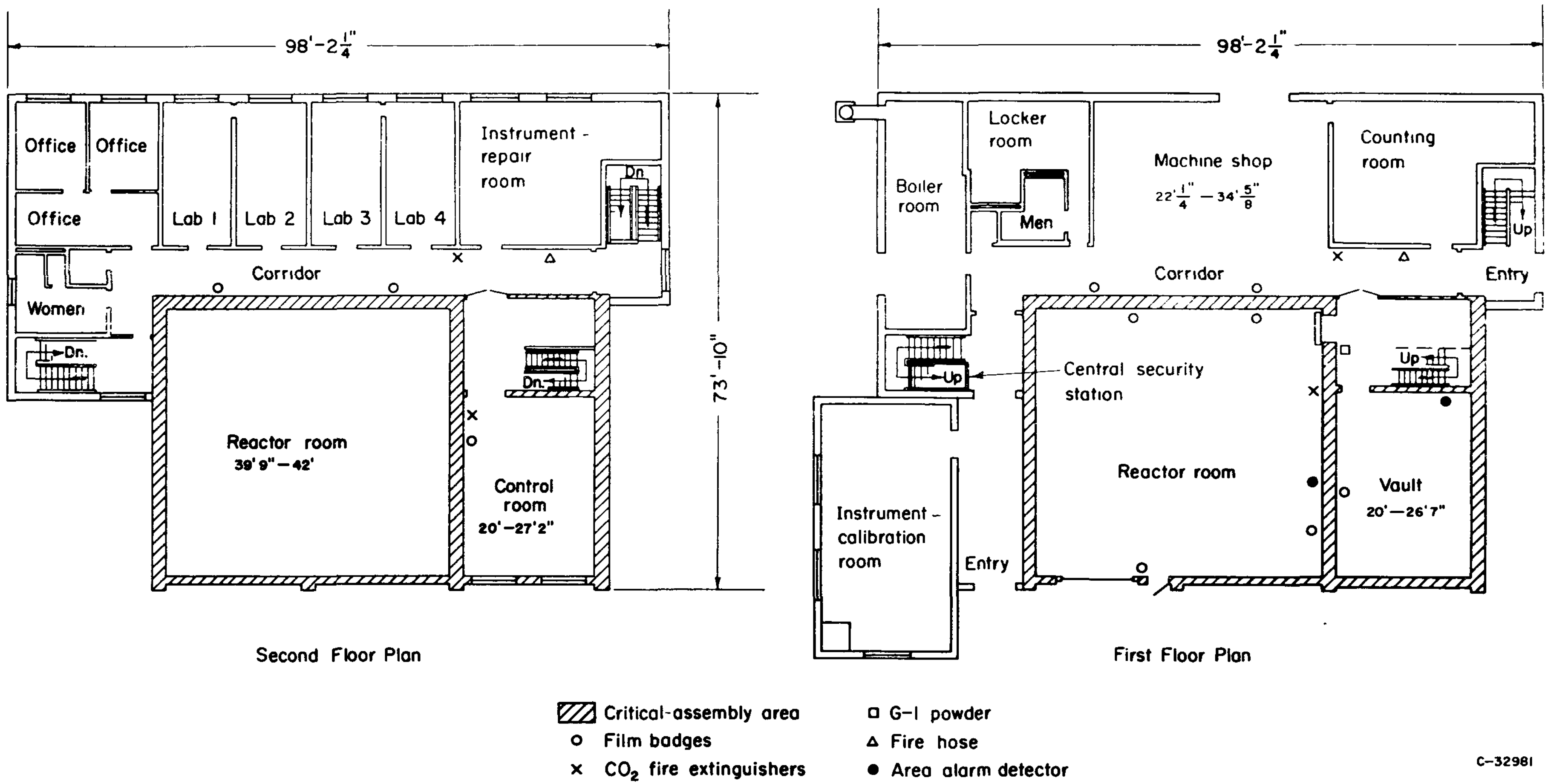

FIGURE 4. FLOOR PLAN OF CRITICAL-ASSEMBLY BUILDING

The assembly room has a single entrance into the remaining part of the building which can be closed off with a steel and concrete door having gamma-shielding properties equivalent to the 2-ft wall. In addition to this door, there is a personnel entrance and a truck entrance to the outside which is kept closed and locked during reactor operations.

There are a number of 4-in. conduit openings between the assembly room and control room for the passage of control wiring. These openings are at a 45-deg angle above head height to prevent radiation streaming from the openings from reaching personnel. The openings which are not in use are fitted with shielding plugs.

Control Room

The control room is located on the second floor adjacent to the assembly room. It is approximately 20 ft wide and 27 ft long. Services in this room include air conditioning and a dehumidifier. The control and research instrumentation is located along one wall.

Storage Vault

The storage vault is on the first floor beneath the control room and is approximately the same size, that is, 20 by 27 ft. The walls, floor, and ceiling are of reinforced-concrete construction. Two walls, the floor, and ceiling are 1-ft-thick reinforced concrete. The remaining two walls are 2-ft-thick concrete. The steel vault-type door is equipped with a four-tumbler manipulation-proof combination lock.

Counting Room

The counting room is located on the first floor so that the use of heavy shielding is not a problem and so that foils of short half-life can be removed from the assembly room to the counting room with a minimum delay. The room is approximately 21-ft square. No special wall construction is provided and shielding is provided for individual detectors as required. There is a grounded bus bar running around the room. Air conditioning is provided to maintain the air at 75 F and 50 per cent relative humidity.

Radiation-Instrument Calibration Room

The calibration room adjoins the Critical-Assembly Laboratory. It is a concrete-block brick-faced room with about 950 ft^2 of work space. It houses laboratory space and special nuclear sources which are used for calibrating the radiation-safety instrumentation in operation at Battelle's Nuclear Energy Center.

Office and Laboratories

Approximately 750 ft^2 of floor space is provided on the first floor for a machine shop. Equipment in this shop includes a power hacksaw, a band saw, a lathe, a drill press, a milling machine, a number of benches, and an assortment of hand tools. The machine shop has a truck entrance for bringing in bulky equipment.

An electronic laboratory for repairing instruments and for building up and modifying the instruments as required is located on the second floor above the counting room. This laboratory is air conditioned.

Seven additional rooms on the second floor provide space for offices, for a conference room, and for laboratory space, should it be required.

Safety Equipment

Fire-control and radiation-monitoring and safety equipment is located in the building as shown in Figure 4. The fire-control equipment is concentrated in areas having any probability of accidental fire.

The corridor and room radiation detectors are film badges which are sensitive to gamma and beta rays and neutrons. Two area alarm-monitors are in operation at points where accidental criticality is possible; that is, where fuel is stored or assembled. In the fuel storage vault the alarm-monitor is a commercial instrument, trade name Gammalarm. In the critical-assembly room one of the reactor instruments, the scintillation crystal, serves in a dual capacity. When the reactor is not operating it is an alarm-monitor. During operations it is part of the normal reactor safety system.

Makeup of Surrounding Area

The location of the site and a brief description of the geography of the region was given above. The sections below discuss other features of the area with emphasis on factors which may be related to the operation of the critical facility.

Population Distribution

The population distribution at various radii from the site was obtained, for the most part, from the Chamber of Commerce 1954 statistics and the State-Wide Highway Planning Survey, 1953. The distribution of population at various distances from the site is shown in Table 1.

TABLE 1. POPULATION DISTRIBUTION WITHIN VARIOUS DISTANCES FROM SITE

Distance Radius	Population
1500 ft	0
2500 ft	0
1 mile	60
2 miles	1,150
5 miles	5,100
10 miles	43,000

Industry Adjacent to the Site

The nearest industry is more than 2 miles from the site. Most of the industries employ less than 100 people; Westinghouse Electric Corporation and the General Motors Corporation, both 8 miles from the site, employ about 4400 and 4000, respectively. The information regarding adjacent industries is presented in Table 2.

Lincoln Village, a housing project, is located 8 miles from the site. The village has a population of approximately 500 families.

Seismology

In determining the earthquake probability of a given area, all that can be done is to examine the earthquake history of that vicinity and then conjecture that future earthquakes are more likely to occur in places where there have been previous ones.

Several areas in western Ohio have suffered minor earthquake damage. There is no record of earthquakes having occurred in West Jefferson, Ohio, and the immediate vicinity. The nearest seismic activity in recent years was recorded in 1937 in the Anna, Ohio, proximity, which is over 50 miles from the proposed reactor site.

The information on western Ohio earthquakes was obtained in 1954 from Reverend V. C. Stechschulte, Xavier University, Cincinnati, Ohio, and from the U. S. Coast and Geodetic Survey. Letters from these two sources are included in Appendix A.

Climatology

The climate in the Columbus area is definitely temperate and continental in character. The normal mean daily temperature for June, July, and August is 73.3 F, although 90 F or higher is expected about 20 times per year. During the months of December, January, and February, the normal seasonal temperature is 31.2 F with three subzero nights per winter average.

The primary prevailing-wind direction is from the southerly quadrant (41 per cent of the winds blow from the general direction SE to SW). The secondary prevailing-wind direction is from the NW. The average wind speed is 8.4 mph with 59 per cent of the winds occurring in the 4 to 12-mph interval. No large seasonal or diurnal variation exists in either the direction or speed of the winds. During a 51-year period in Columbus, peak wind speeds have been observed to exceed 51 mph in every month of the year. The maximum recorded speed was 84 mph occurring in July.

Rainfall, averaging nearly 3-1/2 in. per month, is quite evenly distributed from April to August. The record single day's rain was 3.87 in. in July, 1957. The bulk of the summer rainfall comes in frequent thunderstorms, and tornadoes are not unknown. However, local storm records show that only four tornadoes have occurred in the Columbus area since 1931.

Since Ohio is located in the path of many winter storms, Columbus receives a generous amount of cold-season precipitation. The bulk of it comes in the form of rain, but the average winter will yield a total of 22 in. of snow. This is quite variable and, in the largest snowfall of recent times, in 1950, 7.5 in. fell in 1 day.

TABLE 2. INDUSTRIES WITHIN A 10-MILE RADIUS OF REACTOR FACILITY SITE

Industry	Products	Number of Employees[a]	Distance From Site, miles
Ternstedt, Columbus Division, GMC	Auto parts	4000	8
Westinghouse Electric Corporation	Refrigerators, appliances	4400	8
Janitrol Aircraft Div. Surface Combustion Corporation	Aircraft parts	500	8
Rexall Drug Company	Warehouse	70	8
Hartley Newspapers	Printing and publishing	70	10
Fisher Cast Steel Products, Inc.	Steel castings	30	2
Ohio Seed Company	Seed processing	20	2
H. J. Upperman & Sons	Lumber	24	9
West Jefferson Sand and Gravel Company	Sand and gravel	15	3
Murray Lumber and Grain Company	Elevator, lumber	10	2
Merriman Cement Products, Inc.	Cement blocks	Less than 10	2
Hartco Printing Co.	Printing	Less than 10	2

(a) December, 1959.

Climatology data abstracted from a report prepared by the Scientific Division of the U. S. Weather Bureau are given in Appendix B.

Geology and Hydrology

The principal glacial deposits at the surface in the Battelle site area consist of till and outwash which accumulated as the Wisconsin ice sheet of the Pleistocene Age receded. The till, an unstratified matrix of clay containing rock fragments, underlies the Battelle site to depths ranging from approximately 60 to 200 ft. The outwash, composed of stratified layers of sand and gravel, is thin and discontinuous in the site vicinity. Fringing the locality is a narrow strip of Columbus limestone, forming in places a 3-ft surface stratum.

Underlying the glacial deposits of the area are several hundred feet of nearly horizontal beds of limestone, dolomite, and shale, through which preglacial streams carved a branched valley system. The distance from the soil surface to the bedrock on the Battelle property ranges from a few feet in areas along Big Darby Creek to over 200 ft in the northwest corner of the property.

There are two aquifers in the Battelle site area. One is shallow and of minor importance and in underlain by the major aquifer of sand, gravel, and limestone. Yields up to 300 gal per min have been obtained from wells drilled into the principal aquifer in the area.

The ground water comes entirely from local precipitation and the shallow aquifer is recharged almost uniformly from the precipitation. The water table is everywhere less than 40 ft from the surface, and the contours are a subdued replica of the surface topography. Calculations indicate that water in the principal aquifer in the vicinity of the Battelle site is moving at a rate somewhat less than 1 ft per day. The water in the till overlying the principal aquifer is estimated to flow at a considerably lower rate, measurable in hyndredths of a foot per day.

Ground-water movement downward through the thick till takes place very slowly. A long period of slow percolation occurs before water reaches a zone in which it may move laterally at appreciable rates. All the ground water is discharged into Big Darby Creek; hence, water entering the ground on the Battelle property is already near its place of discharge.

Big Darby Creek accounts for the principal surface-water flow. The mean flow is 420 ft^3 per sec, based on a 24-year record. Ground-water seepage from the impermeable deposits in Madison County adds little to stream flow. The water of Big Darby Creek is of good quality and is not polluted.

The conclusions of a report prepared by the U. S. Geological Survey on the geology and hydrology of the Battelle site are given in Appendix C. It is concluded that in case of liquid spillage, most of the liquid would flow overland to the Big Darby Creek and the remainder, once reaching the water table, would also discharge into the creek. The changes for radioactive contamination of well water in the surrounding area are considered nil.

DESCRIPTION OF THE CRITICAL ASSEMBLY

The Core and Reflector

The design characteristics of the Plastic Reactor Facility for the current operations are summarized in Table 3.

The fueled cans described in Table 3 are mounted between two adjustable grid plates. The bottom grid plate is fastened to the table base plate and the upper grid structure is rigidly mounted to the table base by means of aluminum angle frames. The core will be surrounded by a lateral polyethylene reflector 4 in. thick. This arrangement is shown in Figure 5.

The lateral 4-in. thickness of polyethylene reflector is constructed from blocks. These blocks are held securely by vertical 1/2-in. aluminum rods which extend through a stack and are fastened to the steel deck plate.

The core is a 2-ft cube with a central void passage for the experimental chambers. This geometry may be changed slightly if it appears desirable.

The control blade moves vertically and is made of stainless steel-cadmium sandwich construction. It is 4-1/2 in. wide and 1/8 in. thick. Safety elements are double-length aluminum cans which contain cadmium in the top half and a fuel element in the bottom half. Fuel elements serve as safety-blade guides in the core-reflector assembly.

The core and reflector are mounted on a split-table assembly as shown in Figure 6. The core is divided into two sections with one part mounted on a stationary table and the other part mounted on a movable table. The movable portion of the table rides horizontally on rails and will be driven by a d-c motor supplied by a thyratron rectifier unit. The motor is coupled to a lead screw through a chain drive, and the lead screw is attached to the table through a nut. The closing speed of the table is changed by limit switches and predetermined by potentiometer settings in the thyratron grid circuits. Design speeds are 25 in. per min from a 48- to a 12-in. separation, 6 in. per min from a 12- to a 2-in. separation, and 1/2 in. per min from a 2-in. separation to the closed position. The opening speed is 25 in. per min.

The entire assembly is mounted on a steel base frame which provides a level surface. The position and speed of the movable table is measured and registered at the console by Selsyns and tachometers, as required to attain sufficient accuracy. The table position can be read to 0.001 in. during the final 1 in. of travel and to 0.01 in. elsewhere.

Each table half is made of four 12-in. I-beams. Two of the beams form the lower support and are connected by cross beams and a steel deck plate. The other two beams support the safety rods and the rod drives. These beams are supported by four columns which rest on the lower beams. The tables are 5 ft wide by 9 ft long by 13-3/4 ft high.

TABLE 3. DESCRIPTION OF CORE COMPONENTS

Fuel Element	
Fuel Can	
Shape	Square
Dimension	1.5 in. in OD x 1/8-in. wall
Material	63-s aluminum
Number	225 or 256
Fuel	
Material	Teflon-coated uranium
Form	Strips 1/2 by 24 by 0.004 in.
Fuel content per can	Approximately 30 g uranium-235
Estimated critical mass	6.5 kg uranium-235
Moderator	
Material	Polyethylene strips
Form	1 by 0.1 by 24 in.
Quantity in active region per can	Approximately 400 g
Reflector	
Material	Polyethylene
Form	Blocks and strips in fuel cans
Thickness, nominal	4 in. – radial 6 in. – top 12 in. – bottom
Control Elements	
Type	Fueled cans with cadmium in upper portion and cadmium sheet
Number	4 cans, 1 cadmium sheet
Approximate worth of each element	1.9 per cent $\Delta k/k$

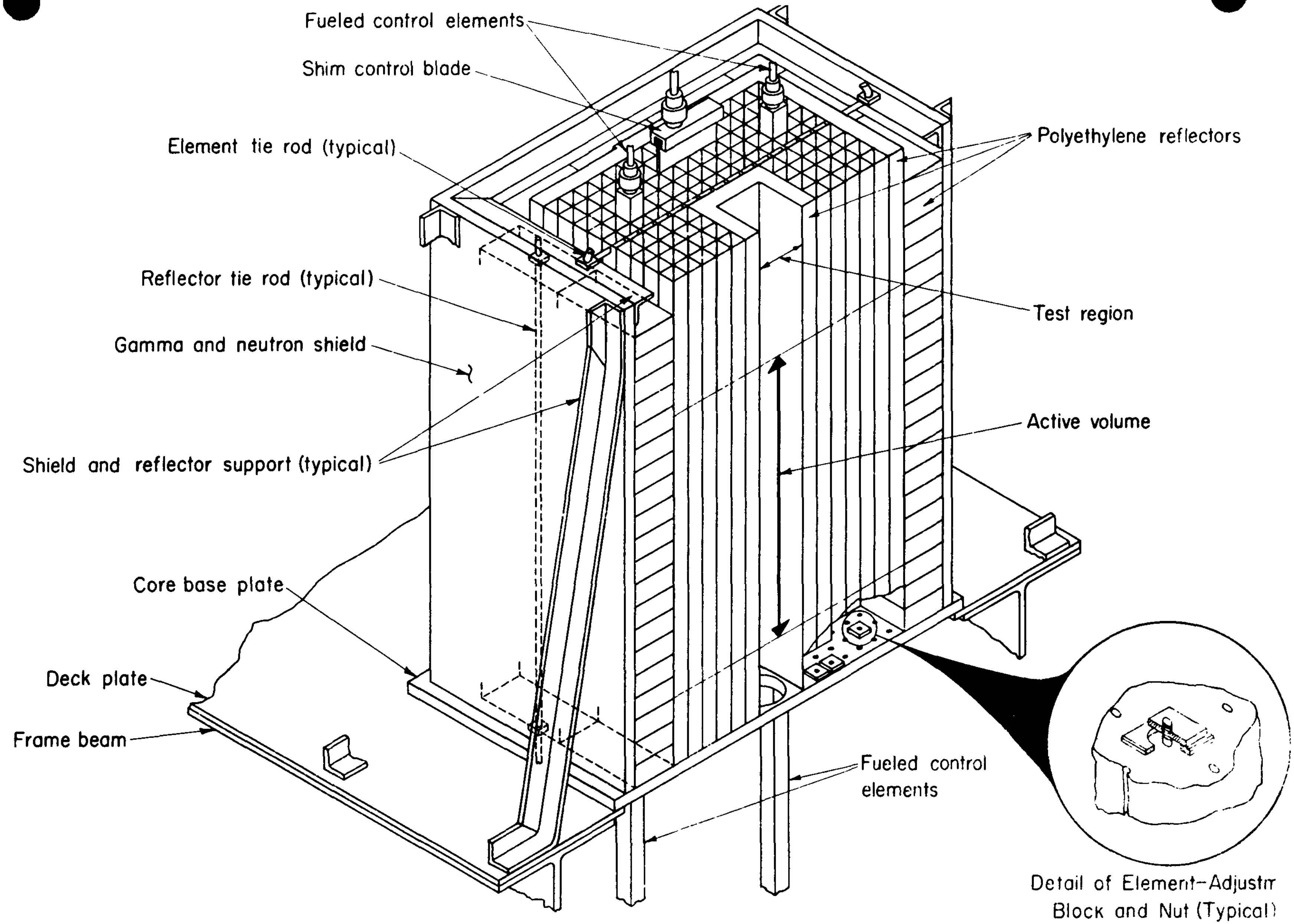

FIGURE 5. CORE AND REFLECTOR ASSEMBLY

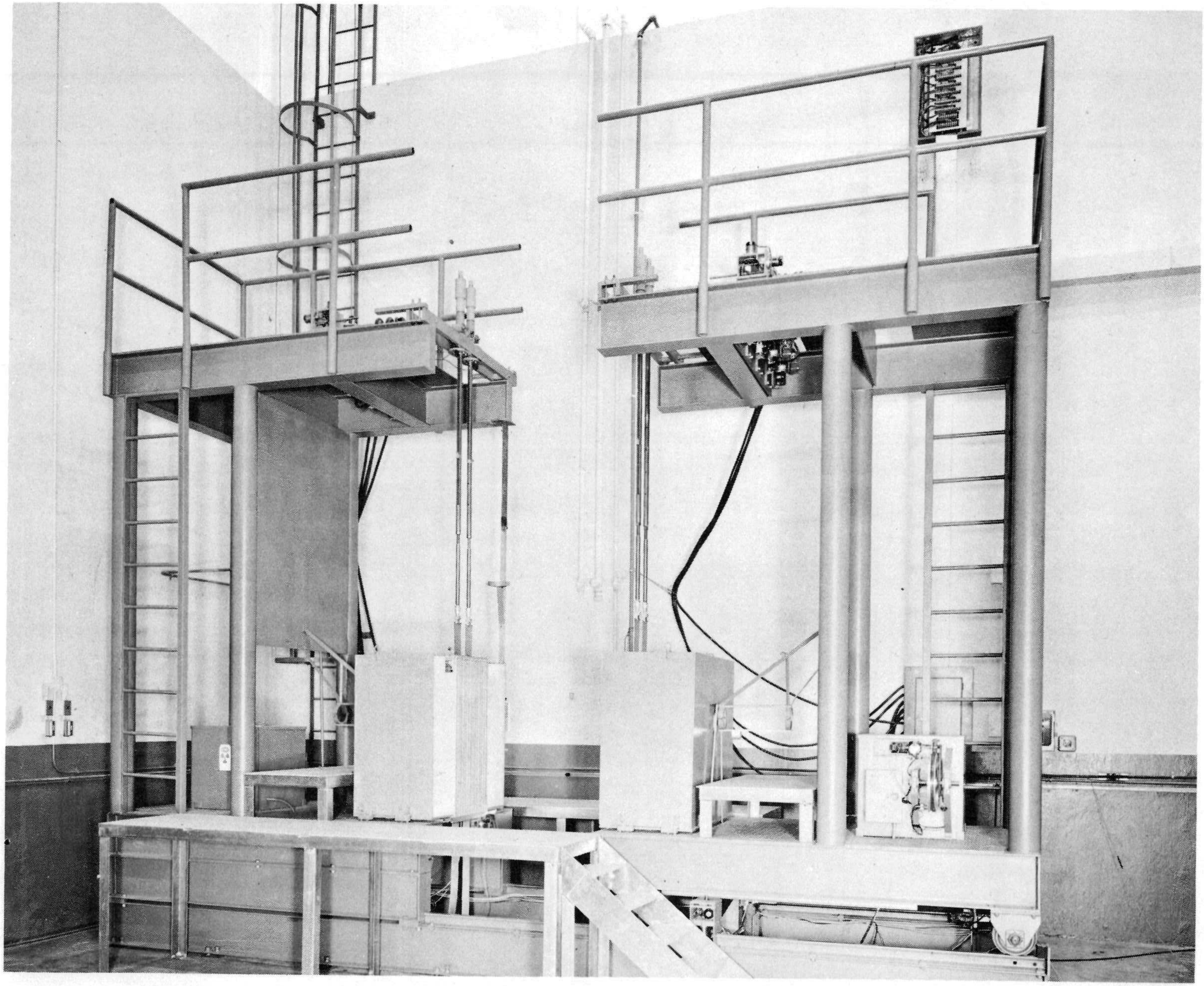

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FIGURE 6. REACTOR TABLE ASSEMBLY

Description of Fission-Chamber Devices

The fission chamber devices are 12 in. long by 5 in. in diameter, consisting of an arrangement of two concentric cylinders. One cylinder will be uranium coated and will contain between 100 to 200 mg uranium-235. The other cylinder will be maintained at voltages near 10^5 v. The high-voltage electrodes are surrounded by a grounded metallic housing. The housing is evacuated and is otherwise well insulated electrically from the electrodes. Low-cross-section materials such as aluminum or zirconium will be used in construction.

Variation in the uranium content, geometry, and material composition will be made throughout the program. In all cases, the device will have generally the same appearance and represent a negligible perturbing influence on the reactor. It is expected that the reactivity effect of the devices will be insignificant. They will be supported in the reactor by a platform to center them at the core mid-height.

CONTROL OF THE CRITICAL ASSEMBLY

In its present application, the critical assembly will not be used as a reactor-physics research tool. It will serve as an irradiation facility for samples inserted in the central void passage. Therefore, the safety and control systems available from previous experiments will be more than adequate. This safety is provided by a group of safety elements and by separating the reactor tables. A system of electrical controls and interlocks and nuclear and mechanical instrumentation tell the operator the condition of the reactor at any instant and will prevent unsafe operation of the assembly.

Operational Controls

The reactor operator can control the positions of the control elements, the movable assembly table, and the neutron source, subject, of course, to various interlocks.

Control-Element Operations

As currently planned, all operations will be conducted with safety elements completely withdrawn in a position to insert maximum shutdown worth. The stainless steel-cadmium control blade will be partially in the core. In this configuration, the excess reactivity in the core is at a minimum. Each of the five elements (four safety, one control) has its own rod-drive unit, but only one power supply is provided. Consequently, power is available to only one unit at a time.

The control-rod drive consists of a motor-clutch-type drive unit, Selsyn position indicators, a rack and pinion gear, and a hydraulic shock absorbed. The details of the drive unit are shown in Figure 7.

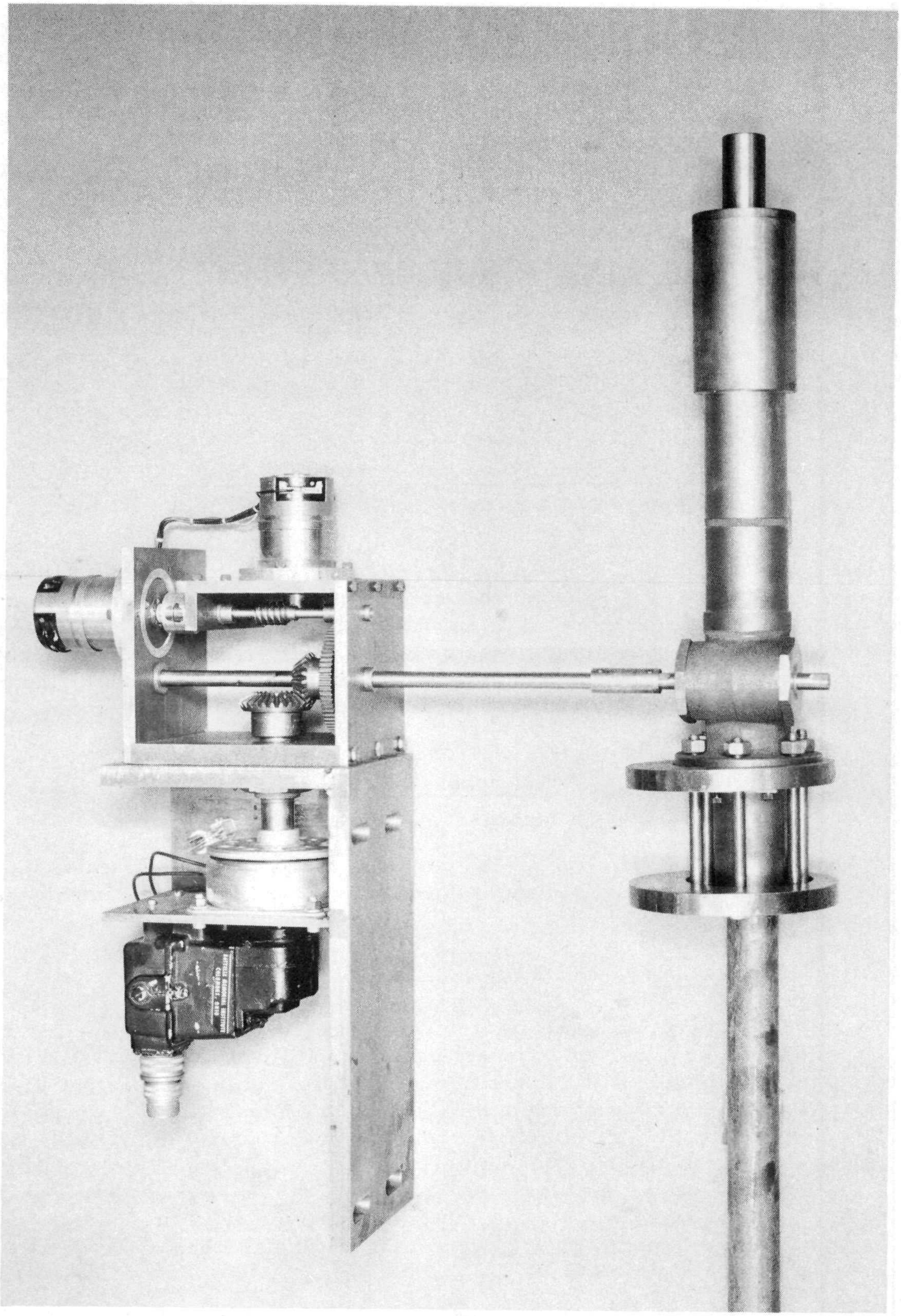

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FIGURE 7. ROD-DRIVE UNIT

The motor-clutch unit contains a reversible variable-speed, 24-v d-c motor with a gear reducer which permits the motor a maximum speed of rpm. The clutch is a stationary-field electromagnetic type which operates on 90-v dc. It may be disengaged automatically or manually from the reactor control console by removing the power to the magnet.

Following the clutch is a unit containing the Selsyn position indicators and a pair of bevel gears. This whole unit can be pivoted about the drive shaft from the clutch. This arrangement permits locating the motor-clutch unit permanently and turning the Selsyn unit so that the drive shaft to the control rod will reach the rack and pinion unit regardless of its direction from the motor-clutch unit.

One Selsyn is coupled to the drive shaft through a permanent-magnet coupling and a pair of spur gears. This Selsyn makes one revolution for 1 in. of control-rod travel. The other Selsyn is connected to the drive shaft through a worm gear and the spur gears which connect the first Selsyn. This second Selsyn gives one revolution for 50 in. of rod travel. These Selsyns are connected to the rod side of the clutch so that they always indicate the control-rod position rather than the position of the driving motor. The permanent-magnet clutch permits the rod to scram without the fine-reading Selsyn following the drop. The magnet rezeros the fine Selsyn after the drop.

The shaft from the drive unit goes to the rack-and-pinion unit and drives the pinion gear. The rack is fastened to a round steel shaft which goes through the bearings in the rack-and-pinion-unit housing. The control rod is connected to the lower end of this shaft. A hydraulic shock absorber is attached to the upper end. This consists of a piston fastened to the rod and a tapered cylinder filled with oil. This shock absorber strikes the upper face of the rack-and-pinion housing to arrest the motion of the steel shaft to which the control rod is attached.

The motor can drive the rod upward or downward at any speed up to 22 in. per min. When the power is cut to the magnetic clutch, the control rod fails under the action of gravity with an acceleration of approximately 0.7 times gravity to scram the reactor.

The rack-and-pinion unit is supported by a pair of heavy steel bars spanning the reactor assembly. The unit is clamped to these bars by a series of bolts passing through a flange in the rack-and-pinion housing and a clamp ring below the bars.

Table Drive

Figure 8 shows the connections for the thyratron-controlled table-drive motor. Two feedback loops are used to regulate the speed and torque of the motor. The triode amplifier monitors the armature current through the 1-ohm resistor and maintains torque constant at the value for rated motor speed. Motor speed is monitored by the tachometer effect of the motor-generated back emf. This back emf is applied to the cathodes of the thyratron tubes and results in a bias voltage on the thyratron grids. This bias voltage is also controlled stepwise by fixed resistors. These resistors are cut in and out by limit switches activated by the table.

Two table-reversing operations are possible. Upon initiating a scram, the movable table is pulled back by means of a weight-pulley arrangement. For other operations requiring shim control of backward motion, the lead-screw drive is operated in reverse.

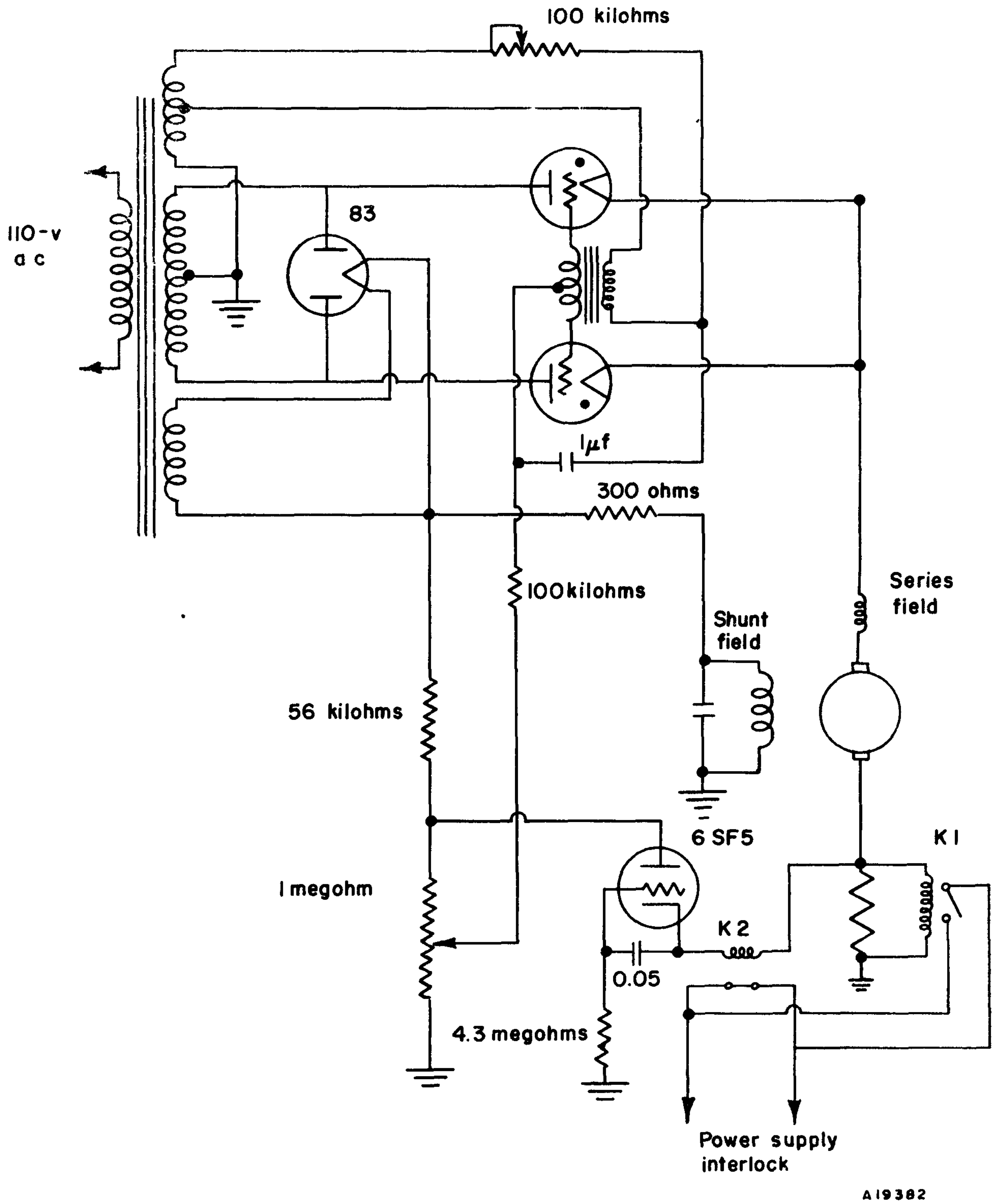

FIGURE 8. SIMPLIFIED MOTOR-CONTROL CIRCUIT FOR TABLE DRIVE

Startup Source

A plutonium-beryllium neutron source will be used for reactor startup. The 5-curie source when not in use is housed in a shielded paraffin-filled box. It will be driven remotely into the reactor region through a closed tube by means of a flexible cable. When inserted, the source will be alongside the reactor at mid-core height, at the outer edge of the radial reflector.

Control and Research Instrumentation

The nuclear instrumentation is shown in the block diagram of Figure 9. Three ion chambers are used as neutron detectors and monitors. These chambers are located at positions around the core away from the startup source. One chamber is connected to a linear micro-microammeter on the console. Negative feedback to the input lowers the input impedance and permits the use of a long cable. The output of this instrument is connected to a strip-chart recorder for visual indication of neutron flux. This output is also monitored by a meter scram relay for the safety circuits.

The other ion chambers are connected to logarithmic electrometers. The output from these electrometers is connected directly to the safety circuits and to differentiating circuits. The differentiated logarithmic signal provides visual period indications and activates the period scram circuits. The output from one of these logarithmic electrometers is also connected to a strip-chart recorder to provide a record of log power or flux level. The slope of the curve on this chart provides a record of reactor period.

A gamma-radiation-monitoring channel consisting of a high-voltage supply and a scintillation detector gives a visual indication of the power level. This channel is also connected into the safety circuits. The detector will be located approximately 20 ft from the core to prevent overloading at operating power levels.

In addition to the safety or control circuits, two research circuits are provided. These channels provide accurate low-level information for startup and accurate neutron indications at operating levels. They are also used to provide an aural indication of power level and additional visual indication of power level. Both channels use boron trifluoride counters as detectors. They consist of a linear amplifier, scaler, and high-voltage supply. The counters and preamplifiers are located in the assembly room. Both of these channels are pulse-counting instruments and are independent of the safety instrumentation.

Interlock and Scram Circuits

Each of the control devices just discussed is interconnected in a manner that prescribes operational procedures and provides automatic shutdown in case of error or malfunction. The interlock circuits are shown in Figure 10.

The interlock and "scram" circuits are entirely switch-and-relay circuits (no electronics). The circuits are designed to actuate by opening switches and relays.

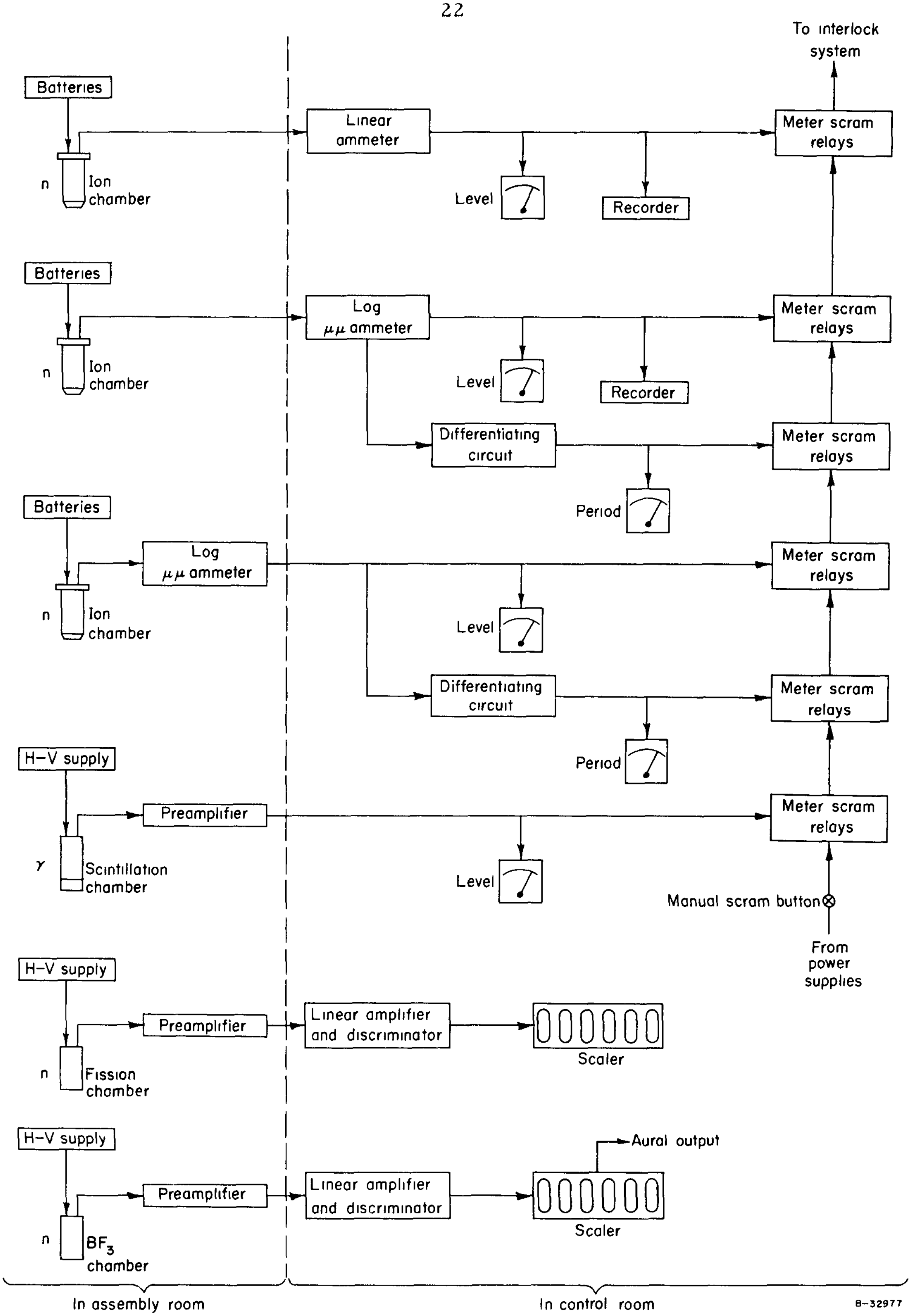

FIGURE 9. BLOCK DIAGRAM OF REACTOR INSTRUMENTATION AND SCRAM CIRCUIT

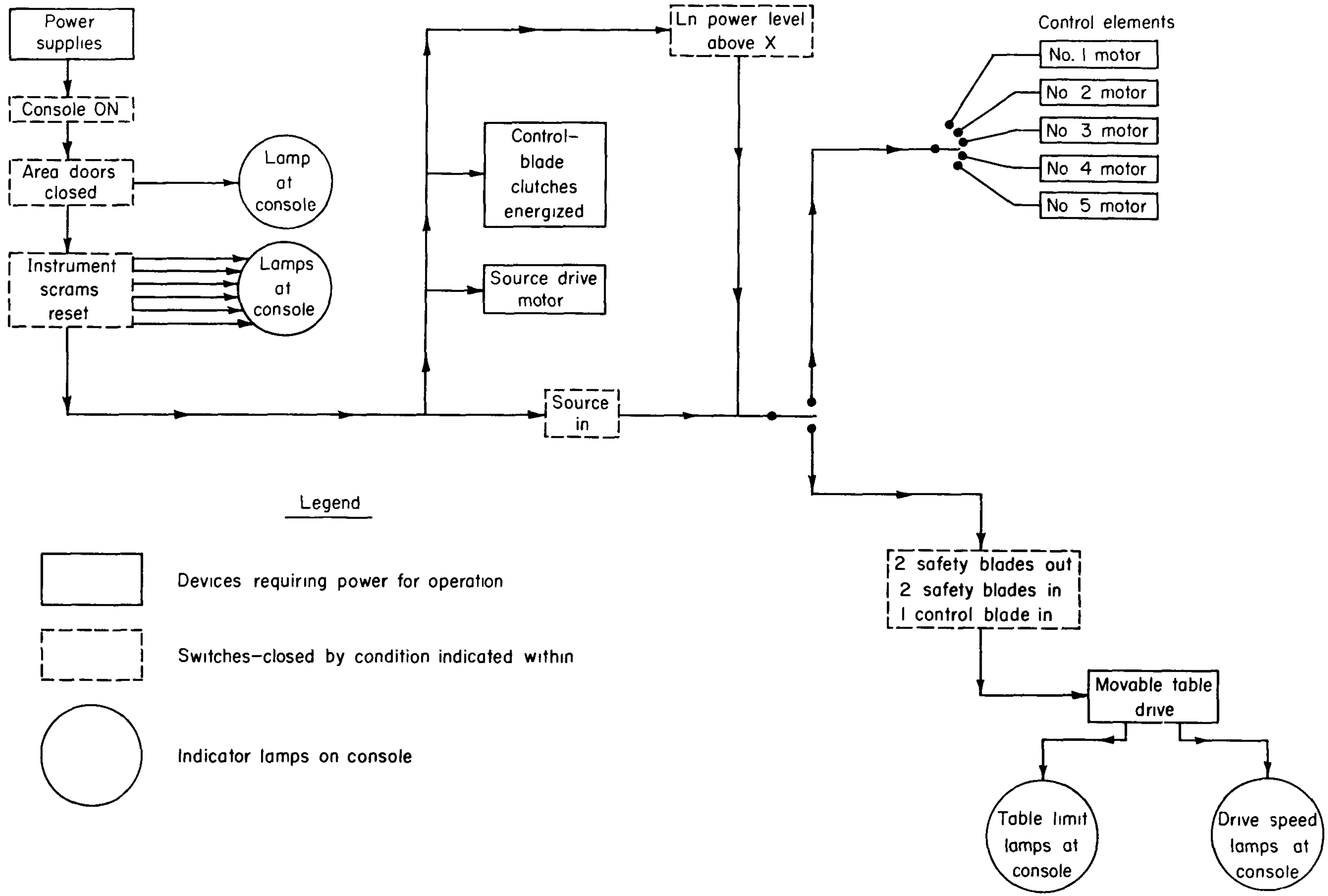

FIGURE 10. BLOCK DIAGRAM OF SAFETY AND INTERLOCK SYSTEM

Relays are fail-safe and are connected so they actuate on removal of power from coils. In circuits containing large inductive loads, precautions include the use of double-break relay contacts and the use of selenium rectifiers to short-circuit the inductive emf.

SUMMARY OF PREVIOUS EXPERIMENTS

Considerable experience in operating the Plastic Reactor Facility has been gained from previous research done for the Army Reactors Branch of the Commission. Details of this research are given in BMI-1245; a brief summary is presented below. From these experiments, which are closely related to the present reactor operations, and from the other critical assembly research, our staff has established a firm basis for conducting the current studies. Furthermore, the research instrumentation to be employed has undergone complete checkout and debugging during 4 years of operation.

Critical Conditions

The plastic reactor has been taken critical in four configurations, involving various plastic densities and void distributions in the core and reflector. Each of the configurations was treated as a major modification in approaching a critical condition for the first time. Initial approach to critical procedures as outlined in a later section were employed. This involves taking data and preparing curves of inverse count rate versus table closure for table separations from 4 ft to fully closed. This procedure is repeated for a number of fuel loadings beginning with 50 per cent of the calculated critical mass. Cross plots of inverse count rate versus full loading with the tables closed are used to predict the critical conditions. In each incremental increase in loading, only one-half the fuel addition required indicated to reach critical is inserted until criticality is imminent with only a very minor fuel addition.

Reactivity Determination

The reactivity potential of the inner radial reflector was measured in each of the four configurations mentioned above. The procedure followed was to adjust the fuel loading to offset reactivity increases resulting in increases in the reflector height (hand stacking with tables separated). At critical the reflector height could be increased remotely about 1/8 in. and the reactor period noted. Curves of reactivity per inch of reflector height were then integrated over the complete reflector height to evaluate total reflector worth. The worth varied from about 6 to 8 per cent $\Delta k/k$.

Flux Distributions

Iron-manganese-molybdenum alloy wires 0.033 in. in diameter and containing about 15 w/o manganese and 2 w/o molybdenum were activated in the reactor to determine flux distributions. The reactor was operated at a power of about 20 w for 30 min. The wires were cut into 1-in. lengths and stacked vertically in 0.038-in.-ID aluminum tubes.

The aluminum tubes were labeled and placed vertically in slots made in aluminum strips in the core-element boxes. For a two-dimensional distribution, a number of tubes were placed at measured distances along a radius of the core.

After irradiation, the aluminum tubes were taken into the counting room where the 1-in. lengths of wire were placed in numbered trays in a sample changer and counted for gamma activity using scintillation detectors.

Discussion of Previous Experiments

The safety aspects of this reactor facility can be judged by the past performance. At no time did any experiment lead to unpredictable performance. The experimental techniques which were prescribed proved to be adequate. Limitations imposed on the motions of control, safety, and research equipment to restrict reactivity addition rate were easily set and maintained. With the exception of improvements made in the table-closure indicators, the initial design of this facility was acceptable.

The adequacy of the present research and control equipment has been demonstrated over a period of 4 years. Only minor modifications are required to reactivate the facility for the irradiation program.

OPERATIONS TO BE PERFORMED WITH THE CRITICAL ASSEMBLY

The purpose of the irradiation studies is to study the performance of the fission-chamber device. Modifications in geometry is one parameter which will be investigated. These modifications will have little effect on reactor operation since no device will contain more than about 200 mg of fuel. On the other hand, the void content of the devices is between 800 and 1000 in.^{3}. Thus, for operational purposes, reactor procedures consider the device to be a void region.

Approach to Critical

Each approach to criticality will follow a set procedure which is described below and which, to a large extent, is enforced by the interlock system. The initial approach, described first, will be used the first time and the reactor is made critical and on any other occasion if significant changes are made in the reactor or in its instrumentation. Once the critical state of a given reactor configuration has been determined, subsequent approaches to criticality will be made with less data taking and plotting.

Initial Approach to Critical

Each approach to criticality will be preceeded by the operational checkout. This includes a complete check of all instrumentation and safety mechanisms of the reactor. Each radiation detector will be checked for calibration with a neutron source. Each scram circuit will be checked and the scram mechanisms activated. The interlocks will be checked by attempting operations contrary to the design purpose. Following this, a visual check will be made of the facility and room; personnel will leave and the reactor room will be closed. The printed checkout list is signed by the persons performing the checkout.

Next the neutron source is driven into the reactor and the two safety rods which are interlocked with the table-drive system will be fully withdrawn. The remaining safety rods and the control block will be interlocked to be fully in before the table can be moved. With the reactor in this condition, counting rates and meter readings will be taken. The table will then be driven to a separation distance of 36 in. and readings repeated. This process will continue at separation distance of 24 in., 12 in., 6 in., 3 in., 2 in., 1-1/2 in., 1 in., 1/2 in., and, if required, at 1/4 in. Then the table will be closed.

The control rods which are interlocked in the core will be removed in steps with count-rate and meter readings being taken at each step. If the reactor is subcritical with all rods removed, the table will be separated, a new fuel loading inserted, and the process repeated. Normally this process begins at about half of the calculated critical mass. Fuel additions are made symmetrically and in steps not exceeding half the fuel addition calculated to reach a critical condition. Fuel increases continue until it is apparent that a very small addition will made the reactor critical. In the additions, the reactivity increase will be considerably less than the available shutdown worth to insure that the reactor does not go critical on table closure.

Criticality is apparent when the reactor power rises into the operating range and the neutron source can be withdrawn without changing the power level. Final adjustments on the control rods are usually required at this time.

Subsequent Approach to Criticality

Once the critical state of the reactor has been determined by the method described above, a simpler means of making the reactor critical will be used. In subsequent approaches to criticality, the table will be closed continuously rather than stepwise. The rate of closure is, of course, still controlled by the three steps in bias voltage on the thyratron grids. After table closure is completed, the control rods will be withdrawn continuously. Counts and meter readings will not be plotted; however, the pulse counters will be in operation to provide a visual and aural indication of the power level. Furthermore, the power level and period scram levels will be set to limit both the rate of increase to greater than 4 to 5 sec periods and levels not to exceed about 1 per cent of full power.

Neutron-Flux Evaluations

In order to provide a high environmental neutron-to-gamma ratio, the flux patterns will be measured in and around the test cell. To do this, 80 w/o manganese, 20 w/o copper (P-Metal) wires or foils will be loaded in the core and activated. These wires will range in size from 0.025 to 0.033 in. in diameter, and the foils will be either 0.002 or 0.005 in. thick. Both total and epicadmium activation measurements will be made in order to deduce the thermal-neutron-flux distributions. A carbon-walled ionization chamber will be used to monitor the gamma-ray dose.

If it appears desirable, some power-distribution measurements will be made. To do these, the irradiated fuel strips are removed from the reactor and their fission-product activity is counted. Alternately, small pieces of aluminum foil may be placed adjacent to bare fuel strips to intercept escaping fission fragments. These so-called "catcher-foils" are then counted.

Irradiations

Irradiation periods will be as long as 1 hour to investigate the characteristics of the fission-chamber devices. During these periods, the system pressure and chamber response will be monitored in addition to the output from all other reactor instrumentation.

The plan of operation is to place the reactor on a stable period of perhaps 100 sec and allow the power to increase to about 200 w. After the power level is stable, a series of readings will be taken to assess the performance of the chambers. Prior to these irradiations, a power calibration will be made by measuring flux or by source insertion. The total flux measured with gold foils can be converted to power by using the uranium thermal cross section and making suitable corrections for fuel self-shielding, flux depression, and epicadmium power contributions. In the source-insertion technique, the linear increase in neutron level following the insertion of a source of known strength into a reactor is related to the power level by

$$P_o = \frac{t_d S K}{\eta \ell}$$

where

K = ratio of watts to fissions per sec = 3.2×10^{-11} watt-sec per fission

η = number of neutrons per fission

ℓ = effective neutron generation time, sec

P = power level at time zero, w

t_d = time for neutron level to double, measured from time zero, sec

S = source strength, n per sec.

During the irradiation, the neutron and gamma levels throughout the building will be evaluated to insure that they are below tolerance levels.

Reactivity Measurements

The effect on reactivity of modifications to the chambers will be determined by measuring the change in reactor period or the change in the position of a calibrated control rod. Since the control rods are calibrated by period measurements, all reactivity is subsequently based on the usual period-reactivity relationship. The periods will be measured by several detectors.

GENERAL LIMITATIONS ON OPERATIONS

Limitations applied to these operations are identical to ones applied to all previous experiments conducted at the Battelle Critical Assembly Laboratory.

Control Limitation

In all operations, the maximum rate at which reactivity can be added will be limited to 0.04 per cent $\Delta k/k$ per sec. This limitation applies to the control rods, table-closure speeds when k_{eff} is greater than about 0.95, and all other controls which can be operated remotely.

The reactor will not be taken critical with less than 2 per cent $\Delta k/k$ available for quick shutdown. This limitation is satisfied by interlocking two control blades out of the core, poised for quick insertion, before startup procedures can continue.

Power Limitation

The critical assembly will normally be operated in the power range from 1 mw to 1 w for startup and calibration. For activation and exposure studies, the core will be operated at power levels up to 200 w for periods as long as 1 hr.

The power-level scrams are present at 0.1 to 1 w in startup and calibration experiments. In irradiation experiments, the power-level scrams will be set at 300 w. Period scrams for all experiments will be set at 4 sec.

Fuel Handling

Procedures and control have been adopted to avoid criticality hazards during core assembly. The fuel-handling operations are based on three criteria: (1) the amount of uranium in process is limited, (2) the amount of uranium handled in a batch is limited, and (3) transfer of uranium between handling operations is controlled.

Construction of Core Elements

Prior to assembly into fuel elements, the amount of uranium handled at one time will be limited to 350 g in one batch and 700 g at any one location. After assembly into fuel elements, not more than 350 g will be carried in one batch or assembled at one point except on the assembly table.

To enforce the procedures, a supervisor will be appointed for each of the operations. He will be fully responsible for seeing that the procedures are correctly applied and that proper health, security, and accountability measures are maintained. To insure accurate, continuous control of the material, a record will be kept at each point at which uranium is handled.

The fuel-assembly operations will be conducted in the area at the foot of the stair well which connects the vault, reactor room and control room. A 10 by 15-ft area will provide enough room for these operations. This area can be locked off from the rest of the building to control access to the operations.

Storage racks for the fuel boxes and the nonfuel metal and polyethylene strips are provided at the fuel-assembly location. Of course, the uranium foil is stored in the vault except the amounts actually in assembly. Trays will be provided on the assembly table to contain these uranium foils. These trays or bins will be separated by at least 2 ft. Separate tables are available for assembly and for weighing materials.

Completed fuel elements will be stored in the vault when not in use. Storage space for individual elements provides a linear array one fuel element thick. The thickness of this slab is less than 1.5 in., and the amount of uranium in any one element will not exceed 250 g.

Assembly of the Core

The people required and their duties in most cases are much the same for the core assembly as for the fuel-element assembly. The personnel required are:

(1) Supervisor of operations.

(2) A man in the vault to hand out fuel elements.

(3) A man to carry the fuel elements from the vault and to aid in loading operations operations if needed. The fuel elements will be carried two at a time by hand.

(4) A man to load the fuel elements in the core.

(5) A man keeping records of the fuel-element location. These records will be kept in a bound book and also on a display board which will show the geometry of the core and the location of each fuel element.

(6) A man at the control console. This man will take and record neutron counts as loading proceeds.

The last-mentioned man is present in the control room to determine the multiplications of the core. These measurements are made continuously when the source does not represent a hazard to personnel. Alternately, after every six elements are loaded, personnel will leave the core and the man at the console will insert the neutron source and measure the neutron level. After the measurement, the neutron source can be withdrawn into its shielded container, thus eliminating this hazard to personnel. These measurements will be taken more often than after every six elements if the supervisor or the man at the console considers it necessary.

As with the fuel-assembly operations, the duties and procedures involved in core assembly may change in some particulars but the principles involved will be observed and the safeguards will be maintained.

Modification of Core

Modifications to the core are expected to be minor, such as making readjustments to fuel loadings to approach a uniform distribution or to produce neutron peaking. Personnel and assignments are quite similar to those described above.

During core modifications, no more than six elements will be out of the core at any one time. A further limitation will be that not more than one batch of uranium strips of a given size will be out of the vault at one time. Each size of strip will be kept in a separate bin and each bin will be 2 ft or more from any other bin.

At the present time, there are no experiments planned which require modifying shape of the uranium strips. However, such a situation could arise. It might become necessary, therefore, to cut the strips to a new length or a new width, or to roll them to a new thickness. Any modifications of this nature would be carried out at the Battelle Fuel-Fabrication Facility in Columbus and not at the Critical Assembly Laboratory, with a single exception, however: if a small number of strips were to be cut to a new length, this would be done at the Critical Assembly Laboratory. Such operations would be carefully monitored by the Health Physicist to eliminate any hazards to personnel and to limit any spread of activity, and the limitations on handling of uranium would apply.

A small amount of uranium foil will be cut into pieces approximately 1/2-in. square to be used in the power and flux measurements. The quantity used in this manner will be less than 100 g and will not produce a criticality hazard. Contamination and health hazards will be carefully controlled.

Unloading the Core

The unloading procedure will be the inverse of the loading procedure, with the exception that the man at the console is not required, since, by removing fuel, the reactivity is continuously decreased. The fuel elements may be removed to the vault for storage and then taken from the vault for disassembly, or they may be taken directly to the fuel-element-assembly area for immediate disassembly and storage of materials.

The process used will depend on the other activities and requirements in the reactor room and the time schedule involved. In general, the fuel strips will be collected in their original batches for final storage.

HAZARDS ANALYSIS

A critical assembly, like all nuclear reactors, is a source of radioactivity produced directly in the fission process or indirectly from the production of radioactive materials. The dissemination of this radioactivity is the hazard which must be guarded against. Because of its low-power operation, the critical assembly does not accumulate significant amounts of radioactivity during nomal operations. Thus, the only real hazards are the radioactivity produced in a power excursion, and the outcome of such an incident would not be as severe as those from a power reactor.

The hazards attendant with the present operation are believed to be minimized by the nature of the program. The assembly will be used for the bulk of the program in a repetitive fashion. That is, research with the reactor per se is not anticipated. As a radiation source, the assembly will be operated routinely and, consequently, the chance of unexpected or unusual occurrences which might be misinterpreted by the operators is reduced.

In analyzing the assembly, hazards from radiation produced by the assembly during normal operation were considered. Incidents which might lead to a power excursion are also presented.

Hazards During Normal Operation

Hazards during normal operations of this Plastic Reactor Assembly are not great. Consideration has been given to possible hazards resulting from direct radiation during irradiation experiments and from handling irradiated fuel.

Direct Radiation

The neutron flux in the control room, based on past experience, will be approximately 30 thermal neutrons/(cm^2)(sec)(w) and 1 fast neutron/(cm^2)(sec)(w) (above 0.5 Mev) if no special neutron shielding is employed at the reactor. The addition of sheets of borated polyethylene to the outside of the radial and axial reflectors will reduce the neutron dose to about 0.1 of this value. Based on 2000 whr per week as an upper limit on the operations, the expected normal radiation dose with the neutron shield at the reactor will be about 0.25 MPE.

Measurements with a survey meter and film badges on previous assemblies indicate about a gamma dose of 0.5 mr per whr of operation. Based on an upper limit on operation – 2000 whr in 1 week – personnel would be exposed to 1.7 MPE. If this upper limit is approached in the course of operations, shielding will be supplied at the reactor probably in the form of 1-in.-thick lead sheets placed at the outside edge of the assembly. This problem will be evaluated after preliminary monitoring is done at low power levels. Operations at the Critical Assembly Laboratory in the past have been completely safe in this regard. Personnel have received only a few per cent of MPE during the conduct of four major critical experiments. The same criteria applied to past research will be enforced on the present operations.

Fission Product Hazard in Handling Core Components

The uranium strips will be coated with 0.1 to 0.2 mil of Teflon. This coating should prevent the escape of all but about 1/2 per cent of the fission products. Components of the lattice will be checked by swipe counts to determine the extent of external contamination. All components will be handled with gloves.

In some experiments, irradiated fuel strips or elements will be handled. The operation staff are experienced in handling radioactive components. Suitable detectors such as β, α survey meters and individual personnel dosimeters are provided.

Accidental Reactivity Additions

Procedures used in these studies predict the beginning of any hazardous condition and permit the operator to take corrective action. Operator error and/or equipment failure are protected against by having a number of parallel safety mechanisms which control the situation and prevent a hazardous condition. However, cases can be imagined where a combination of serious equipment failures and operator error could produce a hazardous situation. These hypothetical cases are considered below. The treatment closely parallels that given in BMI-1166 since the reactors are essentially identical.

Continuous Withdrawal of All Control Rods

Based on the previous control-rod calibrations and the rod-withdrawal rate of 22 in. per min, the maximum rate of $\Delta k/k$ addition possible is 0.01 $\Delta k/k$ per sec.

Continuous Table Closure at Maximum Rate

Assuming the reactor becomes critical at some separation distance combined with a failure of the control-rod circuits, reactivity may be added at the rate of 0.02 $\Delta k/k$ per sec.

Collapse of Central Void

The worth of filling the central void with fuel is expected to be about 0.04 $\Delta k/k$. This neglects a shutdown effect from any change in geometric buckling resulting from the elements which are assumed to displace the void region.

Energy Release From the Maximum Credible Accident

Calculations pertaining to the energy released in a nuclear accident are given in Appendix D. The shutdown mechanisms were assumed to be loss of vaporized fuel from the system and complete disassembly of the core. The two curves in Figure 11 summarize the results of this analysis. One curve indicates the total energy release and the other shows only the energy required to shut down after sufficient energy has been added to vaporize the fuel.

The effect of continuous linear additions of reactivity such as rod withdrawal or table closure may be related to equivalent step additions. The relationship has been developed for the largest of these ramps (0.02 $\Delta k/k/sec$) and is given in Appendix D. It is seen that the step equivalent is 0.006 $\Delta k/k$. This equivalent is calculated at the time when fuel vaporization has shut down the system. The energy release from this accident can be evaluated from Figure 11 to be about 8.0 megawatt-sec.

The worst of the conceivable accidents arises from a collapse of the central void. No mechanism is postulated which can accomplish this. This accident provides an estimated step-reactivity addition of 0.04 $\Delta k/k$. From Figure 11, this may be seen to give a nuclear-energy release of 15 megawatt-sec.

HAZARDS TO THE PUBLIC AFTER AN ACCIDENT

Of major concern here are the hazards created in the area following a reactor accident. In most azimuthal directions, the exclusion radius is considerably more than 1500 ft. The minimum distance to the fence is 1200 ft and a swamp is on the other side of this fence. Thus, an actual vaporization and release of the fuel elements must occur to endanger public persons. Possible danger to the population might result from (1) direct irradiation by a cloud of fission-product gases, (2) direct irradiation by contaminated ground surfaces due to a fall-out or rain-out from the cloud, and (3) inhalation of radioactive particles or gases and other toxic materials.

Radiation From Radioactive Cloud

To evaluate the cloud problem, the nomographs constructed by J. Z. Holland were employed. The meteoreological data were prepared by the Scientific Service Division of of the U. S. Weather Bureau and are shown in Table 4.

Using these data and the nomographs, the total radiation dose was determined for various distances downwind from the reactor for a megawatt-sec fission-energy release. It was estimated that the initial cloud height and cloud radius would be 25 and 8 8 m, respectively. The results are shown graphically in Figure 12 for several meteorological conditions.

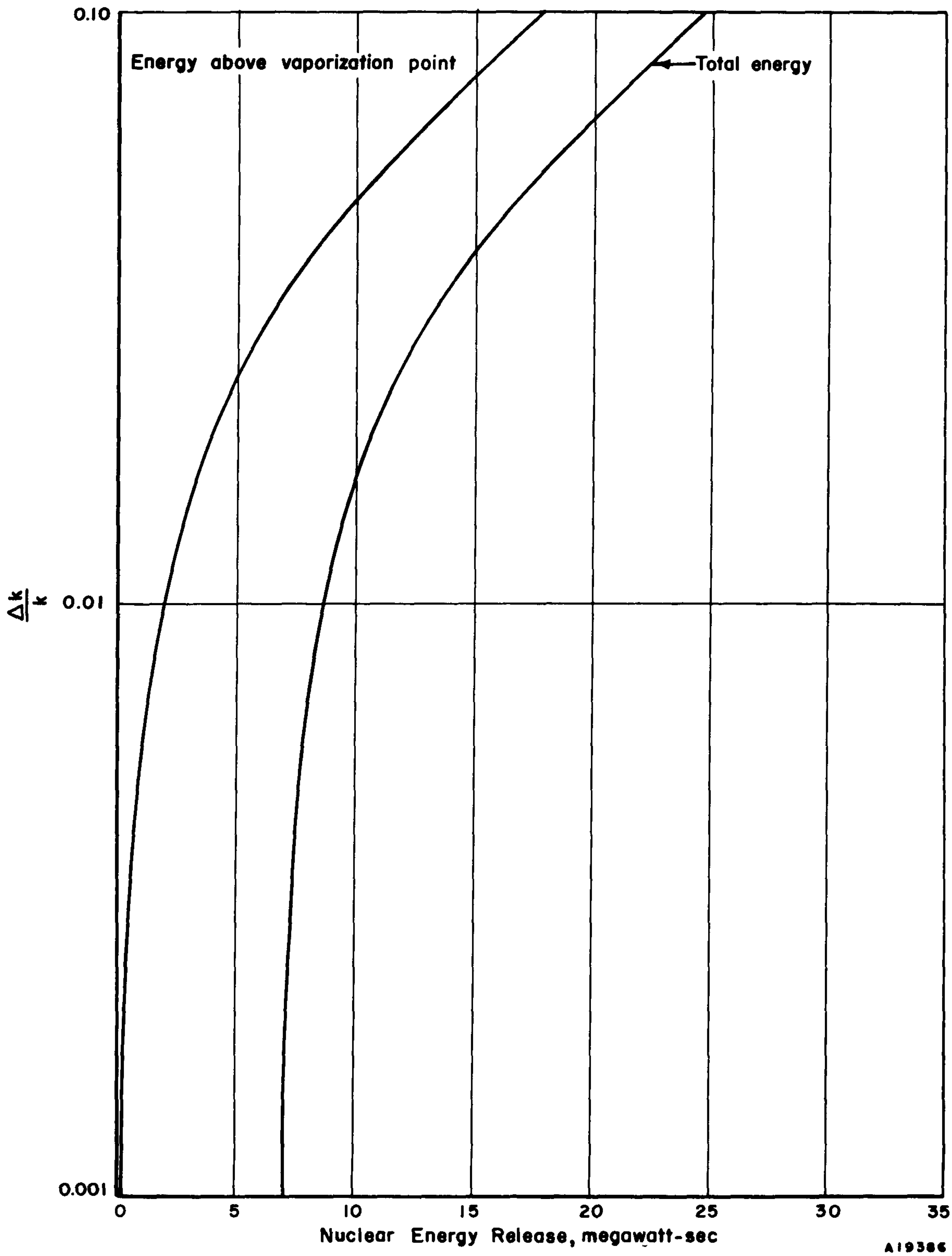

FIGURE 11. NUCLEAR-ENERGY RELEASE

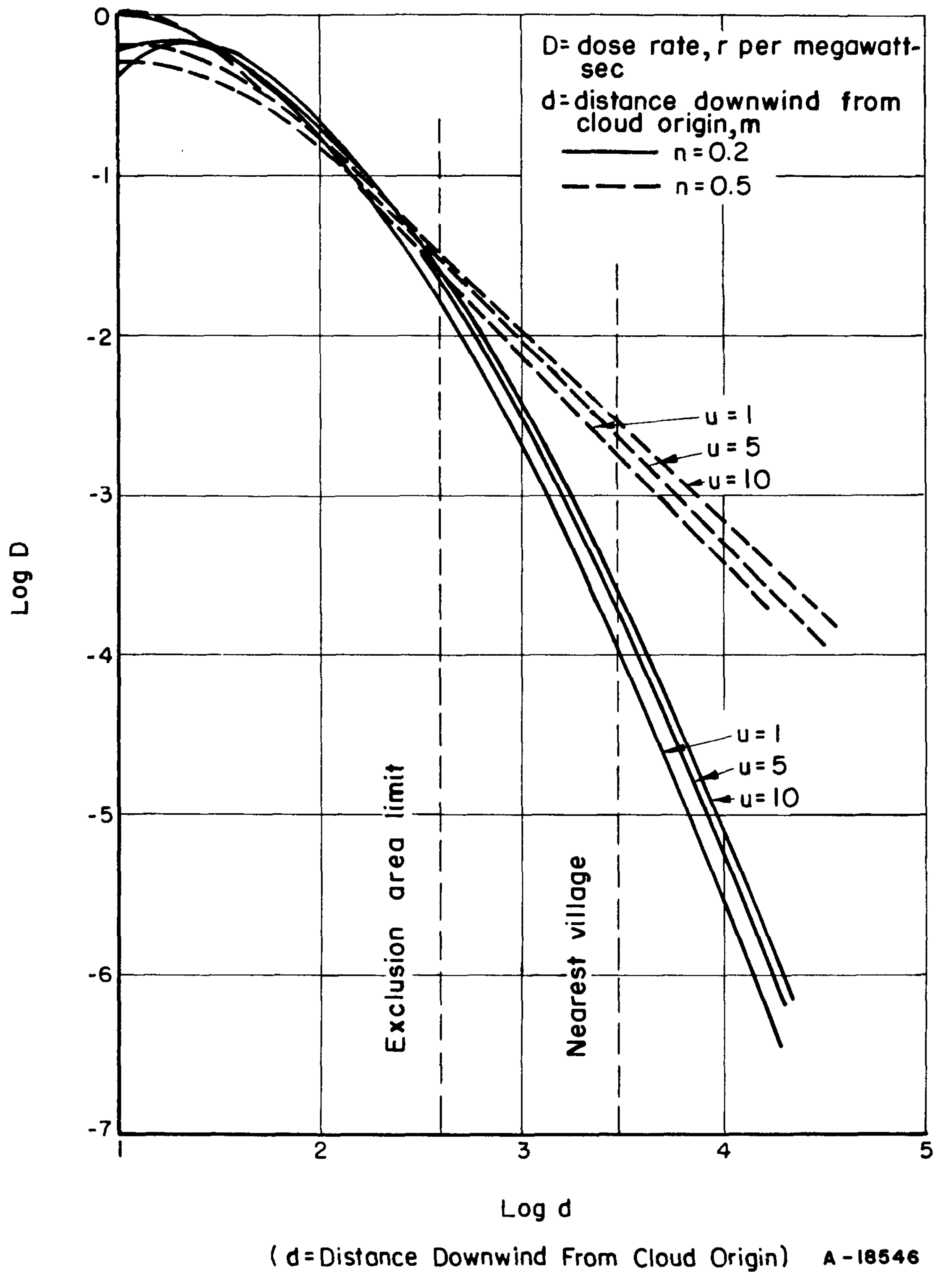

FIGURE 12. DOSES DUE TO PASSING RADIOACTIVE CLOUD

From Figure 12, it will be noted that at the exclusion limit the dose is approximately 0.03 r per megawatt-sec. For the maximum energy resulting from 0.04 $\Delta k/k$, this amounts to 0.45 r.

Radiation Due to Fall-Out or Rain-Out From the Radioactive Cloud

In this case, the fission products contained in the cloud following an accident are assumed to fall to the ground as the cloud travels downwind. The dose 1 m above ground level after the fall-out was calculated as a function of distance downwind. The equations used are reported in Appendix D. The doses calculated are shown in Figure 13.

From Figure 13, it may be noted that at the exclusion area limit, the intergrated dose is approximately 2.5 r per megawatt-sec and at the nearest village, the dose is approximately 0.1 r per megawatt-sec. For the maximum accident (15 megawatt-sec) these figures indicate a 37.5-r dose at the exclusion limit and 1.5 r at the nearest village. It should be emphasized that these doses are based upon continuous long-term exposure following fall-out. If a shorter, more practical, length of exposure is considered, the dose is much less. For instance, in the first hour of exposure at the nearest village, the dose is only 0.42 r for the maximum credible accident.

Inhalation of Radioactive Material

The equations used for calculating the inhalation activity are developed in Appendix D. The results are shown graphically in Figure 14 and 15. The maximum permissible amounts of the various isotopes of major concern are given in Table 5.

Including the combined effects of iodine-131, strontium-89, strontium-90, yttrium-90, barium-140, lanthanum-140, cerium-144, praseodymium-144, and yttrium-91, only 0.3 MPE is possible at the exclusion limit as a result of the maximum credible accident.

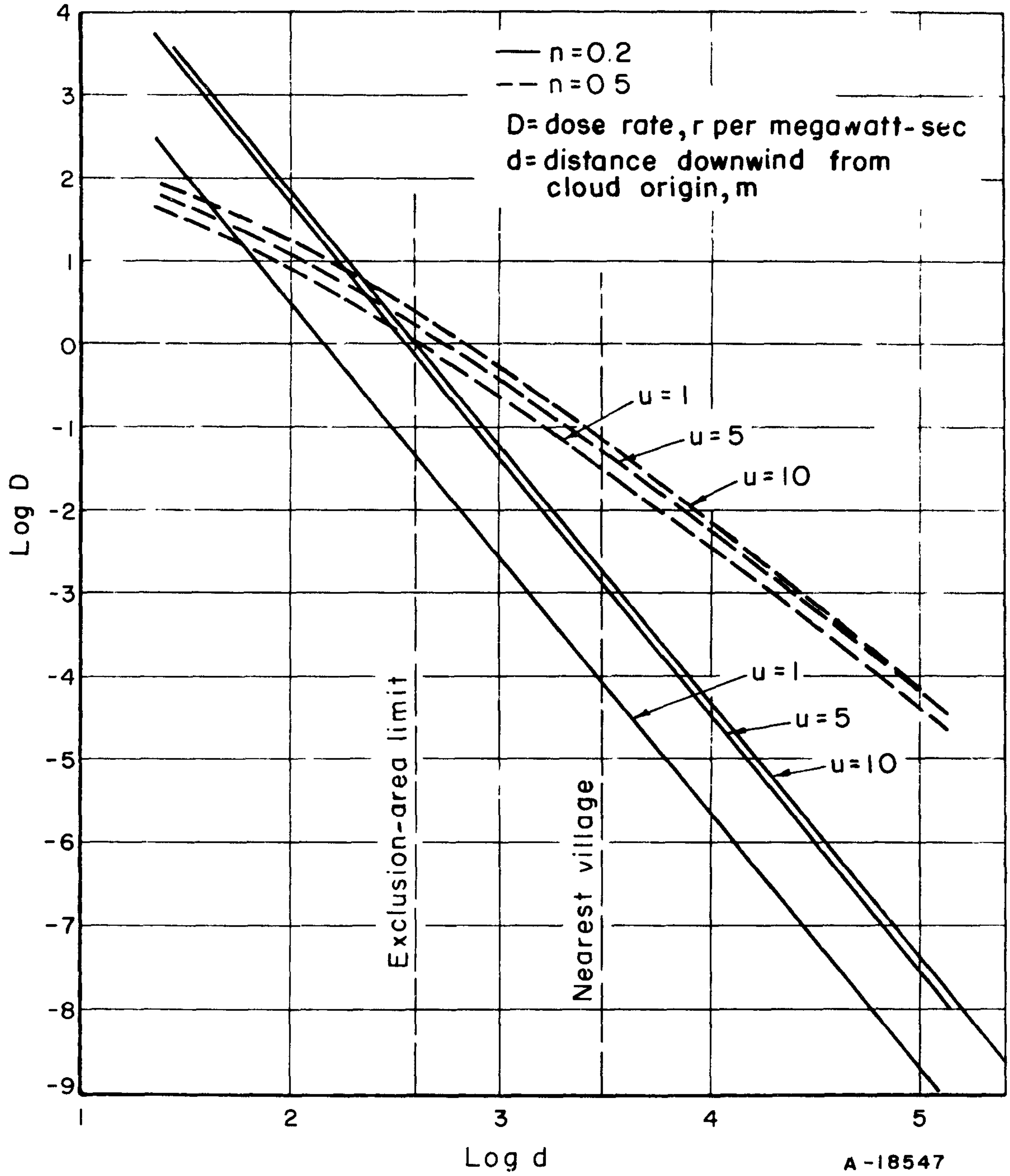

FIGURE 13. DOSES DUE TO FALL-OUT FROM PASSING RADIOACTIVE CLOUD

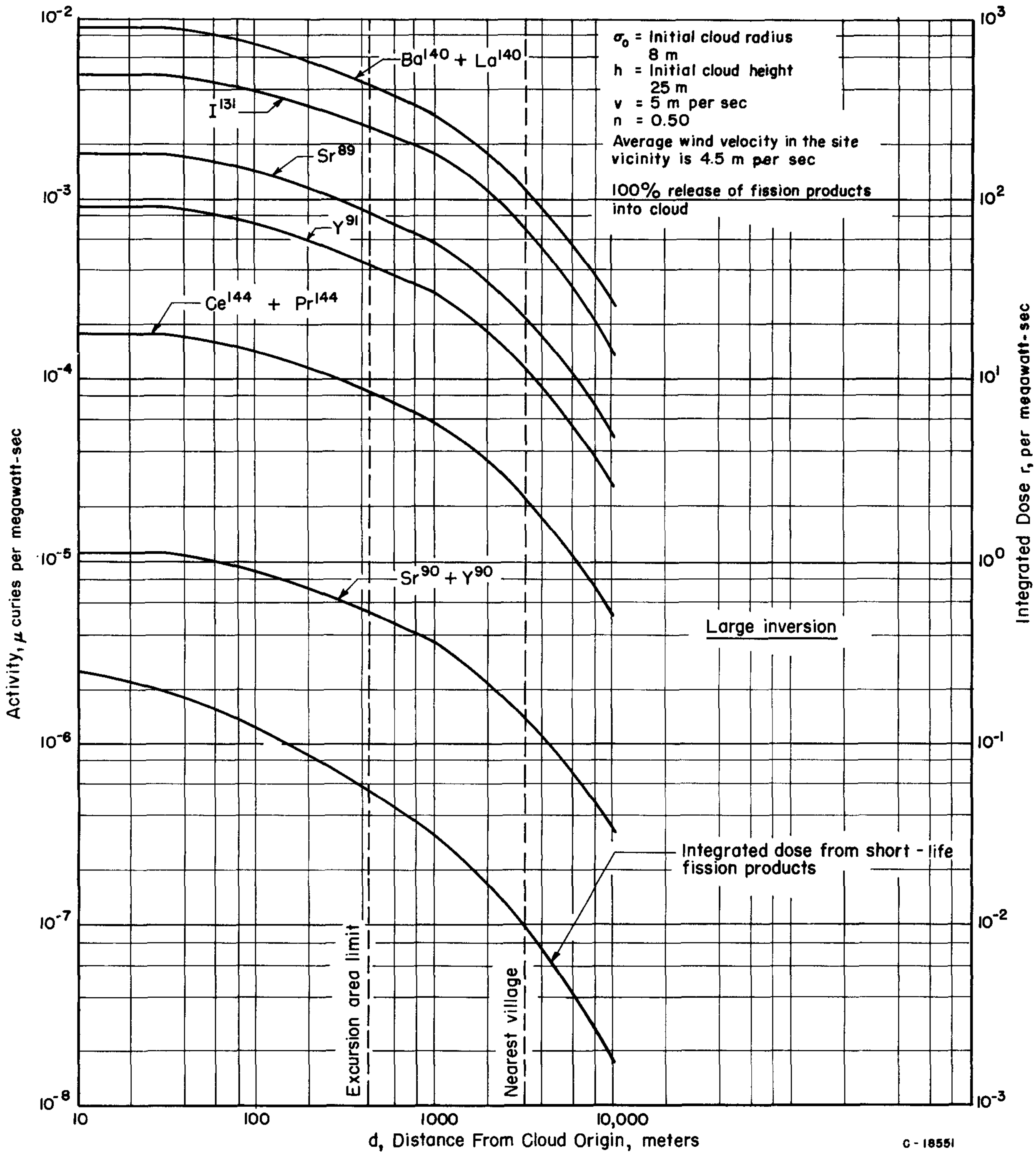

FIGURE 14. INHALATION ACTIVITIES FROM RADIOACTIVE CLOUD (LARGE INVERSION)

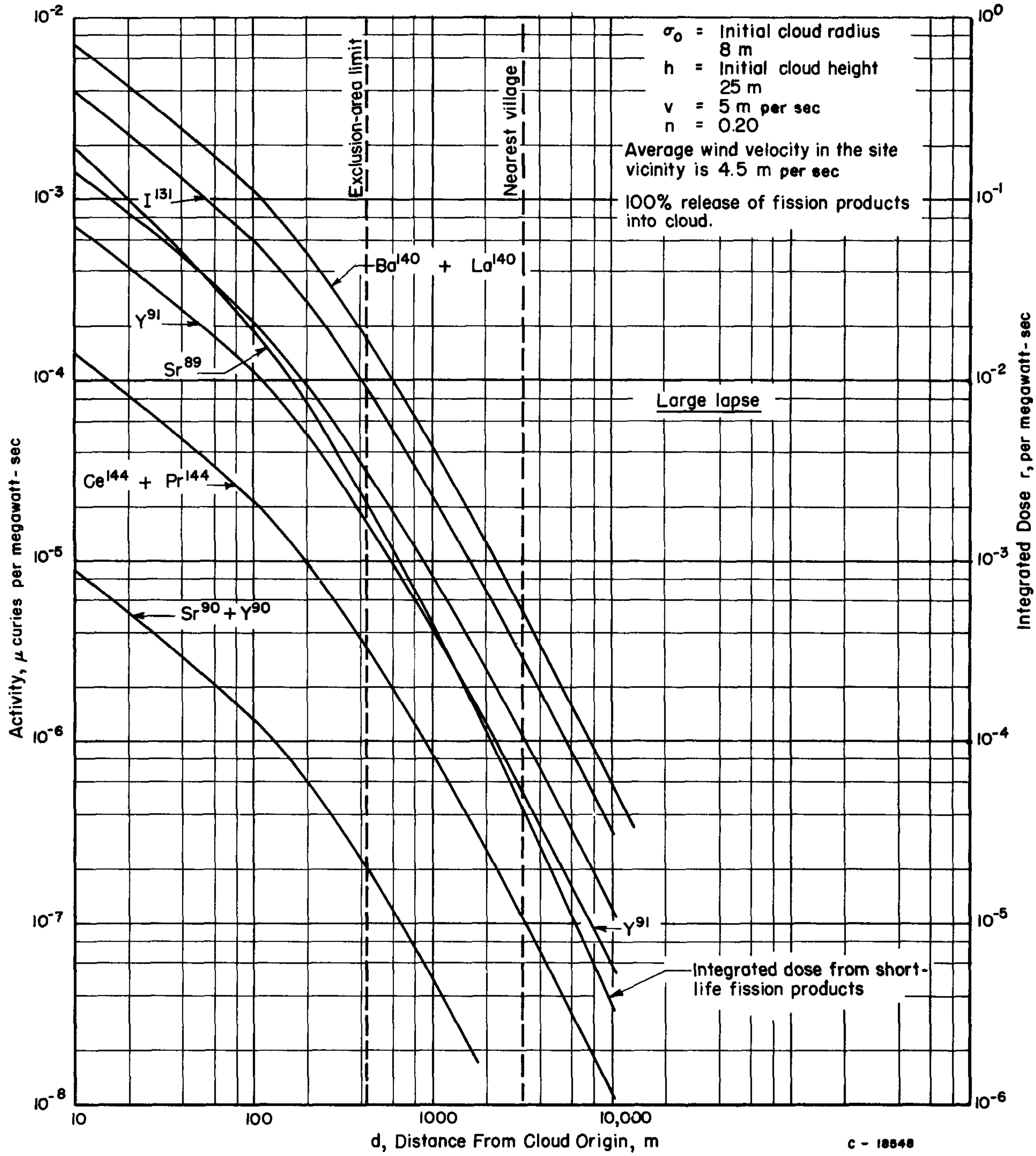

FIGURE 15. INHALATION ACTIVITIES FROM RADIOACTIVE CLOUD (LARGE LAPSE)

TABLE 4. PARAMETERS FOR DOSAGE CALCULATIONS[(a)]

h	n	c^2 u = 1	c^2 u = 5	c^2 u = 10
25	1/5	.064	.046	.040
	1/4	.021	.014	.012
	1/3	.009	.005	.004
	1/2	.006	.002	.002
50	1/4	.015	.010	.008
100	1/4	.008	.005	.004

(a) h = height of cloud from ground, m
u = mean wind speed, m/sec
c = virtual diffusion coefficient, $m^{n/2}$
n = Sutton stability index, dimensionless

The stability parameter, n, may vary from 0 to 1 such as

Large lapse	1/5
Zero or small lapse	1/4
Modified inversion	1/3
Large inversion	1/2

TABLE 5. MAXIMUM PERMISSIBLE AMOUNTS OF SOME ISOTOPES

Isotope	Maximum Permissible Amounts in Total Body, microcuries
Iodine-131	0.3
Strontium-89	2.0
Strontium-90 + yttrium-90	1.0
Barium-140 + lanthanum-140	5.0
Cerium-144 + praseodynium-144	5.0
Yttrium-91	15.0

APPENDIX A

LETTERS ON EARTHQUAKES

APPENDIX A

C
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P
Y

DEPARTMENT OF COMMERCE
U. S. COAST AND GEODETIC SURVEY
WASHINGTON 25

August 24, 1954

Mr. James N. Anno, Jr.
Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio

Dear Sir:

Replying to your request of August 19, 1954, we find no record of earthquakes having occurred in West Jefferson, Ohio, and immediate vicinity. However, as Rev. V. C. Stechschulte stated, there have been several minor earthquakes in western Ohio. Among the most noteworthy are the following which are briefly described in SP 609, Part 1, Earthquake History of the United States.

1776	Muskingum River, Ohio
1875	Urbana & Sidney
1884	Columbus
1901	Wellston & Portsmouth
1909	Ohio Valley (38. 7 N. & 86. 5 W.)
1929	Bellefontaine
1931	Anna
1937	Anna & Sidney (Mar. 2 and 7)

If we may be of further service please do not hesitate to write again.

Very truly yours,

/s/ Robert W. Knox

Acting Director

Enclosure

XAVIER UNIVERSITY
CINCINNATI 7, OHIO

C
O
P
Y

August 18, 1954

Mr. Jim Anno
Battelle Memorial Institute
Columbus, Ohio

Dear Mr. Anno:

This is in reply to your telephoned request of yesterday afternoon.

The problem of determining seismic risk in a given area is largely a guessing game. All that can be done is to list the earthquakes, with the damage done, that have occurred there within the comparatively few years of our historical record, and then to say that where earthquakes have occurred in the past, they may more likely occur again in the future rather than in places where there has been no seismic record.

The catalogs that would be pertinent to your purpose would be:

Serial 609, Earthquake History of the U. S., Part I (pp 39-46).
Serial No. 511, United States Earthquakes, 1929 (p. 8)
Serial No. 553, " " " , 1931 (p. 7)
Serial No. 619, " " " , 1937 (p. 8, 9).

These will give you more detail than is indicated by the maps, listing places where the earthquakes were felt and where damage may have been reported. What it will all add up to is that there has been minor damage approximately within the 50-mile circle with more severe damage in a small area around Anna, Ohio. The small earthquake in the vicinity of Zanesville two or three years ago would make no significant change in the picture.

Sincerely yours,

V. C. Stechschulte, S. J.

(Rev.) V. C. Stechschulte, S. J.
Director of the Seismological
Observatory

APPENDIX B

METEOROLOGY REPORT

APPENDIX B

METEOROLOGY REPORT

Introduction

The purpose of this report is to review the meteorology of the Columbus, Ohio, area for use in the site evaluation and compilation of a hazards analysis.

Source of Data

Although no meteorological data exist for the proposed site itself, very complete meteorological records have been taken for many years at several locations in Columbus. There does not appear to be any significant difference in the general topography of the area between the site and Columbus, so, for most purposes, the meteorological data which have been previously collected should be adequate for this preliminary evaluation. The Local Climatological Data* for Columbus, Ohio, presents a good general description of the weather of this area. The table headed Normals, Means and Extremes on page 2 of this annual summary presents average data on temperature, degree days, precipitation, snow, humidity, wind, etc.

Climatological Review

In the present brief report, those meteorological parameters will be stressed which influence directly the spread of atmospheric wastes.

Surface Wind Direction

The hourly wind observations for a 6-year period, 1948-1953, for the Weather Bureau Airport Station (WBAS) at Columbus were studied in detail. Table B-1 presents the percentage frequency of the wind direction. The prevailing wind direction is from the southerly quadrant (41 per cent of winds blow from the general direction SE through SW). The secondary prevailing direction is from the NW. There does not appear to be any major change in

* U.S. Department of Commerce, Weather Bureau, "Local Climatological Data", for 1953, Columbus, Ohio, U.S. Government Printing Office, price 10 cents.

TABLE B-1. PERCENTAGE FREQUENCY OF WIND DIRECTION, WEATHER BUREAU AIRPORT STATION, COLUMBUS, OHIO

(Based on hourly observations January, 1943, through December, 1953)

Wind Direction	Winter	Spring	Summer	Fall	Annual (All Observations)	Annual (8 am - 4 pm)	Annual (5 pm - 7 am)	Annual (Only When Precipitation Was Occurring)
N	3.9	5.7	6.9	4.5	5.3	4.5	5.8	4.3
NNE	2.4	3.8	4.0	3.0	3.3	3.0	3.5	2.7
NE	3.2	3.7	4.7	2.9	3.6	3.1	4.0	2.9
ENE	2.9	3.4	3.0	2.6	3.0	2.6	3.1	2.8
E	3.8	4.9	4.9	4.2	4.5	3.4	5.1	3.3
ESE	4.2	4.0	3.4	3.6	3.8	2.5	4.6	4.2
SE	9.0	8.3	9.9	11.0	9.5	7.0	11.1	8.9
SSE	8.4	5.2	7.5	8.7	7.4	6.5	8.0	6.9
S	10.8	7.6	9.2	10.5	9.5	10.8	8.7	8.4
SSW	9.6	7.4	7.0	8.2	8.0	11.4	6.0	9.6
SW	6.8	7.4	6.6	7.0	7.0	10.6	4.7	7.6
WSW	4.7	5.0	2.8	3.5	4.0	5.1	3.4	5.4
W	4.5	4.6	1.8	2.8	3.4	4.1	3.0	4.8

TABLE B-1. (Continued)

Wind Direction	Winter	Spring	Summer	Fall	Annual (All Observations)	Annual (8 am - 4 pm)	Annual (5 pm - 7 am)	Annual (Only When Precipitation Was Occurring)
WNW	7.5	7.1	3.8	5.2	5.9	6.7	5.5	8.6
NW	9.8	10.9	8.3	9.1	9.6	9.8	9.4	11.2
NNW	6.1	7.6	8.0	7.4	7.3	7.4	7.3	6.8
Calm	2.4	3.4	8.1	5.7	4.9	1.6	6.9	1.3

wind-direction frequency from season to season except that northwesterly winds predominate in the Spring, while the south and southeast winds reach their maximum frequency in the fall. Table B-1 also compares the wind frequencies for two periods of the day - 8 am to 4 pm and 5 pm to 7 am. From a study of these data, it is clear that no large diurnal change in the wind direction should be expected on the average, although night-time conditions favor southeasterly directions and calms, whereas the prevailing daytime wind is south-southwest.

It is necessary to examine the wind structure during periods of precipitation in order to consider the effect of wash-out of possible waste contaminants. Table B-1 also presents the percentage frequency of wind directions at Columbus during those hours when precipitation was falling. (This was approximately 15 per cent of the time.) In this case, also, there does not appear to be any major shift in the prevailing wind direction frequencies, although NW is the primary maximum in this case.

Wind direction is also important when the lower atmosphere is very stable and atmospheric diffusion is at a minimum. From other meteorological studies of this correlation (Cincinnati, Dayton, and Detroit), it seems probable that the most stable weather in the Columbus area would accompany the southerly and southeasterly winds. The northwesterly winds would be associated with unstable or good diffusion atmospheric conditions. This tendency is borne out by the seasonal and diurnal variations, spring and daytime being the periods in which low-level instability is most common.

Surface Wind Speed

Table B-2 presents the percentage frequency of wind speeds in various class intervals. There is a striking persistency to the distribution. Approximately 58 per cent of the winds in the Columbus area will occur in the 4 to 12-mph speed interval. The average speed is 8.4 mph, although it is slightly weaker in the summer months and stronger in the winter. Winds less than 4 mph occur approximately 21 per cent of the time on the average (10 per cent during the day, 28 per cent during the night, and 10 per cent during those hours when precipitation is occurring). During a 51-year period in Columbus, peak wind speeds have been observed to exceed 51 mph during every month of the year. The highest recorded speed was 84 mph during July.

Two very localized types of storms which are accompanied with high wind speeds deserve special mention - thunderstorms and tornadoes. Thunderstorms occur on the average of 41 days per year, primarily in the late spring and summer, although they have occurred during every month of the year. The peak activity is in June and July. These months average 8 thunderstorm days apiece. Thunderstorm activity is extremely variable,

TABLE B-2. PERCENTAGE FREQUENCY OF WIND-SPEED GROUPS, WEATHER BUREAU AIRPORT STATION, COLUMBUS, OHIO

(Based on hourly observations January, 1948, through December, 1953)

Wind Speed, mph	Winter	Spring	Summer	Fall	Annual (All Observations)	Annual (8 am - 4 pm)	Annual (5 pm - 7 am)	Annual (Only When Precipitation Was Occurring)
Calm	2.4	3.4	8.1	5.7	4.9	1.6	6.9	1.3
1-3	12.0	11.9	23.4	17.7	16.2	8.9	20.6	8.5
4-12	57.9	56.2	59.0	57.6	57.6	57.2	57.9	55.0
13-24	27.0	27.8	9.8	18.8	20.8	31.5	14.3	34.2
25-31	0.7	1.0	(a)	(a)	0.5	0.7	0.4	0.9
32-46	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
46	-	-	-	(a)	(a)	-	(a)	(a)
Mean wind speed	9.7	9.7	6.4	7.9	8.4	10.5	7.1	10.8

(a) Only a few observations.

but a rare severe storm may cause winds in excess of 50 mph, 1 to 3 in. of rain in an hour, and hailstones 1/2 in. or larger in diameter. Situations favorable for the formation of severe thunderstorms are also conducive to tornado formation. However, this more violent storm is rare in the Columbus area. A 35-year study of United States tornadoes shows that 111 tornadoes occurred in Ohio during this period, with the largest percentage of these storms in the northern and western portions of the state. Local storm records from 1931 through 1954 show only four tornadoes in the immediate Columbus area.

Precipitation

The Columbus area receives approximately 38 in. of precipitation annually, which is spread over approximately 140 days. Precipitation is distributed rather evenly throughout the year with the maximum occurring in the late spring and early summer. The maximum amount of precipitation ever observed in 24 hr was 3.91 in. Columbus has an average snowfall of 22 in., which falls on approximately 6 days per year. The greatest amount ever recorded for a 24-hr period was 11.9 in., and for 1 month was 29.2 in.

Atmospheric Stability

Measurements of the vertical temperature distribution are not made in the Columbus area. However, measurements made at other locations have shown a high degree of correlation between low winds periods, restricted visibility, and the occurrence of inversions. Conversely, high wind speeds and good visibility are indicative of lapse conditions and good diffusion weather. The Columbus area experiences approximately 15 days on which a heavy fog occurs for a few hours. Visibility is reduced to below 6 miles approximately 43 per cent of the hours annually. For just fog, it is reduced to below 6 miles approximately 8 per cent of the time.

Inversions form nearly every night, but there is nothing in the records which could be interpreted to signify that the Columbus area experiences an unusual amount of poor atmospheric stability conditions.

APPENDIX C

CONCLUSIONS OF GEOLOGY AND HYDROLOGY REPORT

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CONCLUSIONS OF GEOLOGY AND HYDROLOGY REPORT

The conclusions of a report* on the geology and hydrology of the Battelle site are reprinted here. This report appears in full in a previous hazards report on the critical assembly.**

"The Battelle site seems to be almost entirely safe for the operation of a nuclear power reactor, with respect to the effects on the ground water resources resulting from accidental spillage of radioactive fluids in the site area. In the event of a spill, most of the liquid would flow overland to Darby Creek. Only a small portion would infiltrate the soil and seep downward to the water table or reach the principal artesian aquifer.

"Infiltration would be greatest when the soil is dry, especially during periods of large soil moisture deficiency, such as would occur during the growing season. Conditions least favorable for infiltration, and those which would promote most rapid runoff, would result from frozen or saturated ground, or would occur during a heavy rainstorm when a large volume of water is flowing overland towards Darby Creek.

"The course of a spilled liquid, once it reached the water table, also would be towards Darby Creek where it would discharge into the stream through springs and seeps. The shallow aquifer is unimportant as a source of water in the site area and the chances are almost nil under present conditions that a contaminant introduced into the shallow aquifer on the Battelle property would be diverted to wells or otherwise intercepted by man in the course of its slow underground journey to the discharge area.

"A greater chance for contamination of ground water supplies would result from radioactive fluid entering the principal aquifer in the site area. This danger is slight, however, for the principal aquifer receives most of its recharge in upland areas some distance west of the Battelle site. Only a relatively small amount of water percolates through the till to reach the principal aquifer in the immediate area of the site. Moreover, a contaminant reaching the principal aquifer in the immediate area of the Battelle property would already be down-gradient from almost all the wells in the area.

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* Norris, Stanley, "Hydrology of a Proposed Reactor Site Near Columbus, Ohio", U. S. Geological Survey, Water Resources Division, Columbus, Ohio (August, 1954).

** BMI-ACRS-600.

"Practically the only potential danger of contamination to a specific ground water supply is to the supply now being developed by the Battelle Memorial Institute near the southeast corner of their property. Pumping from the well now being drilled, and from possible future wells, would lower ground water levels in the principal aquifer in the immediate area of the wells. This would induce more recharge locally from the overlying till by creating a cone of influence which might encompass areas where the danger of contamination would be greatest. In view of this possibility a careful record should be maintained of the natural radioactivity of the water from the Battelle plant wells, to be used as a basis for comparison to detect any contamination should spillage occur.

"The greatest danger to human life and property resulting from spillage of radioactive fluid in the Battelle site area would be for the fluid to reach Darby Creek in volume and to move downstream in toxic concentration. Darby Creek is not now used either as a source of public or of large-scale industrial water supply, though it undoubtedly will be used eventually for both purposes. It is however, an important source of water for stock all along its course and it flows into the Scioto River above several important water supply developments, including the supply for the Atomic Energy Commission plant in Pike County.

"The velocity of flow in Darby Creek ranges from very low, when the stream is in pool stage and the only perceptible flow is over the riffles, to very high when the stream is in flood. The velocity of flow is important to any further evaluation of the fate of a spilled liquid once it reaches the stream and it should be studied under various conditions of discharge. Surface water samples should be collected and analyzed to determine the natural radioactivity of the stream, and the records maintained as a basis for future comparison."

APPENDIX D

HAZARDS CALCULATIONS

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HAZARDS CALCULATIONS

Dose Rates From Fall-Out From an Explosion Cloud

The term wash-out is here used to describe that condition in which continuous rain-out and fall-out from a radioactive cloud occurs as it drifts downwind from the origin. The fundamental assumption is that a constant fraction of the radioactivity in the cloud falls out per unit distance as the cloud travels downwind and that for each distance this fall-out rate is that which renders the dose a maximum at that point. Assuming uniform concentration of activity and correcting for attenuation, the dose rate may be expressed as*

$$D_r = \frac{2\sqrt{\pi}\,\alpha C_x}{\sigma} E_1\left(\frac{h}{\lambda}\right), \tag{D-1}$$

where

D_r = dose rate, r/(hr)(megawatt-sec)

α = unit dose rate per unit concentration on the ground, 0.57 E(mev), $\frac{r\text{-}m^2}{\text{curie-hr}}$

E = energy per disintegration, 0.5 mev

$C_x = \frac{C_o}{eX_o}$

X_o = distance from cloud origin to the point where the dose rate is being considered, m

C_o = activity of the cloud without fall-out but including decay at distance X_o, curies per megawatt-sec

σ = cloud radius at distance X_o, m

$$= E_1\left(\frac{h}{\lambda}\right) = \int_{\left(\frac{h}{\lambda}\right)}^{\infty} \frac{e^{-t}}{t}\,dt$$

*Fitzgerald, J. J., Hurwitz, H., Jr., and Tonks, L., "Method of Evaluating Radiation Hazards From a Nuclear Incident", KAPL 1045 (1954).

h = height above the ground that the dose is measured (1 m)

λ = attenuation length, 200 m.

The above equation overestimates the dose rate at all distances.

The value of the activity of the cloud at any time, assuming no fall-out, may be derived as follows: According to the empirical relationship of Way and Wigner* the rate of release of both beta and gamma energy after fission is $\cong 2.66t^{-1.2}$ mev per sec-fission for time between 10 sec and 100 days after shutdown. Hence, the rate of energy release in the cloud per megawatt-sec is

$$\frac{2.66 \times t^{-1.2} \times 3 \times 10^{16} \text{ mev/sec}}{\text{megawatt-sec}}$$

or

$$7.98 \times 10^{16}\, t^{-1.2} \frac{\text{mev/sec}}{\text{megawatt-sec}} ,$$

where

$$1 \text{ megawatt-sec} = 3 \times 10^{16} \text{ fissions.}$$

Hence,

$$C_o = \frac{7.98 \times 10^{16} t^{-1.2}}{0.5 \times 3.7 \times 10^{10}} \; \frac{\text{curies}}{\text{megawatt-sec}}$$

$$= 4.31 \times 10^{6} \times t^{-1.2} \frac{\text{curies}}{\text{megawatt-sec}} , \qquad \text{(D-2)}$$

where $0.5 \frac{\text{mev}}{\text{disintegration}}$ and $3.7 \times 10^{10} \frac{\text{disintegrations/sec}}{\text{curie}}$ are assumed.

If it requires time t_o for the cloud to reach X_o, the dose rate at X_o at time $t > t_o$ is given by

$$D_r(t) = D_r(t_o)\left(\frac{t}{t_o}\right)^{-1.2} , \qquad \text{(D-3)}$$

where $D_r(t_o)$ is the dose rate at X_o immediately after fall-out. $D(t, X_o)$, the accumulated dose at X_o over some time interval, $t_o < t < t_1$, is given by

$$D(t_1, X_o) = 5D_r(t_o)t_o \left[1 - \left(\frac{t_o}{t_1}\right)^{0.2}\right]. \qquad \text{(D-4)}$$

*Way, K., and Wigner, E. P., Phys Rev., 70, 115 (1946).

The value of the cloud radius, σ, at various distances downwind is obtained from the nomographs constructed by J. Z. Holland.

The results, giving the doses for various distances, stability parameters, and wind velocities, are shown in Figure 12.

Inhalation Dose From Radiactive Cloud

An observed receiving an internal dose from inhalation of a radioactive cloud from an explosion would be in danger of having the thyroid gland, bones, and lungs affected by the more hazardous fission products I^{131}, Sr^{89}, $Sr^{90} + Y^{90}$, $Ba^{140} + La^{140}$, $Ce^{144} + Pr^{144}$, and Y^{91}. The short-lived fission products will also damage the lungs.

Experimental work* has shown that the lungs retained about 50 per cent of the total small particles in the inhaled air. This 50 per cent factor will be assumed to apply to all fission products inhaled. The total activity resulting from the retention of radioactive isotopes in the lungs must be further reduced by an "effective" retention factor, f_o, which varies with the isotope and corresponding organ which is affected. The activity retained in an organ may be obtained from the equation

$$\frac{A(\text{millicuries})}{\text{megawatt-sec}} = (0.50)(16.8 \times 10^{-3}) f_o \frac{J}{v} \frac{Q}{V^{2/3}} , \qquad \text{(D-5)}$$

where

J = inhalation rate, 17 liters per min

v = cloud velocity, m per sec

Q = total curies of given isotope in the cloud at time of inhalation per megawatt-sec

$V = (\sqrt{\pi}\,\sigma)^3$, m^3

σ = radius of cloud at time of inhalation, m

f_o = effective retention factor.

The integrated lung dosage for the short-lived fission products is given by

$$D = \frac{88.6}{v\sigma^2} \left(\frac{v}{x}\right)^{0.2} \frac{r}{\text{megawatt-sec}} , \qquad \text{(D-6)}$$

*Landahl, M. D., and Tracewell, T. N., "On the Retention of Air Borne Particles in the Human Lung, II", TID 365.

where it is assumed that each disintegration in the lung leads to the absorption of 0.5 mev of energy in the lung tissue.

$$Q = f\, e^{-\lambda \left(\frac{X}{v}\right)} \lambda \frac{3 \times 10^{16}}{3.7 \times 10^{10}} \; \frac{\text{curies}}{\text{megawatt-sec}}$$

$$= 8.11 \times 10^{5}\, f\, e^{-\lambda \left(\frac{X}{v}\right)} \; \frac{\text{curies}}{\text{megawatt-sec}} \quad . \qquad \text{(D-7)}$$

Table 5 gives the important data for the hazardous isotopes of interest. The cloud radius at the time of inhalation was obtained from the nomographs constructed by J. Z. Holland.

The short-lived fission products were assumed to decay according to the Way-Wigner formula. The amount of activity from this source is given by Equation (D-6), where

$$Q = 2.16 \times 10^{6} \left(\frac{v}{X}\right)^{1.2} \frac{\text{curies}}{\text{megawatt-sec}} \quad . \qquad \text{(D-8)}$$

Energy Release

Instantaneous Reactivity Additions

The analysis presented here is an attempt to estimate the fission energy release after an instantaneous addition of reactivity. It is postulated that the reactivity is decreased only by core expansion caused by internal pressure buildup due to vaporization of fuel. The vaporization of fuel is assumed to begin after sufficient energy has been supplied to heat all of the fuel to the boiling temperature. If the core contains 10 kg of fuel, the energy required to reach the boiling temperature is 6.76 megawatt-sec. An additional 16.5 megawatt-sec would vaporize the fuel. The model chosen is a spherical reactor with reflector.

The equations which were used to define the physical model are as follows:

$$\Delta R(t) = \frac{2\lambda}{\rho R} \int_0^{t} \int_0^{t'} P_o\,(t'')\, dt''\, dt' , \qquad \text{(D-9)}$$

$$\frac{dP(t)}{dt} = \frac{\Delta k_p(t)}{\ell} P(t) , \qquad \text{(D-10)}$$

$$\Delta k_p(t) = \Delta k_o - \alpha_1 \Delta R(t) , \tag{D-11}$$

$$\frac{dN(t)}{dt} = \left[\frac{N_o - N(t)}{N_o}\right] \frac{P(t)}{\Delta H_v} , \tag{D-12}$$

$$p_o(t) = \left[p*(t) - p*(o)\right] \alpha_2 , \tag{D-13}$$

$$p*(t) = \frac{\overline{R} N(t) T(t)}{V(t)} , \tag{D-14}$$

$$\frac{dT(t)}{dt} = \frac{P(t)}{C_v N_o} - \frac{\overline{R}\ T(t)}{C_v} \left[\frac{1}{V(t)} \frac{dV(t)}{dt} - \frac{1}{N(t)} \frac{dN(t)}{dt}\right] . \tag{D-15}$$

$$\frac{dV(t)}{dt} = 4\pi R^2 \frac{d\Delta R(t)}{dt} , \tag{D-16}$$

where

t = time after vaporization begins, sec

$\Delta R(t)$ = radial distance core-reflector interface changes as a function of time, cm

R = initial effective radius of core-reflector interface, 36.8 cm

$p_o(t)$ = pressure above atmospheric pressure at center of core at time t, atm

ρ = mean density of core

$P(t)$ = reactor power at time t, megawatts

$\Delta k_p(t)$ = prompt excess multiplication at time t = $k_{eff}(1-\beta) - 1$

k_{eff} = effective multiplication factor

ℓ = mean neutron generation time, sec

Δk_o = initial value for $\Delta k_p(t)$

α_1 = core expansion reactivity coefficient, cm^{-1}

$N(t)$ = number of g-moles of uranium-235 in gas phase at time t

N_o = number of g-moles of uranium-235 in core

ΔH_v = heat of vaporization, megawatt-sec per g-mole

$p^*(t)$ = average gas pressure in core at time t, atm

$T(t)$ = temperature of gas phase at time t, K

$V(t)$ = volume of gas phase at time t, liters

$\overline{R}$ = gas constant, $\frac{\text{liter-atm}}{\text{g-mole/K}}$

C_v = heat capacity of gas phase at constant volume, $\frac{\text{liter-atm}}{\text{g-mole/K}}$ or $\frac{\text{megawatt-sec}}{\text{g-mole/K}}$.

Equation (D-9) is an approximate solution of the equation of motion for mass particles in the core. This equation is obtained in a manner similar to that employed by Mills*, except the pressure variation in time is not assumed to be known. The parameter λ, following Mills, is taken to be 1/3.

Equation (D-10) relates the rate of power rise with the multiplication and power at time t. It is approximate in that delayed neutrons are neglected, but since prompt critical conditions are of interest this is not serious. The mean generation time, ℓ, was calculated to be approximately 3.6×10^{-5} sec.

Equation (D-11) relates the core expansion to the reactivity. The coefficient α_1 was calculated to be 0.0224.

Equation (D-12) relates the rate of vaporization of fuel to the power level and the number of moles already vaporized. The values of N_o and ΔH_v are 42.5 moles and 0.389 megawatt-sec per mole, respectively. It is assumed that only fissions which occur in the solid phase are effective in vaporizing fuel. The fissions occurring in the dense gas phase are assumed to increase the internal energy of the gas.

Equation (D-13) relates the pressure at the core center to the average pressure in the gas core. The constant α_2 was calculated to be 1.25.

Equation (D-14) is the perfect gas law and Equation (D-15) is an energy balance for the gas phase. Equation (D-16) is an approximate equation relating the rate of gas-volume change to the core expansion.

*Mills, M. M., "On the Hazards Due to Nuclear Reactors", Reactor Science and Technology, p 55.

Equations (D-9) and (D-16) were solved by means of an electronic operational analog. The initial conditions were chosen so that for a given value of Δk_o, the power level was such that 6.76 megawatt-sec had already been supplied, i.e.,

$$P(o) = 6.76 \text{ megawatt-sec} \left(\frac{\Delta k_o}{\ell} \right).$$

The transient was terminated when $k_p(t) = 0$ and the fission energy of the transient was obtained. The results of several determinations of the energy release for different values of Δk_o are noted in Figure 18.

Gradual Reactivity Addition

The energy release for the case of maximum rate of reactivity addition upon closure ($3.20/sec) was calculated as follows: An approximation for the inverse period, p, when an energy E has been generated is

$$p^2 = \frac{2}{\ell} \frac{dk}{dt} \ln \frac{Ep}{P_o \, 10^2} , \qquad \text{(D-17)}$$

where

$\frac{dk}{dt}$ = rate of reactivity addition, sec^{-1}

E = 6.76 megawatt-sec

P_o = startup power, megawatts.

Taking $\frac{dk}{dt}$ equal to 0.021 Δ k/k per sec and $P_o = 5 \times 10^{-10}$ megawatt, it is found that $p = 169 \text{ sec}^{-1}$ and this corresponds to an instantaneous addition of $\Delta k_p = 0.00610$. Approximately 1 millisecond is required to disassemble the core after E = 6.76 megawatt-sec for this case and hence the reactivity added during this time is negligible. Consequently, Equation (D-17) may be used in conjunction with Figure 18 in order to estimate the fission-energy release for the addition of reactivity upon closure.