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SUMMARY REPORT ON THE HAZARDS OF THE ARGONAUT REACTOR

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DISCLAIMER

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TABLE OF CONTENTS

4

TABLE OF CONTENTS

TABLE OF CONTENTS

Page

APPENDICES

LIST OF FIGURES

SUMMARY REPORT ON THE HAZARDS OF THE ARGONAUT REACTOR

D. H. Lennox and C. N. Kelber

I. SUMMARY

This report covers installation of an Argonaut Reactor at the DuPage site of the Argonne National Laboratory. The reactor is to be operated by trained members of the staff, assisted by other laboratory personnel, and by students at the International School of Nuclear Science and Engineering, as a facility for nuclear engineering training and research. The design anticipates use of an Argonaut reactor in universities and in other less specialized institutions. Therefore, safety is a prime design feature through choice of a self-limiting system.

The present design is the result of theoretical work that has been supplemented and extended by a series of multiplication experiments on the proposed configuration. It is expected that minor design improvements will be suggested from time to time to utilize new opportunities for cost reduction and requests for specialized experimental facilities.

Argonaut is a 10-kw (max.) thermal reactor moderated by water and reflected by graphite. Plate-type fuel elements are spaced with graphite wedges to form an annular core. The total fissionable material required is about 4 kg U^{235}. The experimentally determined void coefficient for the lattice is negative: -0.25% k per void per cent. The temperature coefficient is also negative. -10^{-4} k/C. Excess k is less than 0 75%. Rapid insertion of up to 4.75% k_{ex}, possible only by deliberate circumvection of procedures, interlocks, trips, and controls, will result in automatic shutdown through a non-destructive BORAX-type process. This postulated situation will not result in over-exposure of personnel near the reactor or contamination of the immediate vicinity. Complete release of fission products contained within the fuel plates by some process not easily imagined would require an exclusion radius of 875 ft, assuming no building containment.

This report does not consider internal multiplicative experiments which could be performed by reloading the internal reflector. Such experiments must be subject to a separate hazards review.

II. GENERAL DISCUSSION

A. Design Criteria

The requirements of the International School of Nuclear Science and Engineering coupled with research experience at Argonne National Laboratory have clearly indicated the Laboratory's need for a low-level supplementary reactor facility. The disassembly of CP-2, the heavy demands for use of CP-5, and the general unsuitability of CP-5 for a variety of experiments in reactor physics motivated the design of a versatile low-power reactor whose experimental scope would make it useful both for training and for conduct of experiments in reactor physics.

1. The reactor as constituted must be usable in a great variety of experiments.
2. Anticipating interest in this type of facility on the part of universities with a variety of space and program requirements, the reactor must be flexible.
3. For the same reason, low cost is desirable to make the reactor available to small institutions.
4. Use as a training facility makes it more imperative that special attention be given to safety consideration.

B. Description of the System

Argonaut is a thermal reactor consisting of an annular core reflected internally and externally with graphite (Fig. 1). The core is heterogeneous; the fuel elements consist of BORAX-type fuel plates in assemblies 3 x 6 in. The moderator in and immediately surrounding the fuel element is light water with graphite moderator pieces between the elements. The critical loading of the system is about 4 kg U^{235} at 20% enrichment. The reactor will normally operate in the range of 1 to 100 watts. It can be operated continuously at 1 kw and is capable of operation at a maximum of 10 kw of thermal power, at which level its negative temperature coefficient would shut the system down after a brief running period. For such intervals, thermal neutron fluxes of 10^{11} n/(cm^2) (sec) are available.

C. Nuclear Characteristics

The nuclear characteristics of Argonaut are similar in many respects to those of LITR, MTR, BSTF, and BORAX. It shares with these reactors the use of water as the principal moderator and the containment of fuel (and, consequently, of fission products) in aluminum plates. The annular core geometry and graphite reflectors peculiar to Argonaut account for a somewhat longer neutron lifetime than in the aforementioned systems. The use of light water as principal moderator makes for a large negative

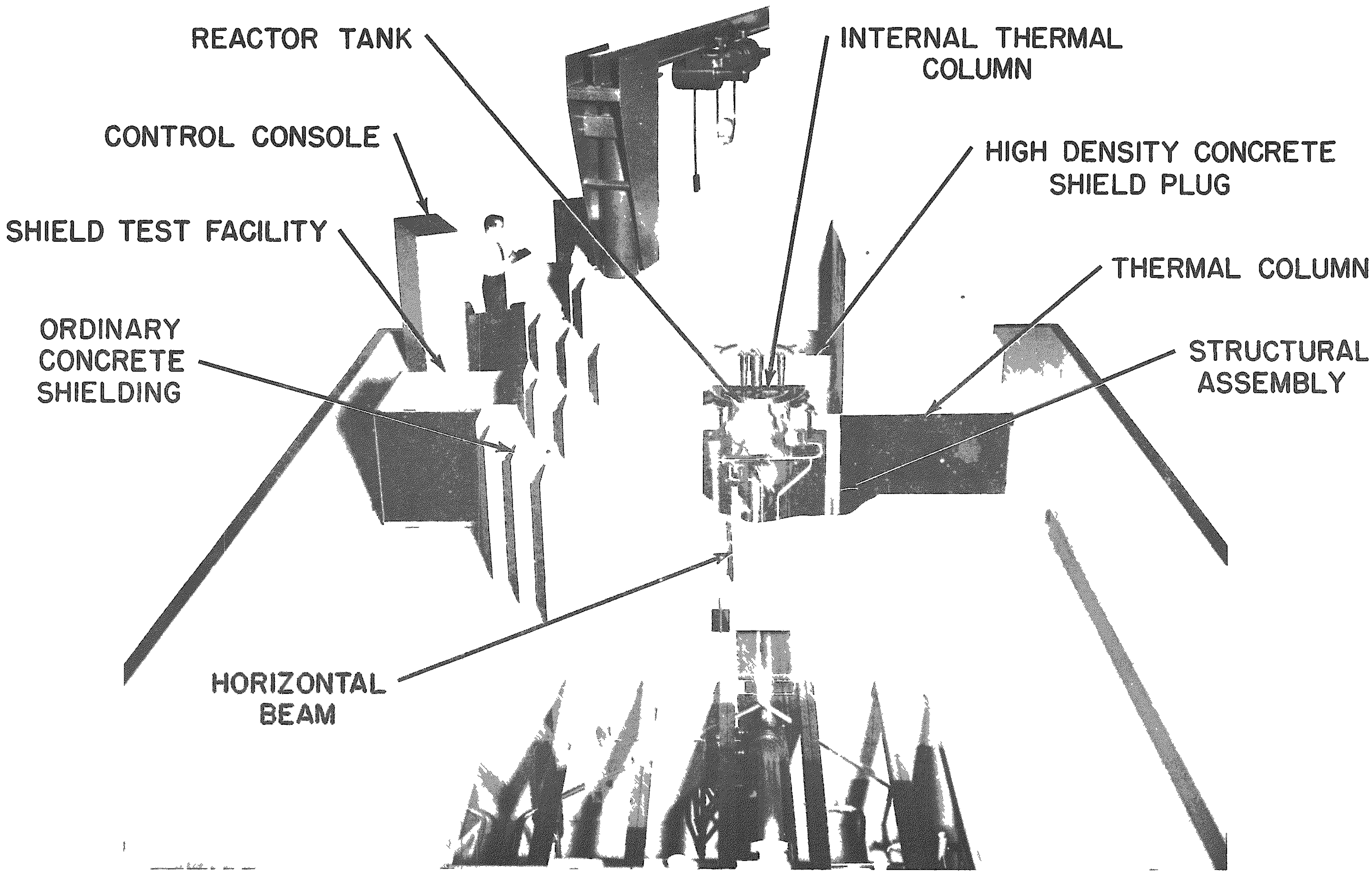

Fig. 1

CUTAWAY MODEL OF ARGONAUT REACTOR

void coefficient provided that not too large a fraction of thermal neutrons are captured in the water. Interstitial water between fuel elements which presumably is the cause for positive void coefficients, sometimes observed in similar reactors, has been avoided by the use of graphite separators.

The critical properties of Argonaut, including void, geometric, thermal, and control effects, were determined by extrapolation from an extensive series of multiplication experiments (see Appendix A). The results are summarized in Table I.

The large negative void coefficient means that a rather large increase in reactivity will be removed by voids introduced through boiling. The reactor finally shuts down when enough water has been lost. The negative temperature coefficient combined with a low circulation rate and cooling capability is sufficient to prevent a slow, steady increase in power level. The same considerations limit the use of the reactor at high power (10 kw), since inevitably there will be a gradual temperature increase at such a power. The prompt neutron lifetime ($\sim 1.9 \times 10^{-4}$ sec) is longer than that of BORAX, since the Argonaut system is better reflected; consequently, the reactivity which must be added to achieve a given period is greater. It is estimated that an instantaneous insertion of 4.75% excess reactivity is required to achieve a period which will make Argonaut suffer a destructive expulsion of water.

D. Experiments to be Performed

One of the principal design criteria for Argonaut was that it be capable of a wide variety of experimental set-ups. Briefly, these capabilities can be enumerated as:

1. External exponential experiments may be performed on the top of the reactor (with the top shield plug removed), or in a water-tank facility on the side of the reactor. The top of the reactor was designed free of protuberances for this reason.

2. Fuel studies, such as reactivity, microscopic flux mapping, etc., can be made in the internal reflector. Similarly, cross sections and reactivity effects can be studied by oscillation and danger coefficient measurements of samples inserted in the central thimble. The internal reflector can be removed and an internal exponential assembly inserted. This, in general, will call for a new safety study since it converts the reactor to an entirely new type. Once this is accomplished and the various requirements are met, it will be possible to carry out a programmatic investigation.

3. Shielding and irradiation effects can be studied in the water tank facility. Migration studies in moderators can also be made in this tank.

4. Irradiations can be carried out in the external thermal column which has a total of 15 beam holes.

5. Instructional reactor demonstration experiments can be performed: multiplication experiments on subcritical loadings; kinetic studies; reactor perturbations; etc.

Table I

SUMMARY OF REACTIVITY CHANGES IN ARGONAUT

Configuration: Two groups of six clusters each, symmetrically arranged (see Fig. 2).	
Critical mass:	3.748 kg U^{235}
Void introduced into fuel cluster:	-0.25% k/% void
Replace graphite with water at edge of fuel cluster:	-1.4×10^{-4}% k/cc water
Bubbles from gas injection system introduced into one fuel cluster:	-0.09% k
7 x 7 in. cadmium sheet centered on fuel mid-plane next to reactor tank:	-3.1% k
24 x 3 in. cadmium sheet:	
Next to tank	-3.7% k
1.5 in. away from tank	-2.7% k
3 in. away from tank	-1.9% k
Removal of stringer from internal reflector	-0.22% k
Insertion of U^{235} at center of internal reflector	+0.026% k/gm
1 x 1 in. cadmium sheet at center of internal reflector	-0.11% k
Insertion of U^{235} next to outer tank	+0.022% k/gm
Fuel box displaced vertically 1 ft.	-3.2% k
4 x 6 in. void next to outer tank, 36 in. high	- 2.2% k
Rise in temperature	-1.065×10^{-4} k/C
Critical mass as a function of fuel box separation:	
Two groups of six boxes each	3.748 kg
Four symmetrical groups of three boxes each	>5.2 kg
Three symmetrical groups of four boxes each	4.6 kg
Slab loading on one side (8 boxes)	2.2 kg
Homogeneous loading with 3-inch annulus on a 2 ft I.D.	4.3 kg
Critical Mass as a function of plate spacing (experimental data taken on slab loading)	
Plate spacing: 1/8 in.	3.4 kg
2/8 in.	2.2 kg
3/8 in.	2.7 kg

In addition, it was observed that a void space between fuel boxes gave a greater reactivity than when the void was filled with water. It was ascertained in the experiments that the sign of the uniform void coefficient, even without the graphite spacers, is negative.

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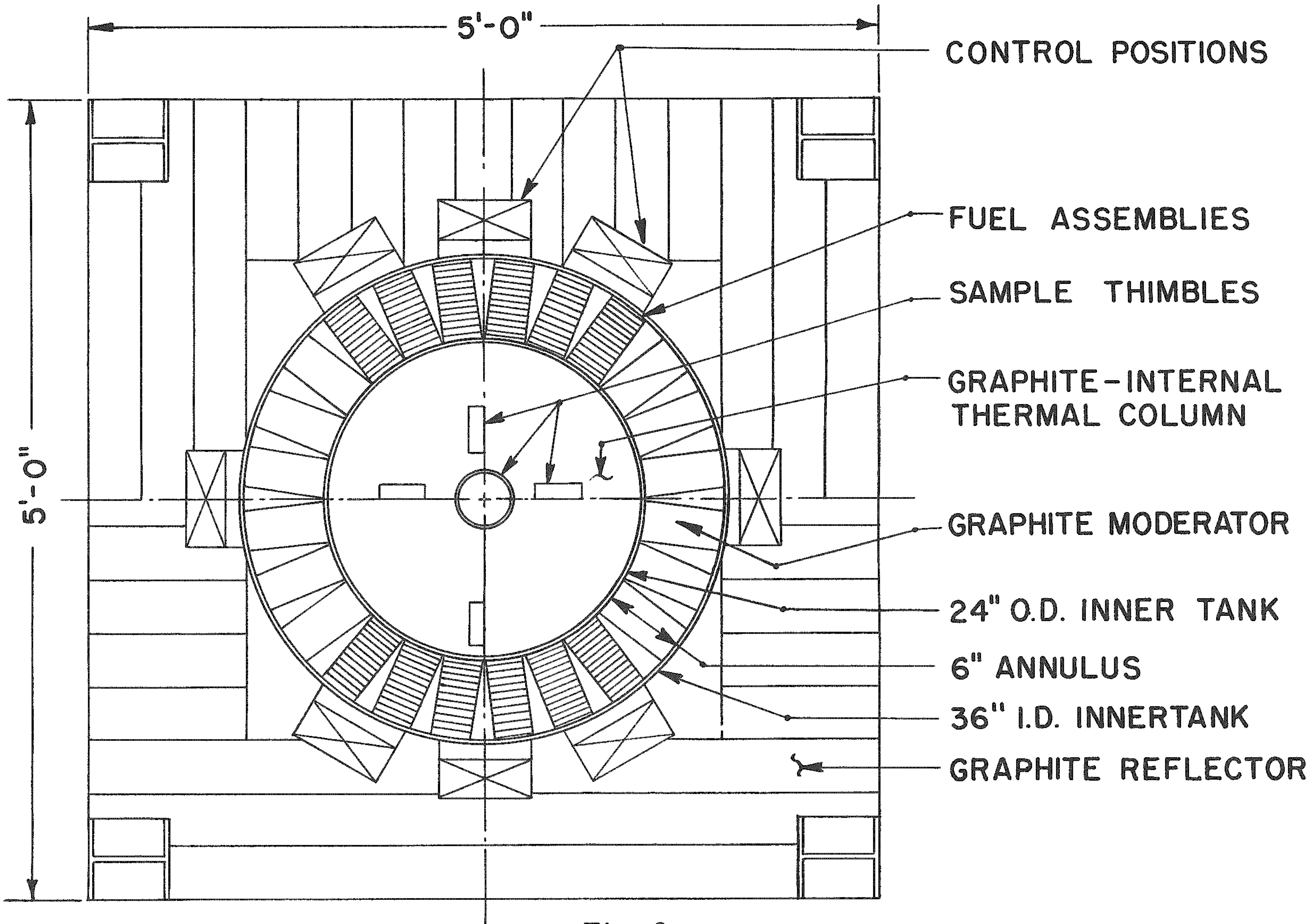

Fig. 2

PLAN SECTION OF CORE LATTICE AND REFLECTOR

III. DESCRIPTION OF FACILITY

A. Site

The Argonaut reactor site is in the east section of the Argonne National Laboratory. The pertinent characteristics of this region have been compiled in a number of previous safeguard reports with only minor changes from year to year. Data from the most recent report[1] is reproduced here (Fig. 3) with two modifications: (1) the addition of a Nike Station; and (2) the change in center of distance contour lines corresponding to a reactor site in the eastern sector of the Laboratory. As described in Appendix F, the site is drained by several small creeks; one of these, Saw Mill Creek, comes to within four hundred feet of the reactor site. This creek drains directly into the Des Plaines River after leaving the Laboratory Site; it does not pass any inhabited areas enroute.

The population make-up of the surrounding area is given in Appendix G. The nearest population center not under direct laboratory control is the Nike Station whose point of closest approach to the reactor is 1650 ft. The next nearest population center is more than $1\frac{1}{2}$ miles distant.

B. Reactor Building

The reactor building (Fig. 4) is located in an unclassified area on the Laboratory site.

Standard prefabricated metal construction methods were used with no effort made to make the building gastight beyond that required for normal protection from the weather. The 24-gauge, galvanized steel walls are insulated with a 1-in. layer of Fiberglas. An aluminized-vinylfilm coating protects the inside surface of the insulation.

The over-all dimensions are 40 x 60 ft (base) with a 21-ft peak roof height. The floor slab is 8 in. thick concrete reinforced with No. 4 welded wire mesh (4 x 4 opening). Compacted Grade 14 crushed stone is used for back fill. The maximum soil bearing is 2000 lb/sq ft. Figure 5 is a floor plan of the reactor, tank pit, and service trenches.

Two roll-up doors (12 x 12 ft), one at each end of the building, provide access for material. Both doors are operated by hand chain inside the building. Personnel access is through two industrial-type, single-hinged metal doors (3 x 7 ft). Triple windows (5 x 4 ft) are installed on 20-foot centers on each side of the building.

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[1] H. H. Hummel, et al, "Summary Report of the Hazards of the Internal Exponential Experiment," ANL-5547 (March, 1956)

15

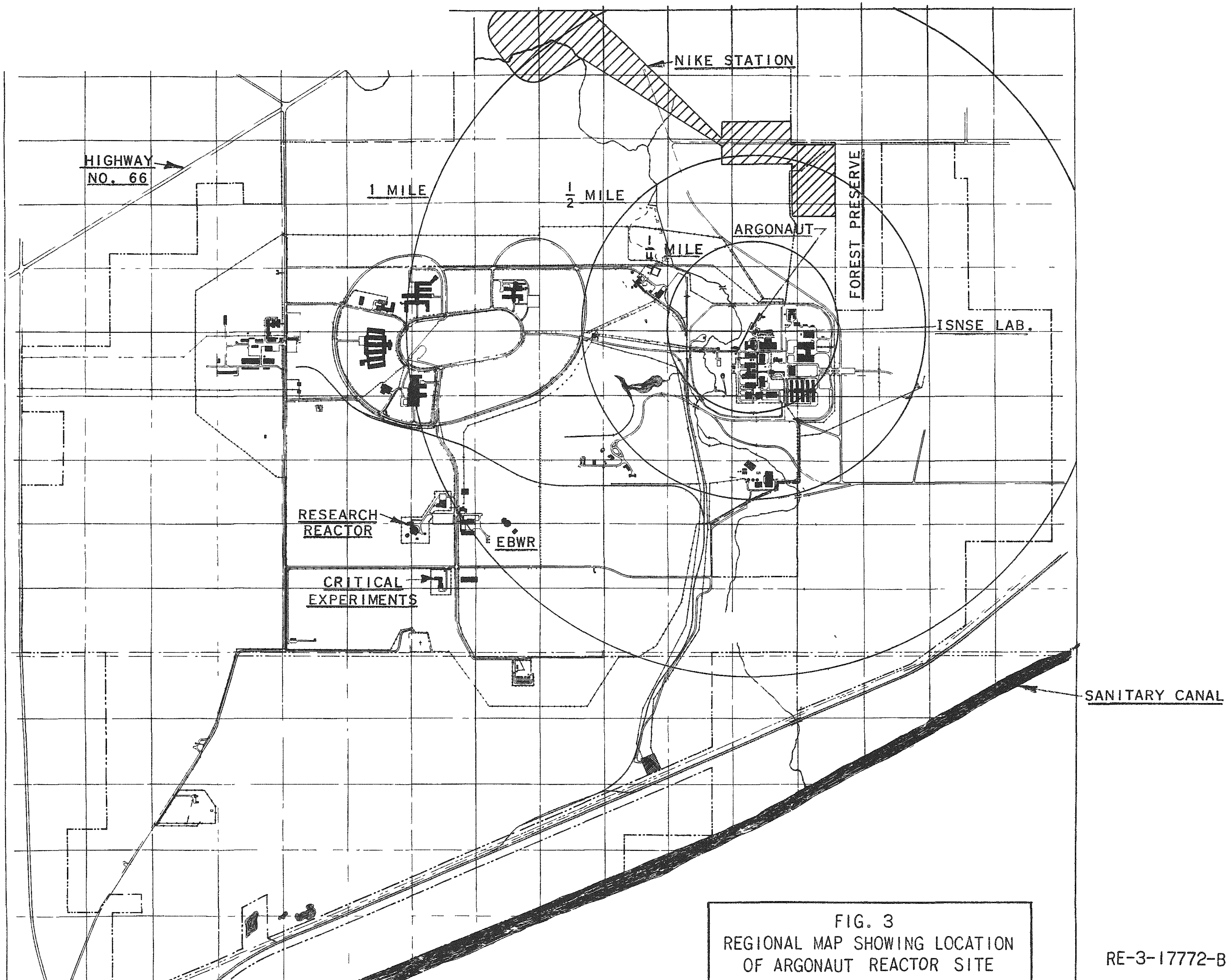

FIG. 3
REGIONAL MAP SHOWING LOCATION
OF ARGONAUT REACTOR SITE

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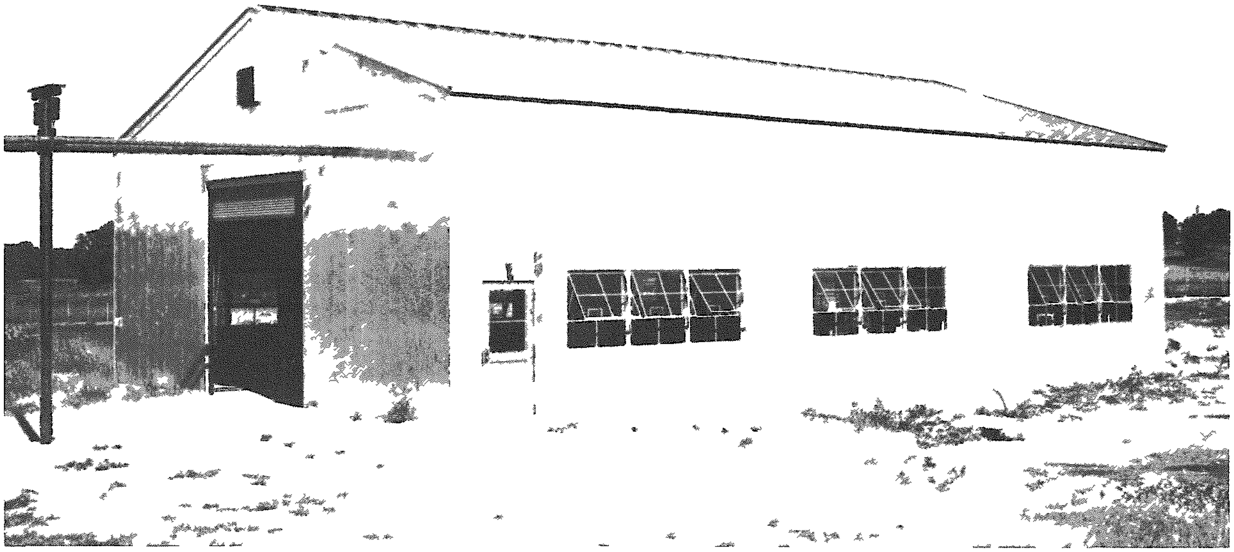

Fig. 4

REACTOR BUILDING

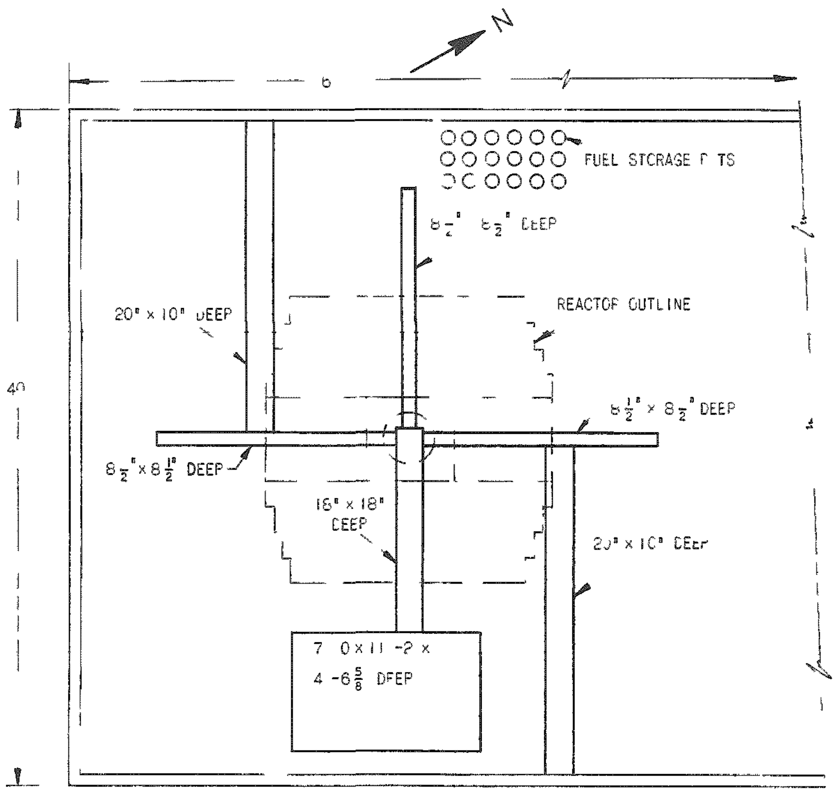

Fig. 5

ARGONAUT FLOOR PLAN

To adapt the building for reactor use, exhaust fan louvers are interlocked to close automatically if the radiation level within the building exceeds tolerance. Also, floor drains are isolated from other sewer systems in the area. Stability of the structure against internal pressure is discussed in Section V.

Building service facilities include:

1. Two 4900-cfm exhaust fans equipped with automatic louvers.
2. Two Modine steam heaters each capable of 230,000 Btu/hr output.
3. One 45-kva, 3-phase, 60-cycle power transformer wound for 440/208Y/120 volts.

C. Reactor Components

1. Internal Thermal Column

Graphite contained in a watertight aluminum tank open at the top provides a reflector and experimental region in the center of the reactor. A right cylinder (2 ft OD by 4 ft high) is made from 4-in. square pieces of graphite banded and machined on the surface. The column has five full-length removable stringers as shown in Fig. 6. For larger experiments, the graphite cylinder can be removed completely as a unit, or partially by removal of individual 4 x 4 in. sections. These changes require prior fuel unloading from the annulus, whereas use of the experimental stringers provided does not.

The graphite used in the internal thermal column as well as other parts of the reactor was salvaged from CP-2. Various grades ranging in diffusion length from 40 cm to 51 cm were originally used in CP-2; however, in some cases, the code designations were obliterated with the passage of time. Sorting the best material for Argonaut resulted in an average diffusion length of approximately 50 cm.

2. Inner Tank

The inner tank is welded 6061-T4 aluminum (2 ft dia., 1/16 in. wall thickness). It is firmly centered and supported by eight structural members ($1\frac{1}{2}$ in. high) welded to the bottom plate of the outer tank.

3. Outer Tank

The outer tank is 3 ft in diameter. It is made of the same material as the inner tank, but of 1/8 in. wall thickness. Both tanks are 4 ft high and open at the top. The bottom plate of the outer tank is 1/2 in. thick and is the reference plate for alignment of other components.

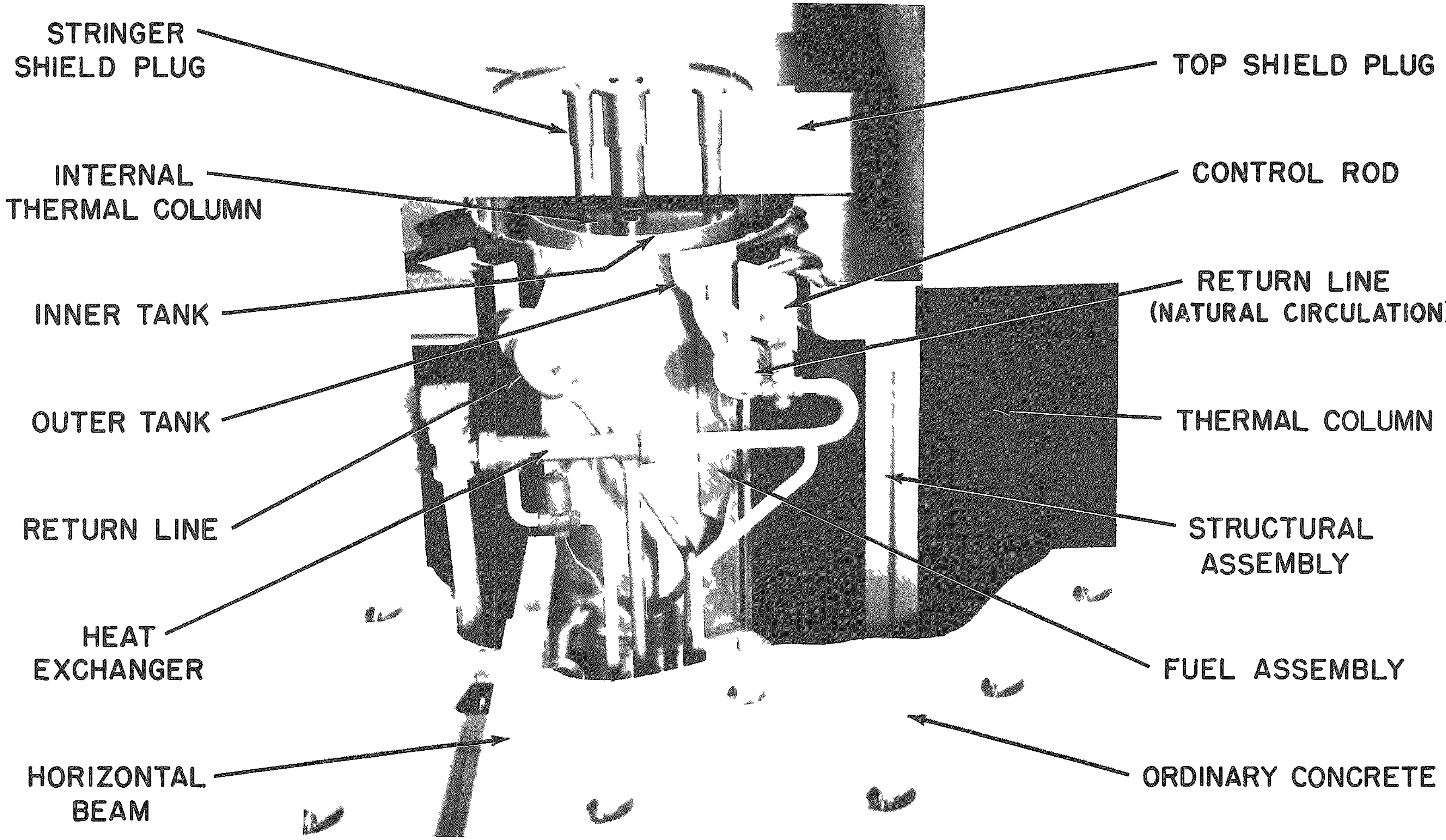

FIG. 6
CLOSE - UP VIEW OF REACTOR

Four water circulation lines are welded to the tank. The dump line is welded to the center of the bottom plate. The water inlet, a 2-inch aluminum line, is welded to the tank side wall close to the bottom. Water outlets for two different types of circulation are similarly attached near the top of the tank side wall.

4. Fuel Region

The reactor core is loaded into the annulus formed by the inner and outer tanks (Fig. 2). The way in which fuel is arranged strongly affects the critical mass. Uniform distribution around the annulus gives a maximum critical mass, while a "slab" loading gives a minimum. The standard loading, which is a compromise to preserve symmetry, consists of two groups of fuel diametrically opposed. Higher order symmetries require more fuel.

The fuel loading is extremely flexible in principle. The annulus contains 24 graphite wedges outlining a like number of spaces of 3 x 6 in. cross section. Theoretically, each of these spaces could be filled with fuel boxes or graphite blocks of equal cross section. In practice, any given loading is governed by the method used for support. The standard loading, which consists of alternate groups of 6 fuel assemblies and 6 graphite blocks, is used as an example. This loading has been tested extensively in multiplication experiments. Other loadings may be achieved by manufacturing new supporting members, and are no less safe if tested by subcritical multiplication measurements.

The fuel assemblies, graphite dummies, and wedges are 24 in. high and are centered vertically in the annulus. A group of seven wedges, with two graphite filler blocks on the ends, are attached to a strip of aluminum running across their bottom ends. This strip maintains proper clearances and also serves to support fuel assemblies. The wedges are supported individually by aluminum straps which are hung over the outer tank wall. The filler blocks are similarly hung from the inner tank wall. Two such assemblies are diametrically located in the annulus. The spaces between may be filled with graphite wedges and dummy blocks hung from the tank; however, if a fuel assembly were inserted, it would slip to the tank bottom, giving a clear indication of misloading.

The fuel clearances are such that, although rattling of a fuel box in its proper place is strongly inhibited, the absence of a bottom support is readily sensed

The hanging of the graphite filler blocks on the inner tank ensures that the removal of the internal reflector must be preceded by unloading of the active region.

5. Graphite Core Pieces

The core contains 24 graphite wedges, each $1\frac{5}{8}$ in. at the base, 6 in. thick, 24 in. high, tapering to a blunt point. It also contains twelve graphite dummy blocks (3 x 6 x 24 in.).

When water is admitted to the fuel region the graphite filler pieces become submerged and hence must be waterproofed. As an inexpensive substitute for aluminum cladding, an aluminum-Krylon plastic spray-coat is used. Irradiation in CP-5 comparable to several years of operation of Argonaut caused no degradation of the coating.

6. Fuel Elements

Each complete fuel assembly box contains 17 aluminum-clad plates (Fig. 7). The over-all dimensions are 6 in. x 3 in. x 24 in. long. The plates are assembled with aluminum bolts at top and bottom. Dummy aluminum plates or graphite slabs can be substituted for fuel plates to vary the quantity of fuel per box. Spacing between plates is maintained by two Teflon washers (1/4 in. thick) attached to each end of the individual plates. This separation gives a metal to H_2O volume ratio of 0.4.

An inexpensive fabrication technique for making fuel plates containing 35 wt-% of 20% enriched U_3O_8 was developed by the Argonne Metallurgy Division. A hot extrusion of a mixture of U_3O_8 and 2S aluminum powder gives plates with negligible void volume and over-all dimensions of 0.098 in. thick by 24 in. long and 2.84 in. wide.

Aluminum powder and U_3O_8 in the proper ratio were placed in a $3\frac{1}{2}$-in. diameter vented aluminum can, heated to 483C, sealed and then extruded in a 400-ton horizontal press. The resulting fuel sheet, approximately 17 ft long, was cut into sections 2 ft long. A clad averaging 2 mils thick covered the plate except on the ends at the point of cutoff and at some scratch points along the surface. Exposed portions of the fuel matrix present no corrosion problems; however, a plastic spray is applied to stop fission recoils.

The uranium oxide content of each plate varies; those cut from the ends of the extrusion contain somewhat less U_3O_8 than the average. The composition of each plate is:

U^{235}	19.6 gm $\pm$ 10%
U_3O_8	114 gm
Al	248 gm

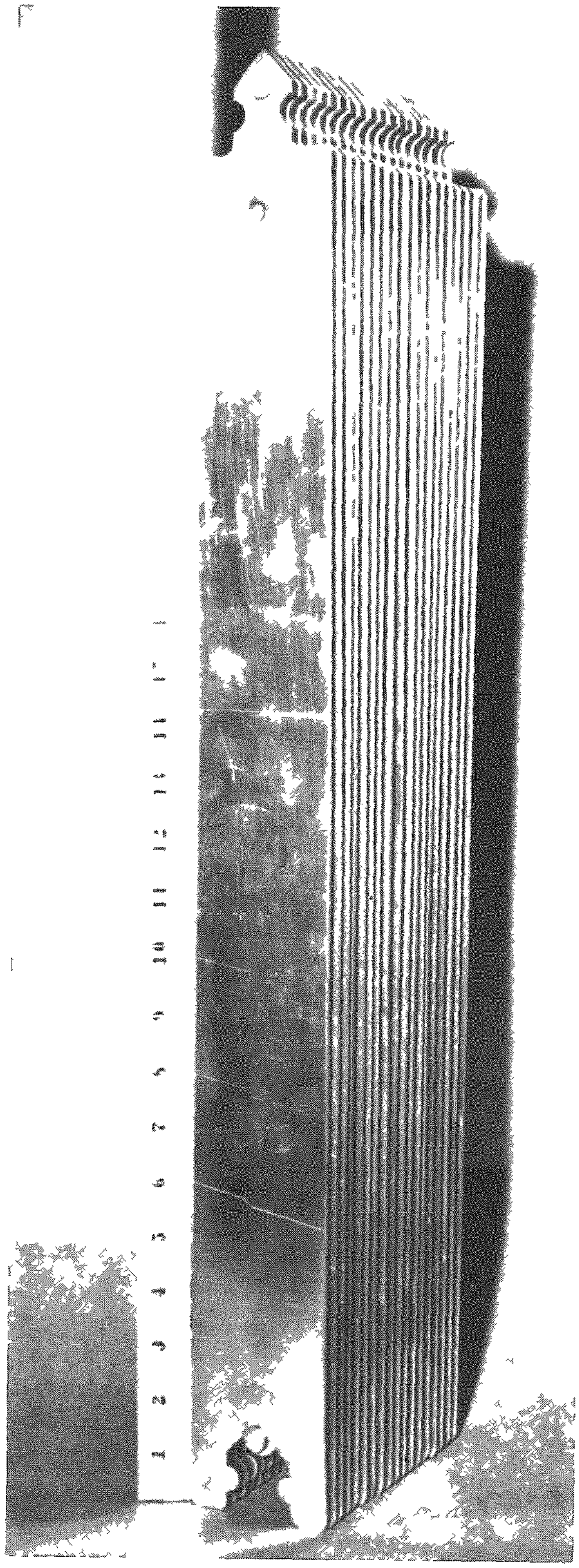

FIG. 7
FUEL ASSEMBLY

7. Reflector

The active core region is surrounded with graphite stacked to make a block 4 ft high and 5 ft square in cross section. This amounts to a minimum radial reflector thickness of 12 in. around the outer tank which contains the fuel. Cutouts in the reflector provide room for control rod sheaths, water lines and various cables. Slots in the top surface of the graphite provide low-pressure steam venting and water runoff should moderator boiling occur.

8. External Thermal Column

One side of the reactor reflector graphite is extended to make a thermal column 4 ft x 5 ft in cross section and 6 ft long. Assorted lengths of graphite 4x4 in. are stacked cross-wise, with slots for 15 removable horizontal stringers (Fig. 8). The column is shielded by concrete blocks.

9. Shielding

Stacked concrete block constitutes the main body of shield (Fig. 1) for reasons of cost and adaptability. Part of the top shield consists of a removable plug to simplify interlocks and to ensure accurate alignment. The shield thickness varies; at points needing maximum attenuation, seven feet is provided, with space for additional layers. Calculations show the present shield to be sufficient for 10-kw operation. The blocks are ordinary concrete; the top plug is high-density concrete.

10. Water Cooling System

Cooling water for the reactor is deliberately limited to prevent continuous operation at 10 kw. After several hours at the maximum power, the moderator temperature will have increased enough to exhaust the excess reactivity.

With reference to the flow diagram (Fig. 9), water is pumped from a 300-gallon aluminum storage tank through a shell-and-tube heat exchanger into the bottom of the reactor tank. Overflow through a 2-inch return line to the storage tank completes the cycle. The pump line can be bypassed through the heat exchanger to establish a thermal convection loop effective up to powers of 3 kw with a resultant moderator temperature of 150F.

A 3-kw electrical heater is in series with the heat exchanger for temperature experiments. This is normally controlled by a manual switch at the control console; but for coarse temperature control a thermal switch is provided to actuate the heater automatically. To ensure that the reactor will continue to heat up during a high-power run, the heater is energized automatically at powers above 1 kw.

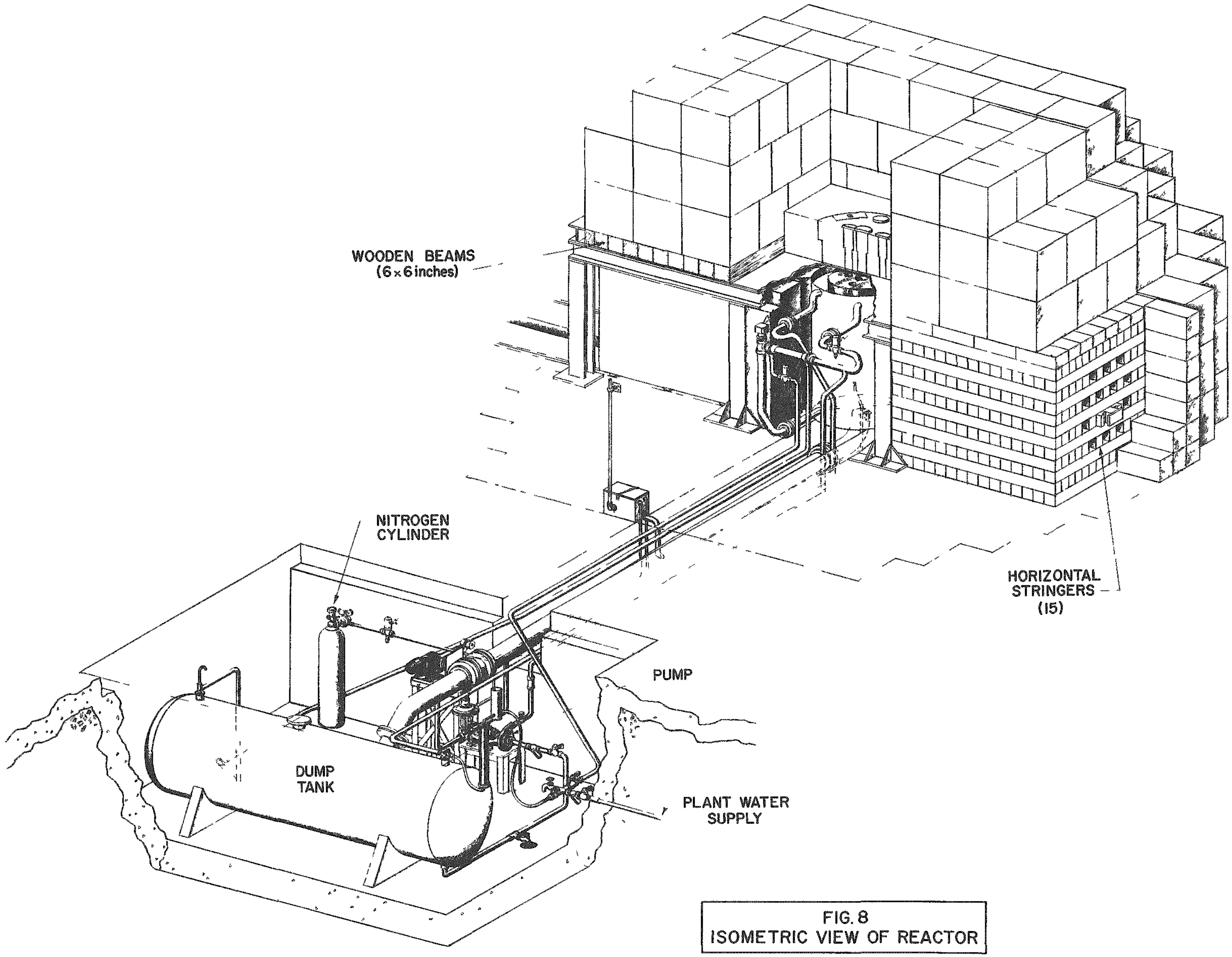

FIG. 8
ISOMETRIC VIEW OF REACTOR

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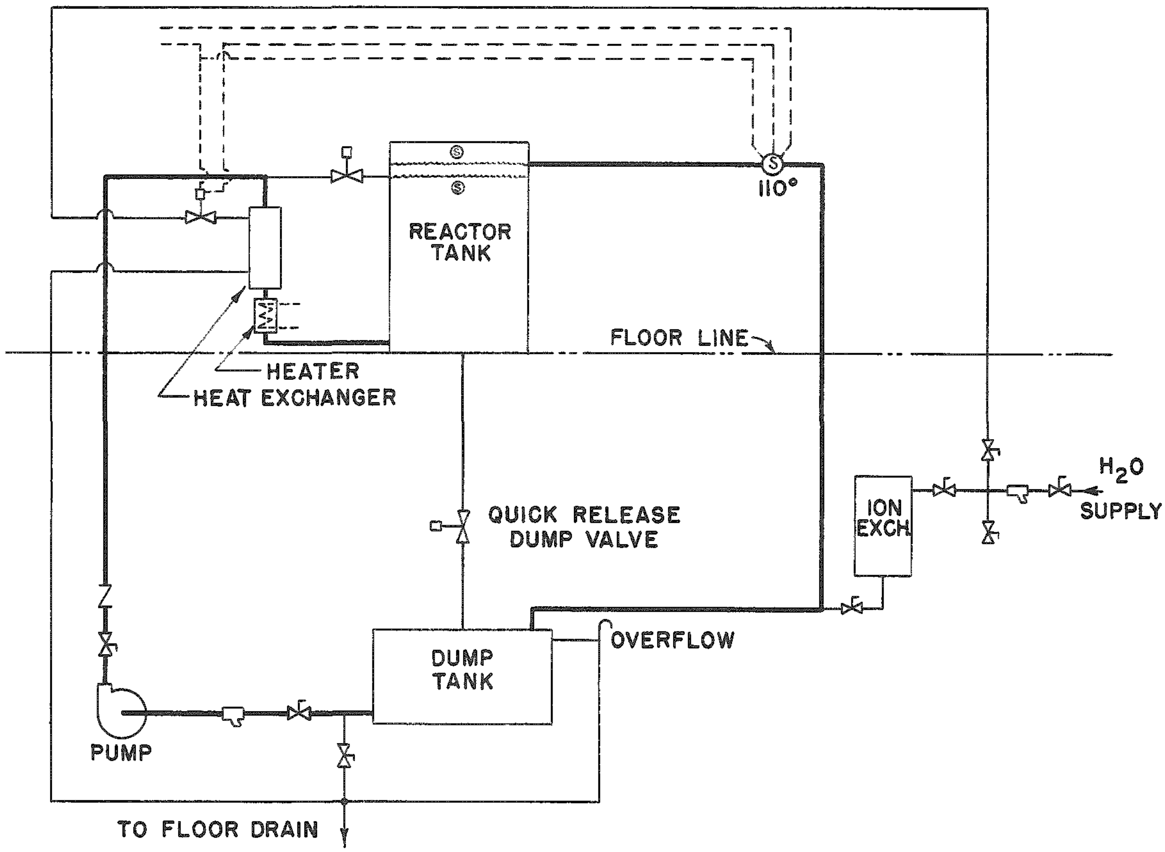


Fig. 9

SCHEMATIC FLOW DIAGRAM FOR ARGONAUT

Make-up water for the storage tank is added in batches through a laboratory-size ion exchange column. An overflow on the tank prevents backup into the reactor.

The rate at which water may be pumped into the reactor tank is limited to 10 gpm by the pump capacity and reduced to 3 gpm by a permanent restriction in the discharge line.

As part of the safety system, water can be drained from the reactor through a 6-inch dump line controlled by a quick-release flap valve. This valve is held closed with a magnetic clutch and opens automatically following a "scram" signal or power failure. The reactor tank empties in approximately 13 sec.

11. Start-up Source

An antimony-beryllium-photoneutron source is used to provide neutrons for start-up and multiplication measurements. The source is motor driven from a loading port outside the concrete shield in a trench under the reactor tank.

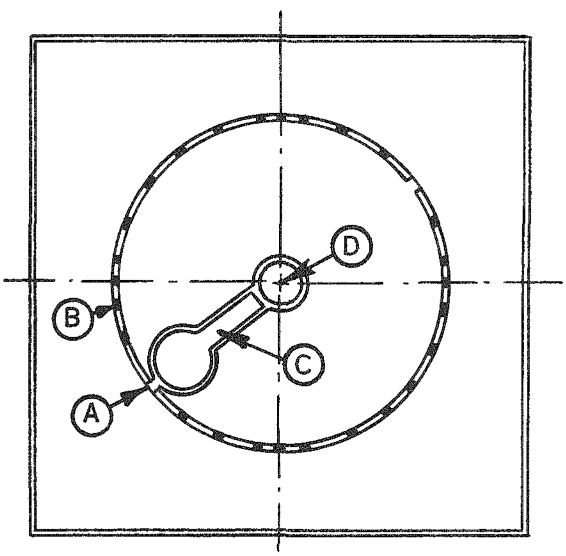
The antimony in the source is removable from the beryllium to permit rejuvenation in CP-5. An activity of $\sim 5 \times 10^8$ neutrons/second is obtained from a solid cylinder of antimony 1 in. OD x $1\frac{1}{2}$ in. long. The antimony is clad with aluminum, irradiated for 5 days in CP-5, and inserted in a 3-inch cube of beryllium.

12. Handling Equipment

A jib-type crane is installed in the floor within the reactor shield so that the jib arc reaches all blocks. The rated capacity is 1/2 ton at the end of the boom and 4700 pounds at a point 6 ft from the mast, corresponding to a position directly over the top shield plug. A portable lead coffin is used for transferring either fuel elements or antimony from the start-up source.

a. Top Shield Plug

A steel-clad, barytes concrete-filled slab ($61\frac{3}{8}$ in. x $61\frac{3}{8}$ in. x 1 ft thick) shields the top of the active region (see illustration).



LEGEND

A Index Key

B Index Slot

C Access to Fuel and Four Radial Experimental Holes

D Central Experimental Port

The slab is pierced with a stepped opening to accommodate a removable steel-clad, barytes concrete-filled plug ($39\frac{1}{2}$ in. diameter). The insert plug, in turn, contains unloading ports which can be indexed over any fuel or experimental port in the internal thermal column. During unloading operations the insert plug is raised with the jib crane, manually rotated to the desired position, and then lowered into the corresponding index slot.

b. Fuel Transfer Coffin

A multipurpose coffin with 6 in. lead shielding is used for fuel transfer. Removable inserts adapt the coffin cavity (3 x 6 x 24 in.) for handling the antimony source and for assembly of fuel elements.

The fuel unloading procedure is as follows:

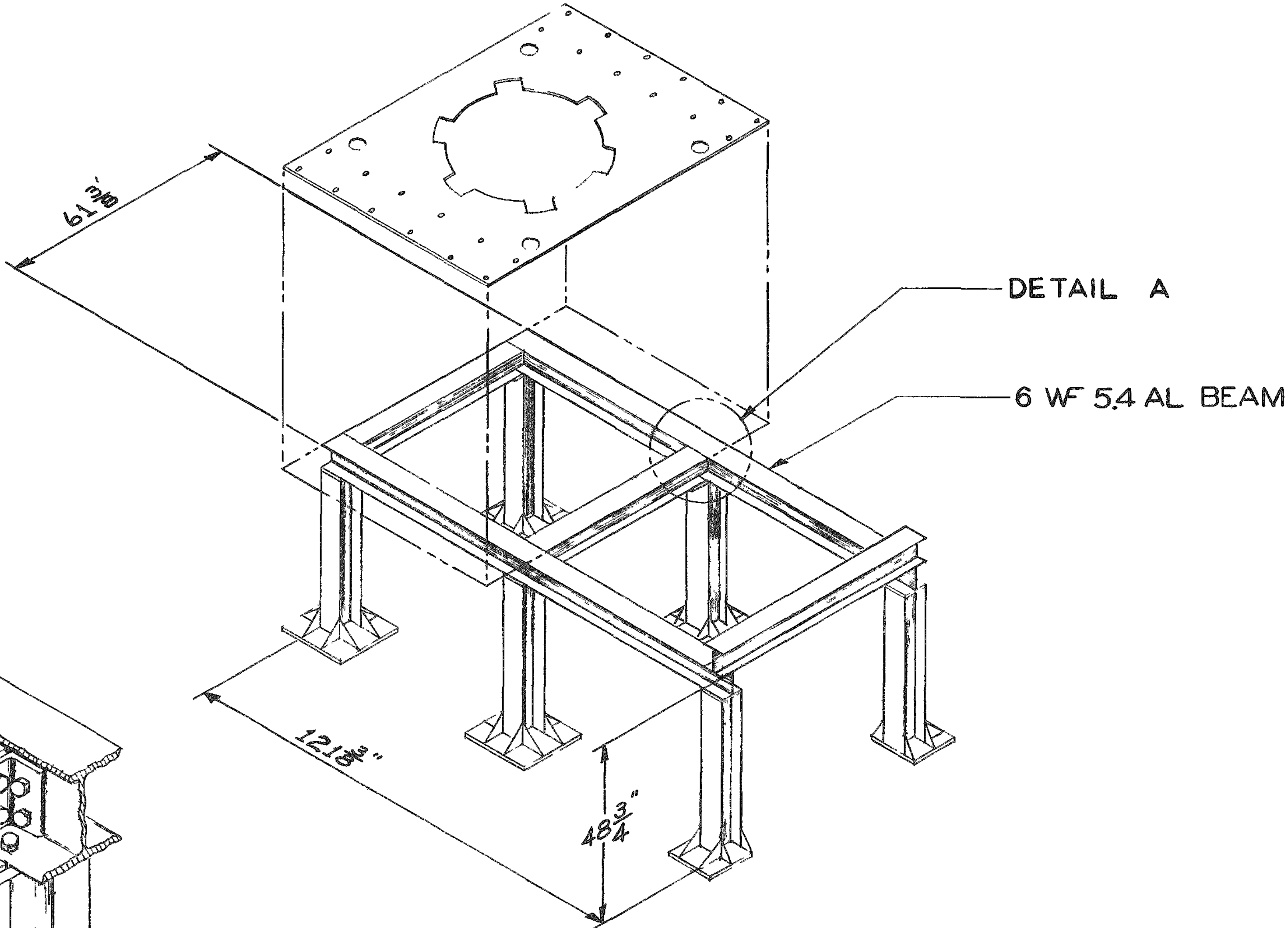
(1) The insert plug is raised, indexed, and lowered into position. The unloading port plugs are removed.

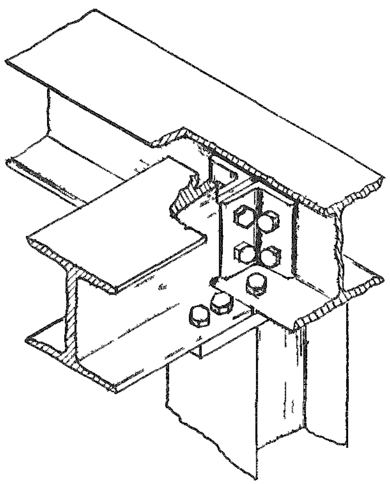
(2) The coffin is raised with the crane and positioned above the unloading port by alignment of a pilot at the coffin bottom with the index slot in the top shield.

(3) A grappling device within the coffin is lowered to grasp and lift the fuel into the coffin. The coffin bottom door is closed, and the fuel is lowered onto it. The grappler is detached and removed from the coffin. The top door is closed and the coffin is lifted and transferred to the fuel storage pits.

13. Structural Assembly

The upper shielding over the lattice and shield test facility is supported by a structural assembly formed by bolting together 6 in. wide flange aluminum beams (Fig. 10). In addition, an aluminum plate (5 ft x 5 ft x 1/2 in. thick) is bolted over the lattice, and wooden beams (6 in. x 6 in.) are mounted over the shielding test tank. This forms an entirely adequate structure which, however, may be dismantled with ease if at some later date it is necessary to move or modify the reactor. The column loading at the four inside columns is 10,000 lb/column, and at the two outer columns, 4700 lb/column. The maximum bending stress on the horizontal beams is 700 psi. The floor loading aside from the column loads is 1500 psf.





DETAIL "A"

FIG. 10
STRUCTURAL ASSEMBLY

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D. Experimental Facilities

Space and structural strength is provided for exponential experiments laid on top of the core region. Removal of the upper shield plug leaves a five-foot square distributed neutron source, which may be shaped by addition of a graphite pedestal. Performance of such experiments temporarily precludes any access to the core.

A tunnel (4 x 5 ft) penetrates one side of the shield and is served with a movable cart. Initially, a water-filled tank will be mounted on the cart, plugging the tunnel. The tank may be used for (1) shielding studies; (2) water-moderated exponential measurements, or (3) solid materials may be located on the cart for migration measurements. Interlocks requiring both that the cart be completely forward and that the biological shielding be adequate before start-up can proceed ensure that cart motions cannot add reactivity to the system and that loss of water in the tank cannot lead to over-exposure of personnel.

The internal reflector has five removable vertical stringers at varying radii. Access to the stringers is through ports in the top shield plug. When these stringers are removed, samples or experimental liners must be in place before operation is permitted. Electrical interlocks ensure this condition.

Two holes (4 x 4 in.), provided by removal of concrete-graphite plugs, penetrate the shield and reflector at the active lattice midplane. The holes extend to the outer reactor tank at points 90 degrees from the external thermal column and the irradiation cart.

The external thermal column has fifteen removable stringers.

Complete removal of the internal tank is possible when the fuel annulus is unloaded. This leaves a three-foot diameter, graphite-reflected tank in which multiplication experiments may be performed; or critical experiments may be performed therein after an additional hazards review. Such review is also required for performance of internal exponential experiments, which require removal of the inner tank before replacement of the inner thermal column. The inner thermal column cannot, by its design, be unloaded while the inner tank is in the reactor.

E. Fuel Storage

The total inventory of U^{235} in the reactor building is 5.3 kg contained in fuel plates. Approximately 3.75 kg are normally contained in the reactor; the remainder are locked in a four-drawer, cadmium-lined, combination-locked file. All storage criteria have been checked to ensure against achieving criticality by flooding or other accident.

External exponential experiments which are contemplated require up to two tons of natural uranium either in the form of oxide lumps or metallic rods, in addition to the fuel in the reactor. Normally, the exponential fuel is kept in the exponential assembly. When unloaded, it is stacked in appropriate storage racks. The only hazard associated with such fuel is that of alpha-particle contamination.

Storage pits, consisting of cylindrical holes (8 in. dia x 4 ft. deep) in the concrete foundation, are provided for spent or highly radioactive fuel. These pits are steel-lined with permanent cadmium inserts, and are spaced on 15-inch centers as shown in the floor plan (Fig. 5). The pits are covered with stepped shield plugs, which can be locked as a group to provide normal security.

Radioactive by-products do not occur in large quantities since the average power is well under 1 kw.

The water moderator is stored in the dump tank when it is not in the reactor. Thus, any activity in the water does not escape from the reactor system.

Foils and other samples inserted for activation measurements represent a very small amount of induced radioactivity and are shielded by lead bricks whenever necessary.

F. Control Systems

1. General

Reactor control is achieved by: (1) moderator removal; (2) addition of neutron absorbers (poisons); and (3) reflector removal. The first method is achieved by having a quick-opening valve to dump the moderator. In addition, there are three safety rods, two control rods, and one shim rod. All rod drives are designed to fail safe, that is, in case of failure gravitational forces cause the systems to return to positions of minimum reactivity.

In addition, the rate of rod withdrawal is limited by mechanical means. Hence, the maximum rate of withdrawal is equivalent to the addition of reactivity at the rate of not more than 0.01 k/min, even for the safety rods.

To keep the top surface of the reactor free for exponential experiments, the various control, safety, and shim rods are mounted next to the reactor tank and the drives inserted into the top of the outer reflector.

Water can be pumped into the core at a rate such that reactivity cannot be added faster than 0.015 k/min.

Aside from the dump valve, there are three types of control systems employed on the reactor: a window-shade system, a winch-type system, and a D_2O system. All of these systems have been cycled several thousand times without failure. The dump valve, in particular, has been employed for several months on the multiplication experiment without trouble of any kind. The D_2O system will be used for two safety columns (rods), and a winch-type drive mechanism will be used for the third safety rod. The control rods will be driven by two window-shade mechanisms. The shim rod drive will be a winch-type mechanism. Alternate systems may be suggested from time to time; these will be tried provided they satisfy the design criteria and are approved by the Argonne Safeguard Committee with the consent of the National Reactor Safeguard Committee.

2. Description of Control Systems

a. Removal of moderator from the core

Under forced circulation conditions, interlocks have been provided so that at high powers the temperature of the reactor will gradually rise; this will cause a shutdown since the temperature coefficient of reactivity is negative. The water system has been so designed that water cannot enter the reactor tank, which is the high point in the circuit, except by pumping.

A 6-inch aluminum dump line is welded to the bottom of the main reactor tank. The terminal end of the dump line is connected to a storage tank in the utility pit by a 6-inch, rubber-lined, electrically operated, butterfly valve which is held closed by a magnetic clutch. A weighted lever arm opens the valve when the clutch is de-energized; under these conditions the water is dumped into the storage tank, and the reactor tank cannot be filled until the dump valve is closed.

The dump valve and line have these control characteristics: (1) a mechanical stop keeps the dump valve from wedging shut; (2) fifteen seconds are required to remove all the water from the annulus; and (3) the top reflector is removed in 8 sec (this is worth 0.09 k).

In addition, there is provided a nitrogen gas injection system which brings about a rapid decrease in bulk water density whenever the dump valve opens. This system is made to fail safely by using the gas pressure to close a 1-inch valve normally open in a moderator drain line to the 6-inch line.

b. Poison systems

The following drives move a cadmium element (7 x 7 x 0.03 in.) from the fuel centerline into the top reflector. Travel is in an aluminum sheath mounted against the outer surface of the reactor tank.

(1) Window-Shade Drive (Fig. 11)

The drive mechanism fits in a $8\frac{1}{2}$ in. x $6\frac{1}{2}$ in. x $6\frac{1}{2}$ in. space and is attached directly to the top of the guide sheath. A stainless steel strip spring (3 in. wide x 0.02 in. thick) drives the control element into the sheath upon scram actuation. The spring is retrieved by being wound up on a drum (5 in. dia.) at a maximum rate of 6 in./min. A limit switch backed up with a mechanical stop prevents over-winding.

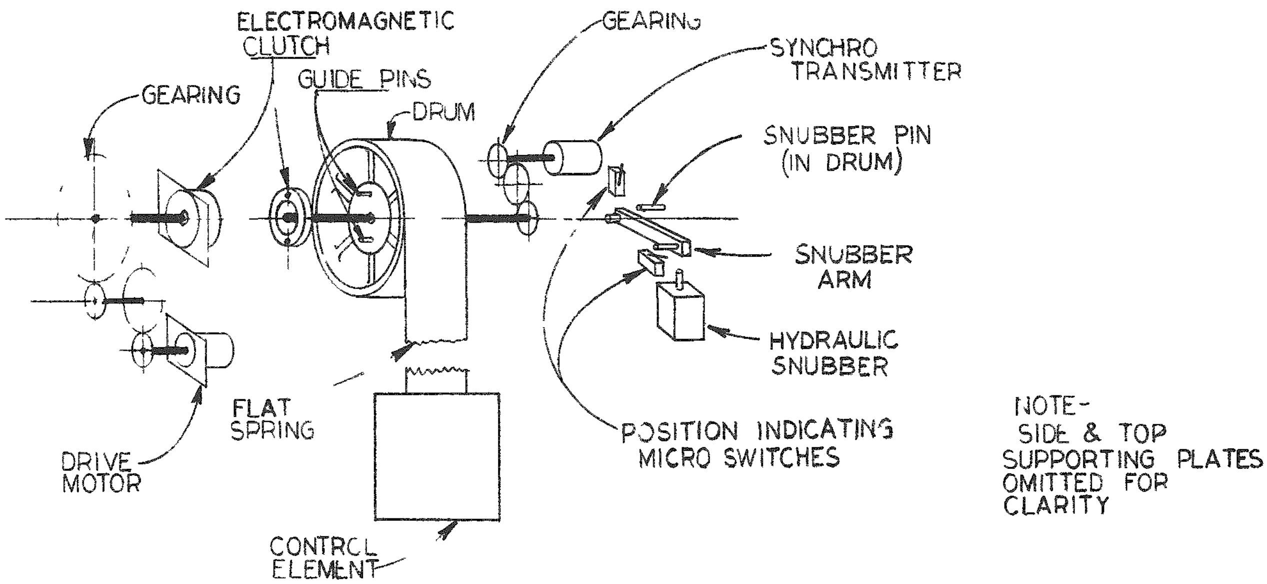


Fig. 11

WINDOW-SHADE CONTROL ROD DRIVE MECHANISM

For control rod use, the d-c drive motor operation can be controlled, stopped, and reversed at any point. The position of the cadmium element would be synchro-indicated at the control panel. For safety rod application, limit switches are provided to indicate the full-up or full-down conditions. An electric clutch between the drive motor and drum can be de-coupled to permit the stored spring energy to insert the control element in less than 0.5 sec.

The window shade concept has been bench tested satisfactorily on a larger model. The compact, improved version described will be recycled several thousand times to prove the design.

(2) Winch-Type Drive (Fig. 12)

The control element is cable-driven by an a-c motor coupled through a magnetic clutch to a take-up drum. The weight of the steel-clad cadmium blade is sufficient to unwind the drum and insert the blade when the clutch is de-energized. A coil spring is attached to the drum to boost the initial acceleration. The scram time for full insertion is approximately 0.4 sec. Less than one revolution of the drum will raise the blade the full travel distance of 20 in. Limit switches actuated by a cam on the drum indicate full-in and full-out positions and provide interlock contacts. Over-travel is prevented by a mechanical stop. Intermediate position indication is transmitted by a synchro geared to the drum. The receiver indicator makes one revolution for complete rod travel to eliminate the need for a revolution counter.

This drive principle has been life tested using a larger control element. The smaller unit is being subjected to the same tests.

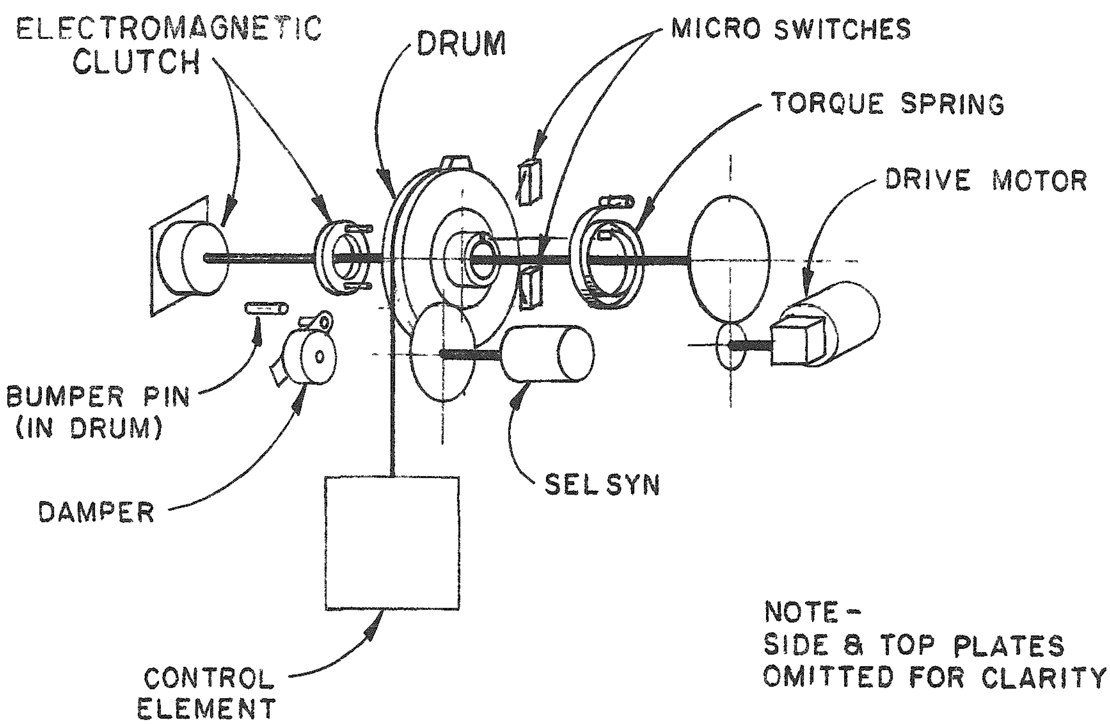


Fig. 12

WINCH-TYPE CONTROL ROD DRIVE MECHANISM

c. Reflector removal - D_2O safety column (rod)

The D_2O safety column design is based on the observation that the introduction of a void into the outer reflector causes a decrease in reactivity. Therefore control can be achieved simply by removing part of the outer reflector to decrease reactivity, and by inserting it to increase reactivity. The desire for compactness led to the substitution of a small volume of D_2O for part of the graphite in the outer reflector. The heavy water is contained in a rectangular column (3 x 7 in.) next to the reactor tank.

The system is shown schematically in Fig. 13. A reservoir is provided at the base of the column. This reservoir has a volume greater than that of the column so that the latter can be completely emptied. The basic principle of a fail-safe design for this system is to pump the D_2O into the column (thereby increasing reactivity) by means of a vacuum pump attached to the upper end of the column. If the pump fails, the heavy water flows back into the reservoir, decreasing the reactivity of the system. The rate of reactivity increase can be limited by the capacity of the pump. A top limit switch is provided.

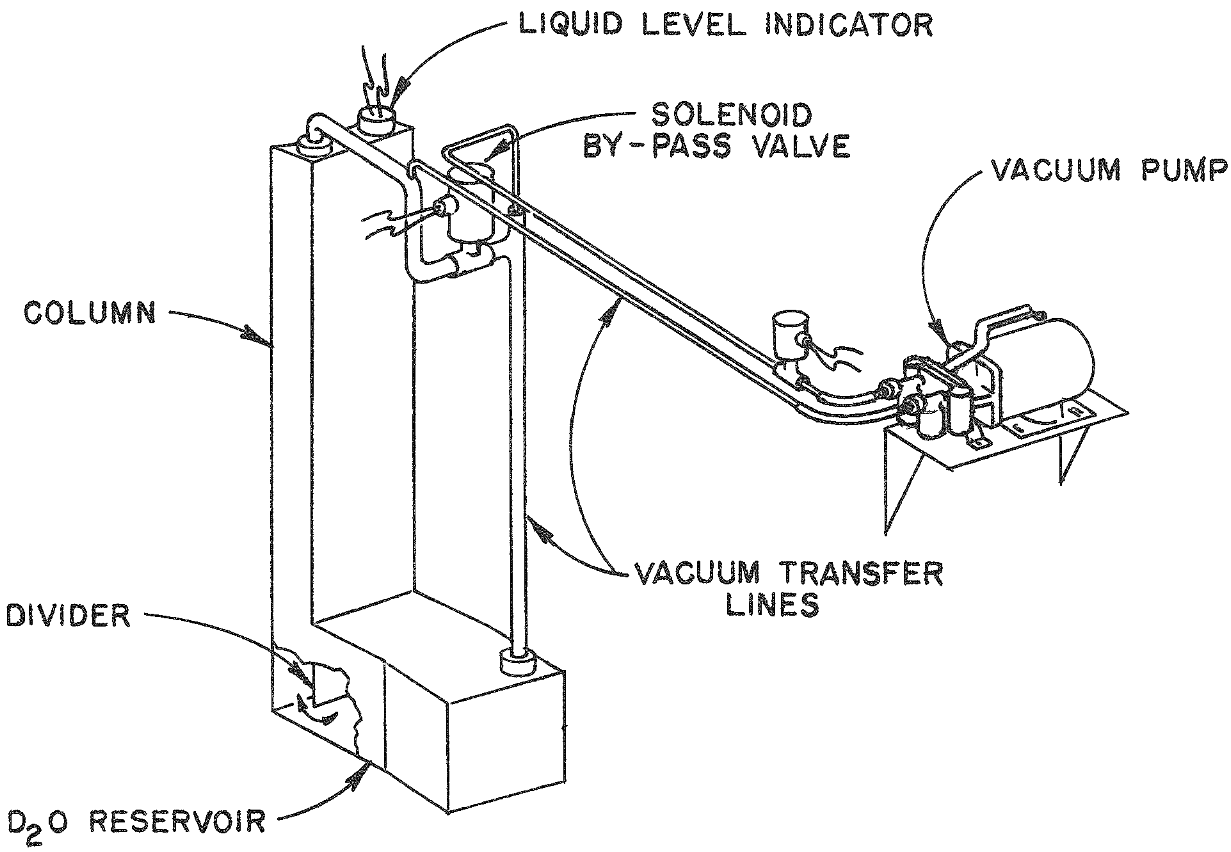


Fig. 13

D_2O SAFETY COLUMN (ROD)

To cock the safety rod (fill column to position of maximum reactivity):

(1) The normally open solenoid valve which by-passes the vacuum pump is energized and thereby closed.
(2) The vacuum pump is started; the exhaust from the vacuum pump goes to the reservoir so the circuit is closed This prevents evaporation and contamination losses. The decrease of air pressure in the column, and the increase of air pressure in the reservoir cause the heavy water to flow from the reservoir into the column until the head developed thereby balances the difference in pressure.
(3) Unless otherwise stopped, the pump continues to run until the heavy water reaches a level high enough to actuate a float switch. When this occurs the pump stops. As long as the by-pass valve is energized, and thus held closed, the water remains up in the column.

To scram the safety column rod·

(1) The by-pass valve is de-energized by action of a trip circuit.
(2) The top of the column is now connected by an open line to the reservoir and the air pressure is the same throughout the system. The head of the water column is no longer balanced by an air pressure differential, so the water column falls until its head is zero.

Reactivity cannot be increased at a rate faster than 0 01/min; the rod column is emptied in 0.3 to 0.4 sec.

G. Instruments

Safety circuits and interlocks (Fig. 14) enforce certain operational procedure and automatically shut down the reactor when necessary.

The conditions which initiate shutdown independently by dumping the moderator and scramming the safety rods are:

(1) Power exceeds $1\frac{1}{2}$ times the preset operating level.
(2) Period less than 10 sec.
(3) Actuation of any one of four manual scram buttons (2 at reactor, 2 at control console).
(4) Power failure.
(5) Trip instrument failure.

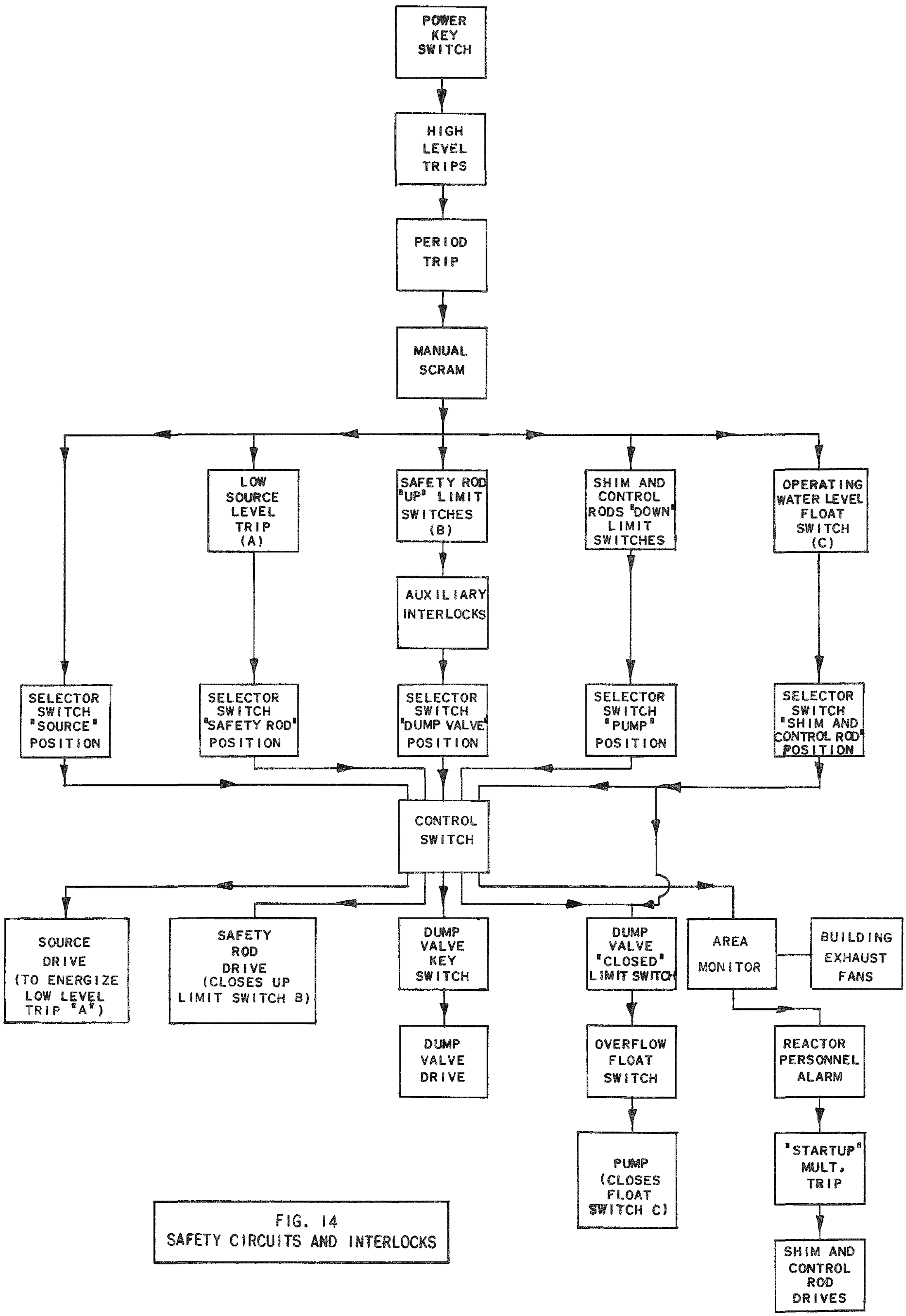


FIG. 14
SAFETY CIRCUITS AND INTERLOCKS

The shim and control rods also are inserted as a result of above conditions and, in addition, by:

(1) Personnel on reactor top during operation
(2) A radiation level above biological tolerance in the reactor room.

Figure 15 shows the electronic equipment in block diagram form. Three high-level trip circuits and one period trip can initiate shutdown independently. Two of the high-level circuits use boron-coated ionization chambers which feed into d-c amplifiers; the third circuit consists of a $B^{10}F_3$ counter, a linear amplifier, and a count rate meter. The output from one d-c amplifier can be varied from 10 to 100 millivolts full scale, and partially bucked out to magnify changes in power level.

An ionization chamber - d-c amplifier circuit similar to that used for high-level trip is the source level and multiplication interlock.

1. d-c Amplifier Circuit

The safety trips were designed primarily from the standpoint of fail-safe performance consistent with reasonable simplicity. Considering only open heaters, grid-cathode shorts, and heater-cathode shorts, the five tube circuit used could fail in twenty-one ways. Of these, only two are fail-unsafe. This does not mean a $(2/21)^2$ probability for simultaneous failure of both d-c amplifiers, because all events are not equally probable. Weighting factors based on tube failure experience are not available, but similar circuits have been used on CP-5 with no record of unsafe failure. A daily operational check is to be made with a current source (Fig. 16) which supplies accurate signals for 10^{-11} to 10^{-3} amp.

The current range covered by the d-c amplifier trip circuits is 10^{-10} to 10^{-5} in decade ranges (Fig. 17). On any range the trip level can be set to an accuracy of 1% by means of a helipot dial which reads directly as a fractional part of the full-scale panel meter reading.

An interlock feature requires that the signal and voltage cables to the chamber be connected at both ends before the safety trip unit will reset and clear the interlock sequence.

2. Positive and Negative Chamber Supply Units

The positive chamber supply (Fig. 18) gives a fixed 500 volts to operate the chambers used with the safety trips, period meter, etc. It has a simple electronic regulator consisting of three tubes which reduces any rapid voltage fluctuations, which could easily affect the performance of the

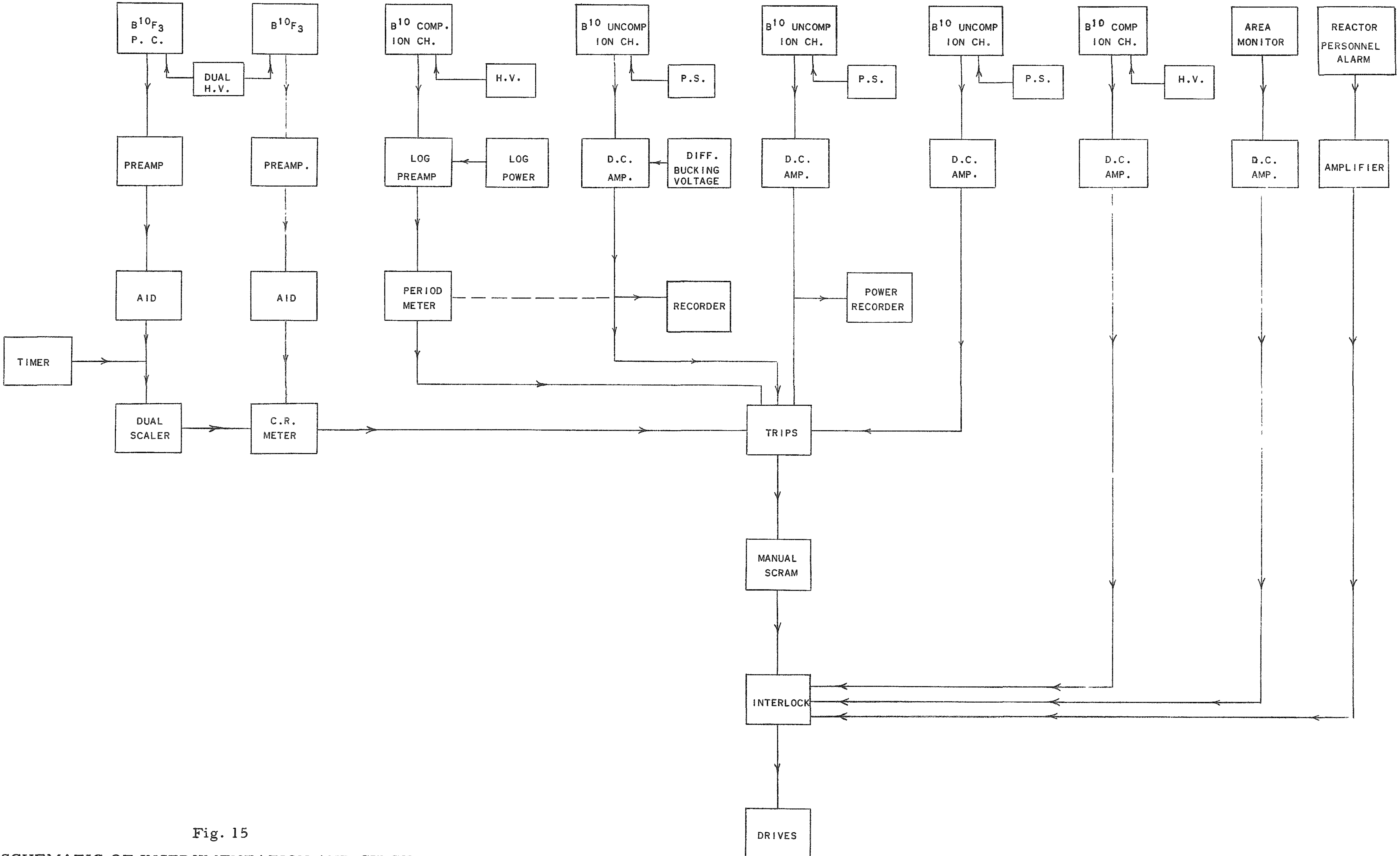


Fig. 15

SCHEMATIC OF INSTRUMENTATION AND CIRCUITRY

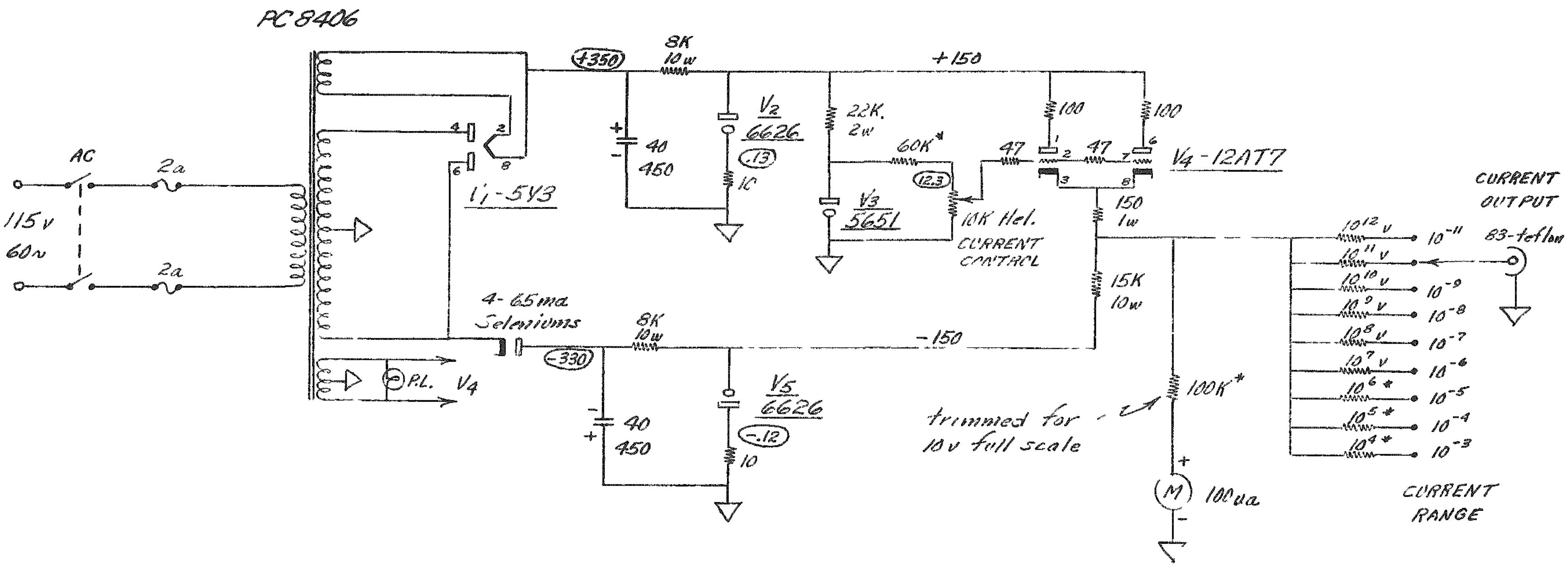


Fig. 16

CURRENT SOURCE (10^{-11} to 10^{-3} amp)

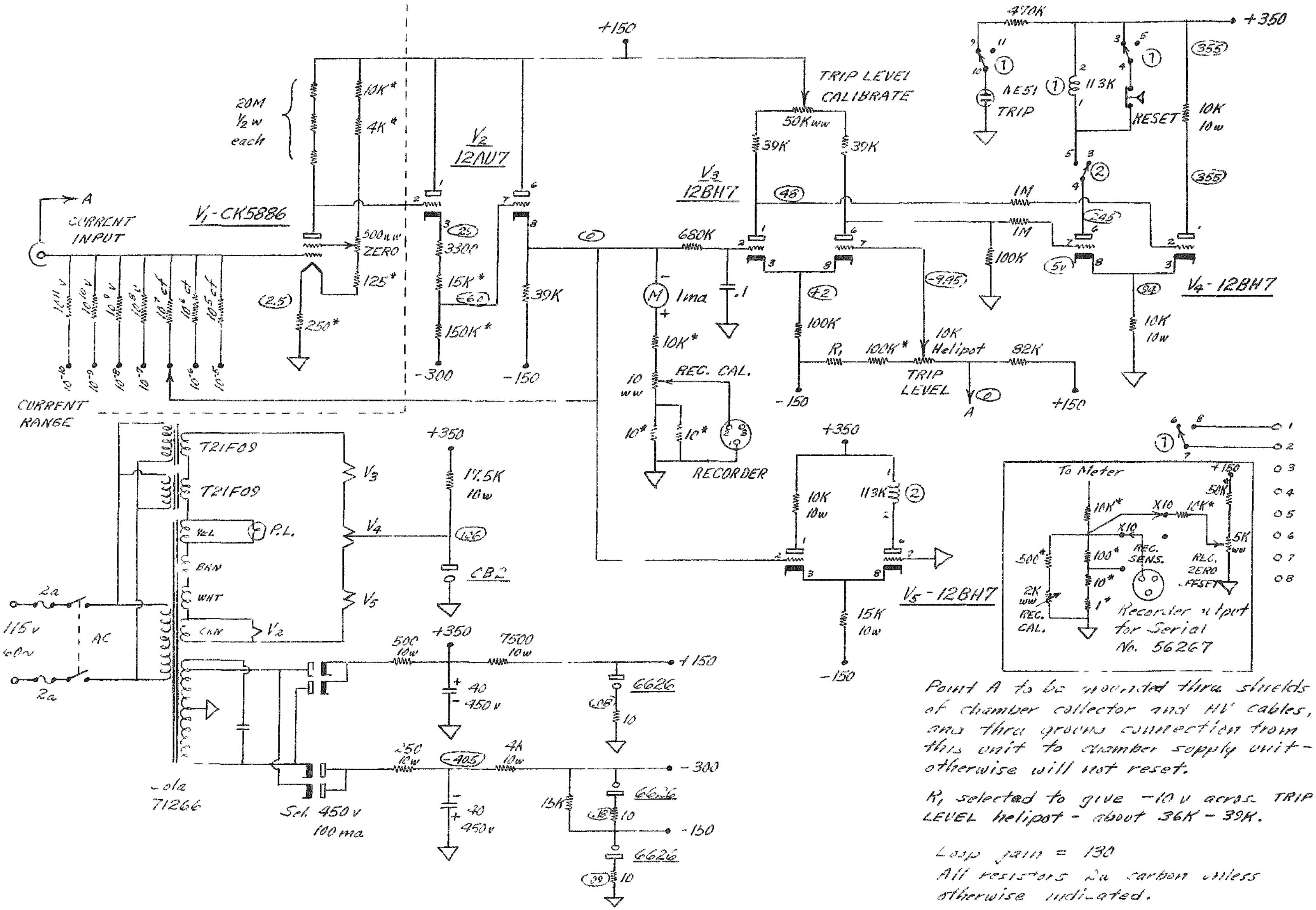


Fig. 17

SAFETY TRIP (UPPER LIMIT)

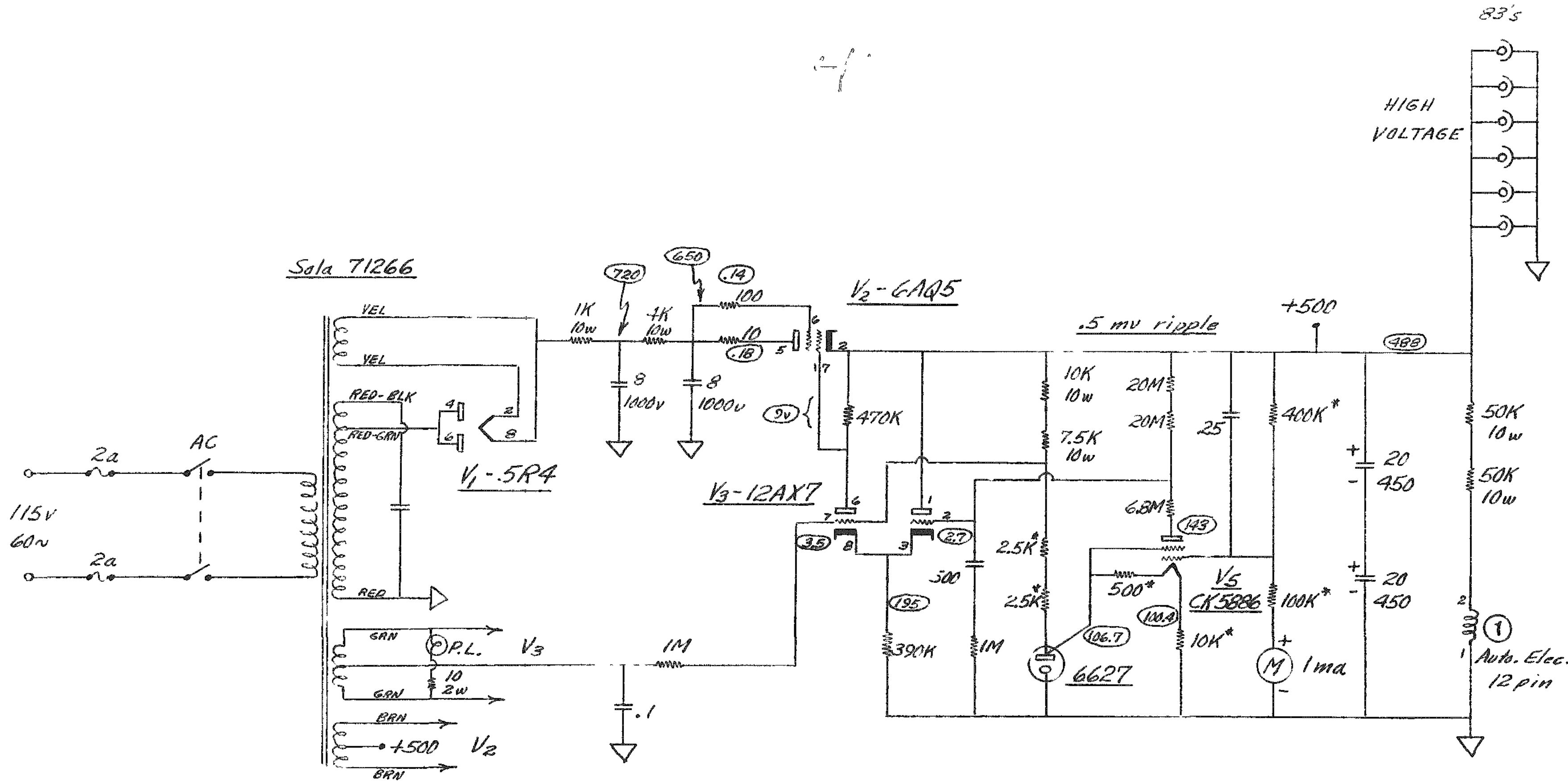
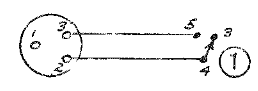


Fig. 18

CHAMBER POWER SUPPLY (500 v, 6 ma)



period meter to a low level. Although the long-term drift may be larger, these rapid voltage changes are held down to about 1 millivolt. An interlock relay requires that the voltage be present before the reactor start-up may be effected.

The negative chamber supply provides 0 to 300 volts for the gamma side of the compensated neutron chambers and is regulated in the same manner as the positive supply.

3. Log Channel (period meter)

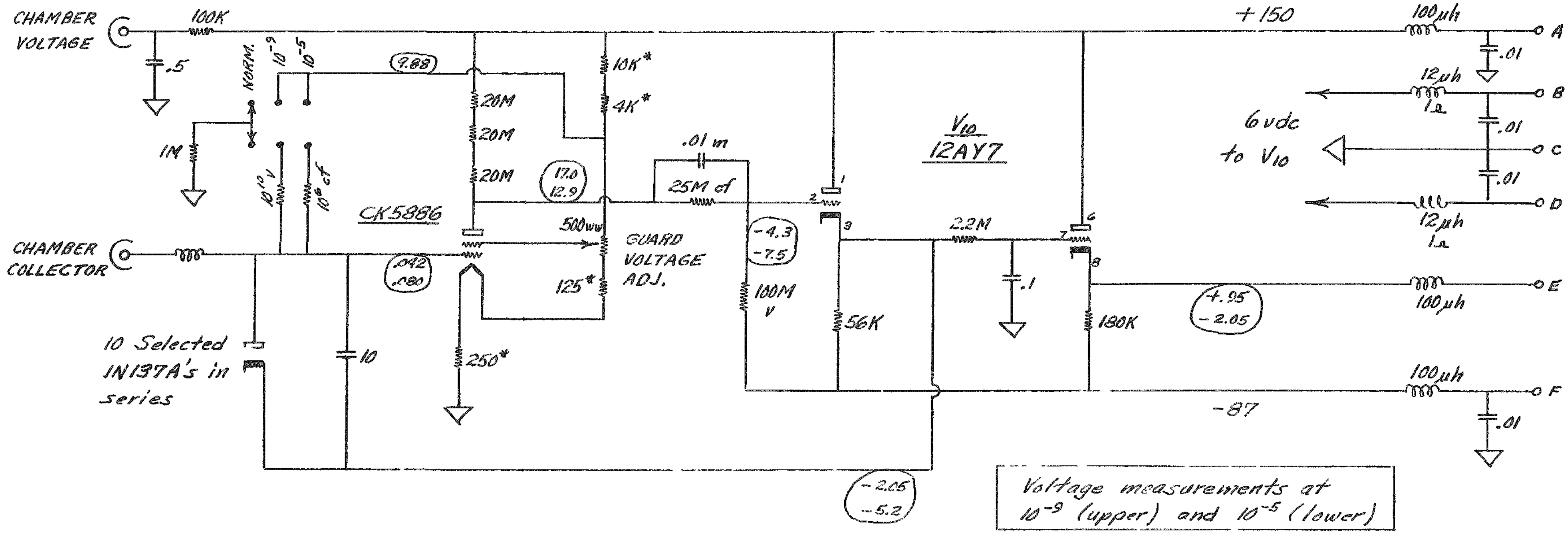
The period meter (Fig. 19) consists of a single chassis plus preamp, which indicates the exponential period of the reactor - positive or negative - and shuts it down if the positive period becomes excessively short. The full-scale period required for tripping is 10 sec. As a by-product of the circuitry required to perform this function, there is also a proportional indication of the operating level by means of a meter reading neutron chamber current over an eight-decade range from 10^{-11} to 10^{-3} amp

The differentiator and trip circuit for the period meter are shown in Fig 20. The most unusual feature of the instrument is the use of silicon diodes for generating the logarithmic function, rather than any of the more widely used methods. The diodes are Type 1N137A (National Semiconductor Products) and are used in their forward conduction region. Ten are used in series to give a signal of about 0.8 volt per decade (Fig. 21). They are housed in the preamp along with a two-tube feedback amplifier. The lines coming into the preamp housing are filtered to reduce interference from stray transient fields which might otherwise cause false shutdowns. The preamp is located only a few feet from the chamber to keep cable capacity low. This, together with the use of feedback to the diodes, keeps the response time of the instrument short over the entire current range. An additional time constant of 0.2 sec is deliberately inserted as a compromise between fast response and freedom from nervousness or false shutdown.

The entire instrument can be set up and calibrated, as well as periodically checked, by means of built-in current test signals.

Previous period meters built at Argonne used the 9004 diode for the log function Silicon diodes, which have been in use on the CP-5 reactor period meter for over a year, have indicated a great improvement in simplicity and reliability.

43



Period Calibration: $RC = \frac{2.3\,ET}{V_0} = \frac{(2.3)(20)(10)}{\frac{1}{4}(.95+2.05)} = 614$

$C = 10.3\,\mu f \qquad R = 59.5$ meg.

Fig. 19

PERIOD METER - PREAMP

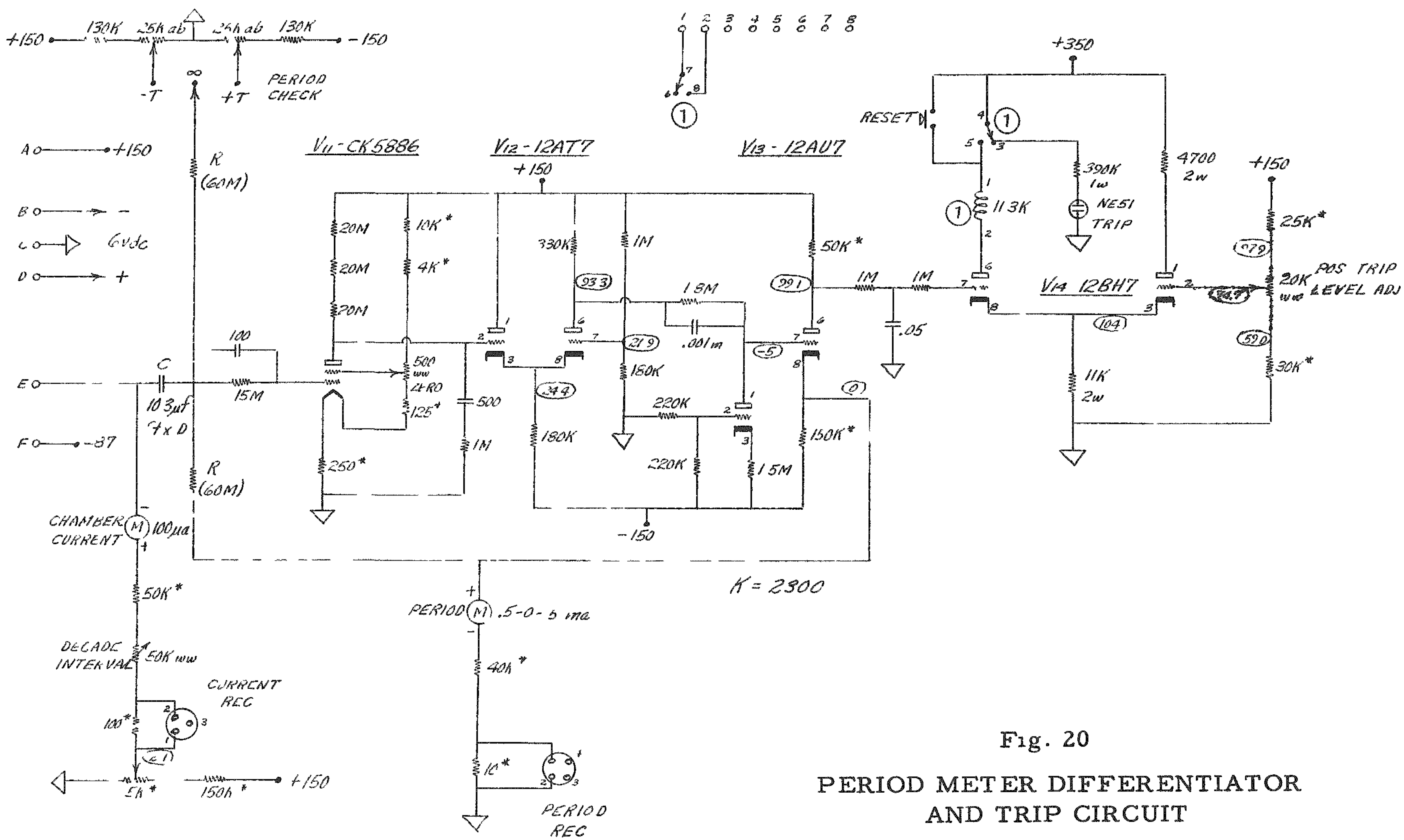


Fig. 20

PERIOD METER DIFFERENTIATOR AND TRIP CIRCUIT

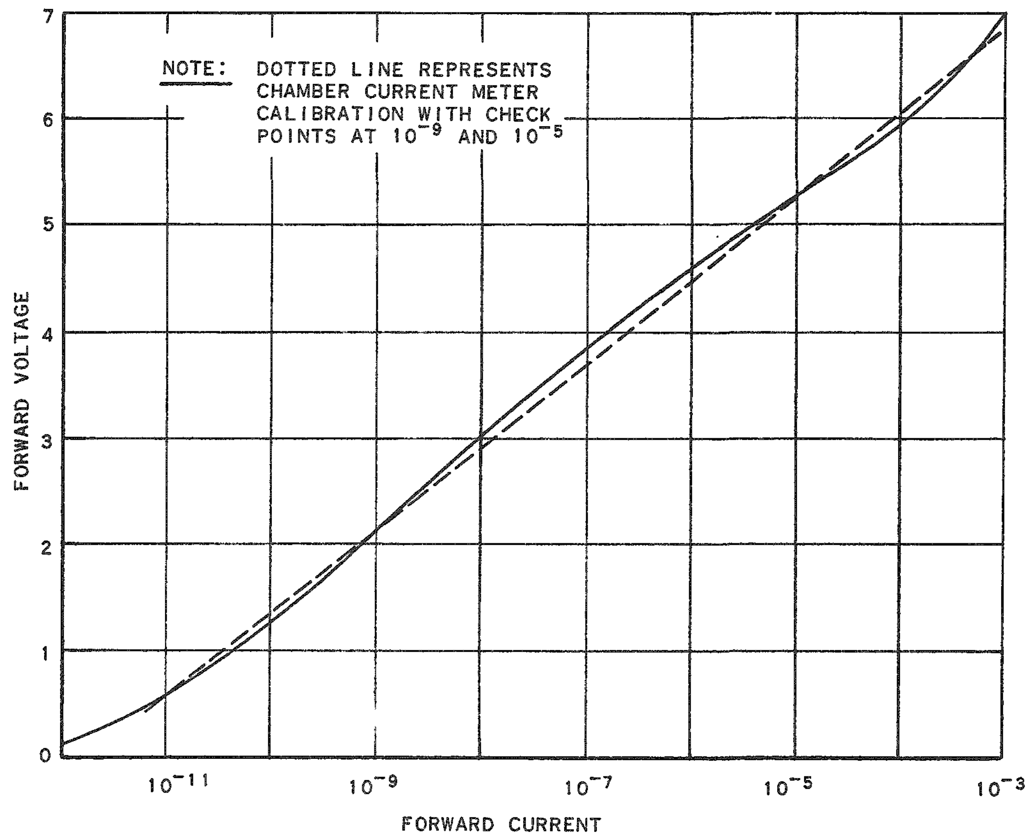


Fig. 21

LOG CURVE FOR COMPOSITE SILICON DIODE
(TEN TYPE 1N137A DIODES IN SERIES)

4. Start-up Interlocks

All access ports, including the shield tank facility, are either interlocked with the start-up sequence through microswitches directly, or with two gamma-sensitive ionization chambers. An uncovered area which emits radiation above tolerance levels will trip the gamma monitor circuit, dropping the shim and control rods. Access holes to the internal thermal column and active lattice have contacts which must be closed with appropriate plugs before start-up can be initiated.

Start-up is controlled by one master selector switch which must be energized in sequence. If a step is omitted, operation cannot proceed.

IV. OPERATIONAL PROCEDURES

A. Supervisory Preparation

Supervision of reactor operation rests with a staff member who has responsibility for the following:

1. Control of fissionable material.
2. Control of keys to all pertinent switches: e.g., main power, crane, dump valve reset.
3. Review and approval of each experiment.
4. Posting of experimental procedures.
5. Training reactor personnel.
6. Scheduled check of safety circuits and control equipment.
7. Records pertaining to the operational history of the reactor.

This supervisor also has the responsibility of suspending operation in the event of equipment failure.

B. Initial Critical Loading

A multiplication experiment is done to predict the critical and control properties of the proposed lattice. (Fuel in excess to that predicted for criticality is locked in storage.) The geometry is fixed and fuel is added uniformly in increments determined from the slope of the reciprocal counting rate curve. Before fuel addition the following checks are made:

1. Install source and check shielding.
2. With the source inserted, and water up, establish counter and ionization chamber locations for 20% of low scale.
3. Check action of trip circuits with current source.
4. Verify dump rate, rod drop and withdrawal speeds, and water fill rate.
5. Verify action of all interlocks.

C. General Start-up Procedure

In the initial approach to criticality, as well as in normal reactor start-up with an established lattice, the sequence of operations is:

1. Post appropriate warning signs.
2. Insert shield plugs in all access holes and lock off power to crane.
3. Unlock and energize control console.
4. Set instruments on most sensitive scales.

The remaining operations are effected through the master selector switch. Starting at position one:

1. Run source in.
2. Raise safety rod No. 1
3. Raise safety rod No. 2.
4. Raise safety rod No. 3.
5. Close dump valve.
6. Pump water up
7. Raise shim rod.
8. Adjust for criticality with coarse control.

If, at any step, an interlock condition is not satisfied, start-up cannot continue. This is indicated by a light at the master switch. For example, the dump valve will not close (Position 5) if any one of the safety rods has not been withdrawn to the cocked position. Conversely, a shutdown, except for scram, must proceed in reverse order. Thus, after the reactor is critical, the safety rod cannot be re-inserted without automatically dumping the water moderator This prevents operation with a large k excess held down by the safety rods

D. Shutdown

As a routine safety check, the reactor will be shut down by switching scales on a trip circuit. A rotational program to check each instrument and the manual scram circuits will be carried out.

E New Experiments

Any program which may affect the reactivity of the lattice must start with a reduced loading in the annulus. The procedure outlined for the initial approach to criticality is then followed. For instance, if it is desired to test a fast reactor fuel element, then

1 The annulus is unloaded.
2. The sample is inserted.
3. The lattice is reloaded in increments.

V. REACTOR SAFETY EVALUATION

A. Characteristics of the System

1. Negligible amounts of fission products are formed at the low operating levels contemplated, and these are contained within the fuel plates. In the event of failure of the cooling circuit pump, the temperature coefficient is such that the reactor will shut down before dangerous power levels are attained.
2. The temperature and void coefficients are negative and large in absolute value
3. The prompt neutron lifetime is long ($\sim 1.9 \times 10^{-4}/C$).
4. In the event of a fast runaway the reactor will shut down by boiling as in the case of BORAX-I and SPERT-I. To achieve a destructive BORAX-I type of excursion requires that a large amount of reactivity be inserted rapidly.

B. General Safety Considerations

The following possibilities have been considered:

1. Damage to operating personnel and casual bystanders.
2. Damage to the reactor system itself during normal operation and in the event of a reactor runaway.
3. Damage to property and equipment adjacent to the reactor and in the reactor building in the event of an excursion or catastrophe.
4. Damage to the region outside of the building.

The possible sources of hazards are neutrons, beta, and gamma rays, due to:

1. Inadequate shielding during normal operation.
2. Slow runaway caused by.
   a. Moving the control rods and safety rods imprudently;
   b. The inadvertent loading of too much fuel;
   c. Raising the water height too rapidly during a startup;
   d. Malfunctioning of equipment, either mechanical or electrical.
3. External physical catastrophe such as fire, earthquake, or external blast
4. Sabotage.

To eliminate these hazards, the following safety devices are used:

1. Area monitors which initiate a scram or prevent criticality if there is too high a level of radiation present outside the reactor.
2. Micro-switches which are in series with the dump valve clutch. These switches are closed when, and only when, the top of the reactor is shielded or covered with an exponential assembly
3. A capacity alarm system which prevents raising the control rods or causes them to drop whenever someone walks on top of the reactor.
4. Additional contact switches which control the external openings and are in series with the dump valve clutch.
5. Safety rods of sufficient size number and speed to protect the reactor against normal accidents.
6. Mechanical limits on the rate at which control rods and safety rods can be removed and at which water can be pumped, to limit the rate at which reactivity can be added to the reactor.
7. Operational and monitoring limitation of the excess reactivity available to 0.5%. The latter is accomplished by measurement of the high-level source flux after the water has been pumped up but before the control rods are raised. When compared with the low-level source flux this yields what is effectively a multiplication measurement of the system. Since the reactivity of the control rods is known, the excess reactivity present is thus measured. Should it exceed 0.5% the control rods cannot be raised.

C. Radioactivity Involved During Normal Operation.

It is anticipated that for most purposes Argonaut will be operated at 25 watts or less. A conservative estimate of stored radioactivity is obtained by assuming that operation is either continuous at 1 kw or intermittent (two hours a day) at 10 kw The two modes of operation are equivalent for this purpose. The radioactivity stored in the fuel just before shutdown is 1.25×10^4 curies. Two days after shutdown the radioactivity decreases to 1000 curies. The induced activity in the reactor structure in the absence of fuel and moderator gives rise to a dose rate of 34.7 mr/hr at a point 25 cm above the top of the graphite. The source for start-up yields about 5×10^8 n/sec and, as shielded by 5 in. of lead, gives a dose rate at the loading port of 3 mr/hr.

The maximum dose rate outside the shield is 5 mr/hr at 10 kw. Operation at this power is limited intrinsically. Exposure levels will be measured continuously; and pre-set monitors will shut the reactor down whenever the tolerance level is exceeded.

D. Hazards During Lattice Alterations and Reactor Start-up.

Multiplication experiments carried out at Argonne National Laboratory show that one fuel plate (containing about 20 gm of fuel) is worth about 0.13% k. Plates of lower concentration are on hand. Thus sufficiently small changes in reactivity can be made by inserting or removing single plates. The procedure of measuring the multiplication of the system before raising the control rods and the small worth of each plate combine to make it impossible to insert more than the allowable amount of excess k (0.5%) by minor lattice alterations in the normal course of operations. Both operational conditions and safety interlocks would have to be circumvented to permit the insertion of more than this amount of excess k.

Major alterations in the lattice combined with circumvention of the aforementioned procedures and interlocks might make it possible that the system would become critical before the water is all the way up. The pumping rate has been adjusted to give a maximum rate of reactivity addition of about 0.025% k/sec. At such a rate of reactivity addition, the control system will shut the system down without damage to equipment or personnel.

Radiation from the fuel elements will be below tolerance after the reactor is shut down except after high-power runs. Under these conditions, a lead coffin and remote handling devices are provided so that highly radioactive fuel boxes can be transferred to storage pits without exposing personnel. Survey meters will be available and put into use at such times, and all personnel will be instructed in their use. The services of the Laboratory Radiation Safety Section will be available to check radiation levels at any time, and to advise and instruct operating personnel in radiation safety.

E. Accidental Operating Errors

1. Accidental Exposure of Personnel

The operator must close external openings and must see that the top plug or an exponential experiment is in place before the dump valve interlock can be energized; in addition, room monitors and a burglar alarm are present -- the former to guard against accidentally leaving out a shield plug, and the latter to prevent any one from going on top of the reactor when it is critical. Thus in order to bring the reactor up to criticality, the operator is required to go through those routines necessary to avoid accidental exposure of personnel.

2. Accidental Scrams

As a result of too rapid addition of reactivity to the system by means of control rod withdrawal, or, in case of a serious loading error, of too rapid a rate of rise of water height, the scram circuits will operate to drop the safety rods and dump the water. A scram signal occurs on 1.5 times operating level or on a ten-second period.

When the magnetic clutch holding a safety rod is de-energized, the rod falls freely with an acceleration of about 1 g. The time for complete insertion of all the rods is then not more than 0.4 sec. The D_2O-void control system, if used, is slightly faster. The time delay of the flux-monitoring instruments varies with the instrument and flux level but, in general, is less than 0.12 sec and is, in all cases, less than 1.1 sec. The longer response times occur only at powers less than 0.1 watt.

The rate of reactivity input by raising the water height will be limited to 0.025%/sec. If the system becomes super-critical, the instruments will act to lower the rods and dump the water. An analysis of this situation is given here:

The source interlock prevents start-up unless a low-level flux condition is satisfied. Thus, when the reactor goes critical, the power level will be in the region 0.01 to 0.1 watt the flux will be about 10^5, and the period and power trips will be well within their working range.

From Appendix D we find that after 15 sec the flux will have increased by more than one decade, and the three power trips will have been actuated. If these have been reset, then this process could continue until the maximum power setting (15 kw) is reached. This occurs at about 6 decades above critical; the flux reaches this level after 26.7 sec. The period trip will have been actuated after 6 sec. Thus, the maximum flux attained in this process is not more than 10^{11} to 10^{12}, assuming that at least one of the four trips works.

In addition, the operator has available the manual scram; failure of all four trips still leaves approximately 15 sec for the operator to use the manual scram before prompt critical is reached. Failure of all these mechanisms will give rise to a low-order BORAX-type of excursion which, by extrapolation from SPERT-I and BORAX-I, will have a peak power of about 1 megawatt. followed by steady boiling until shutdown, which should occur in about 30 minutes as a result of loss of water from the system. The total dose for personnel next to the reactor would be about 2.5 mr under these conditions. If reactivity could be added at forty times this rate, i e., at 1%/sec, then failure of all trips would lead to a significant power excursion, however, it is extremely doubtful that there would be any core damage.

Under conditions of operation at maximum power (10 kw), it might be envisaged that reactivity could be added to the system by some means not presently imagined. If this addition is very slow, the reactor circulation system is such that the reactor will shut down in less than two hours through the increase in the moderator temperature. For more rapid additions of reactivity, the worst case would be relatively fast but steady addition of reactivity, accompanied by steady boiling such as was discussed previously. The total dosage would be about the same since SPERT-I tests show that under these conditions steady boiling is about the same regardless of initial power. As discussed in Appendix C, the release from a BORAX-type excursion would not damage the core until instantaneous insertion of about 4.75% k has been achieved. Extrapolation of BORAX and SPERT-I data reveals that total doses of more than 60 mr would be difficult to obtain in a single excursion unless the excursion were so severe as to damage the core.

3. Dropping Fissile Material into the Internal Thermal Column

Since the importance of both fissile material and poison is very high in the internal thermal column, it is possible to get a considerable reactivity change by inserting such material into the center thimble. For this reason a switch has been located in that thimble such that a sample must be in place before start-up can be completed. If the reactivity of the sample is too high, the high-level source flux trip will be actuated and start-up cannot proceed. If the reactivity is too low, then the rods can be raised and the sample removed to make the reactor go critical. Sample removal would normally scram the system, but in case of interlock failure the total reactivity addition still would not be more than 0.5%, and this would shut the reactor down in about one-half hour with a total dose of about 0.8 mr

F. Malfunctioning of Equipment

As far as possible, all electrical and mechanical equipment has been designed to fail safely Electrical failure causes the rods to drop. Failure of the flux monitors causes a scram. Cable failure lets the rods drop into the reactor Dislocation of the safety rods serious enough to prevent their insertion is conceivable only as a result of sabotage or as a concomitant of an external catastrophe. The rods cannot be damaged by a system accident which did not already depend upon their previous malfunctioning. In addition, multiple trip circuits and six rods are provided for control. Any one rod can shut the reactor down with the exception of the fine control rod, thus the reactor can be shut down even though as many as three trip circuits and four rod drives fail simultaneously.

An external exponential with liquid contents may leak into the core. Water leakage leaves the annular condition unchanged but lowers the reflector savings, thus slowly decreasing reactivity. D_2O leakage increases filling voids and thus causes a slow rise in reactivity. In any event, there is ample time to actuate the manual scram.

G. External Physical Catastrophe

In order to have an effect, a physical catastrophe would have to be of such proportions as to disrupt the normal arrangement of materials in the reactor system. An earthquake of sufficient intensity to alter the geometry of the experiment has never occurred near the site in recorded times and would be very unlikely (Appendix F).

H. Sabotage

A well-informed saboteur presents the most effective means of destroying the reactor system and, in fact, the area as well. The main reliance must be placed upon the enforcement of Laboratory Security regulations.

I. Hazards to Building and Surrounding Area

1. Slow Runaway

If all control methods fail and the system runs away with the maximum permitted excess reactivity of 0.005, the flux will rise with a period of 2.5 sec. If all the water and the aluminum in the system heats uniformly and the system starts at 10 kw, then the total heat capacity of the system is 0.46×10^3 kw-sec/C. The temperature will have risen 20C after about 14.75 sec, the reactivity thereby being reduced to 0.003, but the instantaneous power will be about 3.6 mw. The reactor will then rise on a period of about 10 sec for another 3.75 sec at which time the negative temperature coefficient of reactivity will shut the reactor down after it has attained an instantaneous power level of about 5 mw. This is consistent with SPERT-I data. There is no damage to the reactor or to the surroundings. The total integrated dose for personnel will be about 0.8 mr.

2. BORAX-type Excursions

BORAX-type excursions will occur whenever there is an essentially instantaneous addition of reactivity of about 0.0100 and will become increasingly severe until the attainment of a period so short that the fuel plates melt This latter point corresponds to the insertion instantaneously of 4.75% k. This is based upon the assumption that the energy release per unit volume is about the same in Argonaut as it is in BORAX and SPERT-I under similar conditions. Details of these calculations are given in Appendix C. It is exceedingly difficult to see how even 0.01 k_{ex}, let alone 4.75% k_{ex}, could be added to the reactor in this way. The only mechanism imaginable would necessitate the following steps.

a. Remove the internal thermal column and reload annulus.
b. Remove, or render ineffective, pertinent trips and interlocks.
c Raise the control and safety rods
d. Raise the water level.
e. Drop a highly reactive system into the position formerly occupied by the internal thermal column.

It is reasonable to assume that such folly would be, virtually, a form of sabotage. Nevertheless, it is instructive to examine the consequences of such an excursion On the supposition that a destructive excursion had been attained under the assumptions previously made, the energy release will be 6.9×10^{14} ergs. Experiments conducted by P. A. Lottes at Argonne National Laboratory show that under the conditions of a BORAX excursion about 4% of the available energy is given to expelled H_2O.* The conservative assumption is that this all appears as sensible heat. In the process of expansion the water will cool and distribute its heat to the building air. Application of the perfect gas law shows that this cooling occurs before the building volume (9×10^8 cc) is filled with water vapor. The over-all temperature rise is then 1.94C, coming from sharing

$$0.04\ (6.9 \times 10^{14}) = 2.76 \times 10^{13} \text{ ergs}$$

between the reactor water of heat capacity 6×10^{14} cal/C and the building air of heat capacity 27.8×10^4 cal/C. The perfect gas law applied to the air in the building with original state at STP yields a pressure increase of about 0.1 psi. This overpressure requires a bolt about every 10 to 20 ft. along the seams of a building such as Argonaut is housed in This condition is met, so that in case of a destructive Argonaut excursion, the fission products will be contained within the building to the extend that there is ample time to seal the building against leaks while the radioactivity decays. The ventilating system is automatically shut off under these conditions. It should be noted that mechanical damage stemming from the destructive excursion in BORAX-I probably came from the creation of a shock wave in the water. The core of Argonaut is too small to permit this under the assumed conditions (See Appendix C).

3. <u>Other Sources of Rapid Energy Release-blast damage</u>

The preceding discussion does not consider the possibility that normal water escape channels might be blocked and the excursion thus

* The remainder of the energy is shared by the fuel plates, aluminum structure, and other core components. The heat capacity of the total structure is sufficient to absorb the heat of the excursion, including the part which caused the overpressure, with negligible increase in temperature

partially contained. At most, such containment would amount to that provided by the top plug (equivalent to not more than 2 atmospheres overpressure). Such containment is easily overcome in the course of a BORAX-type excursion without materially changing the nuclear characteristics of the reaction. The containment necessary to promote a more severe reaction is not attainable in practice. Nevertheless, to obtain an estimate of the greatest possible damage from blast, two types of nuclear-chemical reactions have been analysed under the assumption that the necessary containment has been furnished. The results are reported in Appendix E, where it is shown that the blast damage would be confined to a region not more than 30 meters from the reactor

It is conceivable that the core might be dissolved by addition of appropriate acids or alkalis and then the mixture might be blown up with explosive. Damage from such an accident is impossible to predict, since the amount of explosive used is unknown. The activity released in this way, however, decays only as $t^{-0.2}$. Under what might be termed standard operating conditions (no more than 2 hours of operation at 10 kw/day), the maximum amount of activity released is about 1/10 that released in a nuclear "accident."

4. Exclusion Radius for Airborne Radioactivity.

The Reactor Safeguard Committee has made an analysis of the radiation damage to be expected from dispersal (in the form of a cloud) of the radioactive material contained in a reactor. They arrive at a delimitation of the exclusion area by a radius measured in miles. This is given by:

$$0.01 \times (\text{operating power of reactor in kw})^{\frac{1}{2}}$$

In the case of Argonaut operating at 10 kw, this radius would be 170 ft. Relatively large amounts of radioactivity could be produced during a runaway and the exclusion radius corresponding to this has been estimated, with allowance for the fact that fission products produced instantaneously will decay more rapidly than those accumulated during operation over a long period of time.

The calculation of the Reactor Safeguard Committee has been repeated along the following lines, with the appropriately modified average decay law.

For the decay law, according to Way and Wigner,[2] it is assumed that the activity is given by

$$A = F \times 2.66t^{-1.2} \text{ mev/sec}$$
$$A = F \times 4.42 \times 10^{-16} t \text{ kw}$$

where

F = total number of fissions produced
t = time, sec

This is to be contrasted with the starting point used by the Reactor Safeguard Committee for steady operation, which is the assumption:

$$A = (0.1) \text{ (power in kilowatts) } (t^{-0.2})$$

with A in kilowatts.

Their calculation,[3] including their assumptions that (1) 50% of the total fission products are contained in the cloud; and (2) 60% of the dosage in the cloud is effective to a ground receptor, is repeated with the new time dependence. The accumulated dosage, in roentgens, is given by

$$R = (F)\ (9.3 \times 10^{5}) \left(\frac{v^{0.2}}{hd^{2.2}} \right) , \qquad \text{(Formula A)}$$

where

v = wind velocity, cm/sec
d = distance from origin of cloud, cm
h = height of cloud, cm

This replaces the result

$$R \propto \frac{1}{(v^{0.8})\ (h)\ (d^{1.2})}$$

obtained by the Committee for activity proportional to $t^{-0.2}$.

It is notable that for the short-lived products, high wind velocity will increase the dosage at a given distance, whereas the contrary is true for the longer-lived products from steady operation. This is understandable qualitatively since a high-wind velocity increases the dosage due to earlier arrival of the cloud, but diminishes it due to the quicker passage over the recipient. For sufficiently short-lived products the former predominates.

[2] K. Way, E. P. Wigner, "The Rate of Decay of Fission Products," MDDC-1194(1947).

[3] Summary Report of the Reactor Safeguard Committee, WASH - 3, pp. 42-44.

Following the practice of the Committee, the radius of exclusion can be defined as the distance within which R = > 300 roentgen units.

An alternative expression has been suggested by the Safeguard Committee for quick evaluation of the exclusion distance:

$$d \text{ (miles)} = 0.003 \text{ (kilowatt seconds)}^{\frac{1}{3}} \qquad \text{(Formula B)}$$

Appendix H gives a detailed analysis of the wind speeds and directions which can be anticipated in this area. The maximum wind speed is infrequently greater than 30 mph and any winds above this value will certainly be turbulent. Assumption of stable winds leads to lower cloud heights and larger exclusion radii and hence are assumed here. In addition, the wind velocity is taken to be 30 mph even though this figure is rarely attained. The cloud height for a given set of conditions is defined on the basis of work performed by Sir O. G. Sutton of England and is reported in detail in Appendix H. In brief, if X is the distance down stream in meters and H the cloud height in meters, then

$$H = (\ln 10)^{\frac{1}{2}} C_z X^{2 - n/2}$$

where C_z, n are given in Appendix H. Insertion of this into Formula A yields a formula for the exclusion radius, corresponding to a maximum permissible dose:

$$r^{3.2 - n/2} = \frac{9.3\ 10^{-5}\ F\ V^{0.2}}{(\ln 10)^{\frac{1}{2}}\ C_z\ R_m}$$

The effects of the various types of accidents are summarized as follows:

Excursion	Blast Damage	No. of Fissions	Energy Released kw-sec	Exclusion Radius, ft Form.A	Form B
BORAX-type	none	2.29×10^{18}	6.9×10^{4}	875[1]	633
Chem. Explosion (Sabotage)	Depends upon amt. of explosive			170[2]	

Note 1: Assumes that building does not contain the products of the reaction.

2: Based on the formula: $R = 0.01\sqrt{P}$ miles, where P is maximum power in kw and the residual activity decays as $t^{-0.2}$

The cloud heights were based on parameters characteristic of a stable atmosphere with a wind velocity of 3 mph even though the velocity is taken as 30 mph in calculating the exclusion radius. This makes the calculation a conservative one.

The reactor building is in the northwest corner of the East area of the Laboratory. The distance to the nearest Laboratory boundary is 1300 ft; to the nearest reactor, 4800 ft. The nearest town is $2\frac{1}{2}$ miles distant.

5. Estimate of Hazard Due to Precipitation of Airborne Radioactivity.

An upper limit to the possible hazard due to precipitation of radioactivity may be obtained by the formula[4] for the total instantaneous washout from an instantaneous point source:

$$w/Q_0 = \frac{1}{\pi C^2 (\bar{u}t)^{2-n}} ,$$

where w/Q_0 is the ratio of the fallout per square meter to the amount of original matter in the explosion cloud; C, the generalized diffusion coefficient for isotropic turbulence; n, the non-dimensional parameter associated with stability; t, the time in seconds; and $\bar{u}$, the mean wind speed in meters per second. It is assumed that the activity in the cloud decays according to the previously stated decay law. From the Summary Report of the Reactor Safeguard Committee (WASH-3), the effectiveness of radiation due to precipitated activity is given 1.3×10^{-4} r-units/day for gamma radiation of 1 mev/(sec)(cm^2), and as 1.3×10^{-3} r-units/day for beta (includes reduction by factor of 10 to account for protection by clothing). Noting that roughly equal fractions of the energy go off as gamma and as beta radiations, and correcting to hours, the effectiveness is 3.0×10^{-5} r-units/hour for 1 mev/(sec)(cm^2) of ground-deposited activity.

The parameters for the cases of 5-meter/sec turbulent wind and for 2-meter/sec stable wind speed are given in Appendix H. Defining the integrated dosage (from time corresponding to one mile to infinite time) as 300 r-units, one obtains the following as the maximum limiting allowed values for the initial fissions in the cloud:

Wind Speed	Initial Fissions in Cloud for 300-r Dosage at 1 mile	
	Assuming Total Instantaneous Washout	Assuming Constant Rate of Washout with Maximum Deposition
5 meters/sec turbulent	2.2×10^{19} fissions	2.3×10^{24} fissions
2 meters/sec stable	2.1×10^{17} fissions	2.2×10^{23} fissions

Also given are the limiting maximum initial fissions for the case of maximum deposition at one mile assuming a constant rate of washout. The deposition was obtained by means of the nomograph given in "Meteorology and Atomic Energy."

4. "Meteorology and Atomic Energy" AECU-3066(July, 1955).

APPENDIX A

MULTIPLICATION EXPERIMENT FOR ARGONAUT

I. General Description

The purpose of this experiment was to determine critical and control properties for a ring of fuel elements in a graphite block by multiplication measurements on the subcritical loading. The annular active region consisted of plates of 20% enriched U_3O_8 moderated by water within and graphite between fuel boxes. The annulus above and below the fuel contained 12 in. of water reflector; the sides were reflected by graphite.

For control, the experiment had three gravity-actuated, cadmium shut-down blades plus a 6-inch flap valve for dumping the H_2O moderator. Two additional safety rods were installed for experimental purposes only. Shut-down was initiated automatically by any one of three independent multiplication trip channels. An Sb-Be photoneutron source, identical to those in the I.S.N.S.E. exponentials, was used. This type of source enabled the trip circuit detectors to see a thermal flux of $\sim 10^5$ at a multiplication of 100.

The site for the multiplication experiment was the north coal bunker in Building 24.[5] This room is enclosed on three sides by one foot of ordinary concrete. The floor is recessed 18 in. below the surrounding area. A small amount of additional shielding was necessary for the multiplied Sb-Be source.

Building 24 is unclassified, as was the fuel for the experiment. Consequently only those security measures required to safeguard valuable materials were employed. Much of the equipment used in the multiplication experiment has been used in the installation of the Argonaut system.

II. Multiplication Level

The first experiments were performed to determine the sensitivity of the system to geometric and control effects with the fuel divided equally among 12 boxes. The arrangement of boxes within the annulus was varied. Starting with the fuel boxes clustered in six equally spaced groups of two around the annulus, three, four, and one box clusters were surveyed. Lattice changes were effected by transposition of graphite segments with fuel boxes.

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[5] A general layout of Building 24, and an expanded view of the experimental area is shown on Drawing No. RE-1-17559-D (not included).

The second series of experiments were concerned with water density effects in the most promising configuration.

For the initial experiments, a multiplication range between 25 and 50 was used with the trip limit fixed at 100. However, depending upon the value obtained for k_∞, a multiplication of 25 or k_{eff} of 0.96 can amount to a loading containing only 85% of the true critical mass. At this loading an accurate extrapolation of the effects of small poisons was difficult to obtain so that higher multiplication levels were occasionally used.

Interlocks were arranged so that fuel addition, rearrangement, and the introduction of voids could occur only when the annulus was drained. The only operational cause leading to criticality would be a serious mistake in fuel bookkeeping. Then if enough extra fuel had been added to the system, it would have been possible to go critical while pumping the water up or when subsequently withdrawing the control rod, provided that the operator neglected to make stepwise multiplication checks. To prevent criticality under these circumstances, the pumping and rod withdrawal rates were limited mechanically so that reactivity could not be added fast enough to outstrip the response of the trip system. Circumvention of the drive unit speed limitation by manual removal of a safety rod was possible only when the annulus was drained. An interlock condition demanded that the safety rods be cocked before the dump valve clutch could be energized. The pertinent operational rates were as follows:

<u>Trip response</u>	
Input circuit time constant	0.100 sec
Trip relay opening time	0.03 sec
Safety rod drop time ($\frac{1}{2}$g)	0.350 sec
Δk/sec	-0.08
<u>Control rod</u>	
Maximum withdrawal rate	2 ft/min
Maximum Δk/sec	+0.0006
<u>Water fill rate</u>	
Pump capacity	8 gpm
Tank fill time	10 min
Maximum Δk/sec	+0.0025

III. Loading Procedure

The annular core had vacant positions within the graphite for 12 fuel boxes. Initially, each fuel plate position within a box contained a dummy aluminum plate. As the loading proceeded, these were replaced by fuel and final adjustments made with half-size plates. For the desired multiplication, a loading of 4 kg was predicted. Actually, for some of the less reactive configurations, the total of 5.4 kg of U^{235} on hand in plates was used.

Addition of fuel was made in steps whose magnitude was determined both by the slope of the reciprocal counting rate curve and the control rod worth as determined from this curve. In general, increments of fuel were made in equal amounts to each box, with the outer plates added first, so that the gradually diminishing water gap remains within the box rather than at an outer edge.

A. Before addition of fuel:

1. Install source and check shielding.
2. With the source inserted, dummy Al plates in, and water up, establish ionization chamber locations for 10% of low scale.
3. Check gamma background with only Sb part of source inserted.
4. Check trip action of all circuits with portable neutron source.
5. Check dump rate, rod drop and withdrawal speeds, and water fill rate.
6. Test action of all interlocks.

B. Addition of fuel:

1. These conditions were satisfied:
   a. Water down, dump valve open, water pump locked off. (Operator retained possession of key during loading.)
   b. Control rod fully inserted.
   c. Two safety rods cocked.
   d. Trip instruments on lowest scale and scaler on for audible monitoring.
2. Withdraw source to cave.
3. Load both side plates in each fuel box (24 plates containing a total of 456 gm U^{235}).
4. Fasten top cover.
5. Insert source.
6. Energize dump valve to close.
7. Unlock and start pump to fill tank (~15 min fill time).
8. Determine multiplication with water up including top reflector and control rod in.
9. Raise control rod by increments; check multiplication at each interval.

10. Obtain multiplication for clean system plus reflector.
11. Drop safeties and repeat multiplication count.
12. Dump water with manual scram button; run control rod in; remove source, and lock off pump.
13. Evaluate reciprocal count rate curve to determine next fuel addition. Do not add more than one-fourth the control rod worth.

C. Shutdown

1. Drop safety rods and dump water.
2. Withdraw source to cave.
3. Lock top cover.
4. Lock main power supply and keyed switch to pump power.
5. Store keys in combination file safe.

IV. Safety System

Shutdown was effected by insertion of cadmium blades and by moderator dump. Three blades operated in the exterior graphite reflector adjacent to the annulus. They were operated by drive units[6] with a magnetic clutch release for dropping a cadmium sheet (24 x 4 in.). The time for full insertion of the gravity-accelerated blades was $\sim$ 0.3 sec.

Three additional positions in the reflector were available for experimental control units other than safety rods.

Water dump was through a counterweighted 6-inch flap valve held closed with a magnetic clutch.

Trip conditions and the resultant actions were as follows:

1. Automatic safety rod drop.
   a. High multiplication.
   b. Power failure.
   c. Trip instrument failure.
2. Automatic water dump.
   a. High multiplication
   b. Power failure.
   c. Trip instrument failure.
   d. Top cover open.
   e. Safeties not cocked.
   f. Source level low.

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[6] H. H. Hummel, et al, "Summary Report of the Internal Exponential Experiment," ANL-5547 (March, 1956).

In addition to the above automatic control, the water and safeties could be dropped at the discretion of the operator with a manual scram button. After this or an instrument scram, manual reset was necessary to re-energize the safety rod and dump valve clutches.

V. Interlocks

The interlocks were wired so that a certain sequence of operations had to be satisfied before water could be added to the system. These were:

A. To close the dump valve.

1. Trip instruments on.
2. Top cover closed.
3. Source level satisfied.
4. Two safety rods cocked.

B. To start the H_2O pump.

1. Conditions listed under "A" satisfied.
2. Control rod fully inserted.

An ionization chamber and amplifier circuit was used for the source detector so that this interlock could be energized only if an active source were inserted. The cover and rod operated from appropriately placed microswitches.

VI. Instrumentation

Three independent trip channels were used: Two d-c amplifiers fed by parallel plate, boron-coated ionization chambers (10^{-13} amp/nv); the third was a count rate meter with BF_3 proportional counter. The counter was located in the internal thermal column and the chambers in the reflector.

Multiplication measurements were taken with BF_3 proportional counters. For a visual indication of small changes in multiplication, a recorder with a bucking voltage was used in conjunction with one of the d-c amplifiers.

APPENDIX B

SUMMARY OF TWO-GROUP NUCLEAR CONSTANTS

The following two-group constants were used in physics calculations for Argonaut. They are reproduced for the benefit of those who may wish to obtain theoretical estimates.

For a ratio of Al: H_2O = 0.4 by volume:

$\tau = 47.5\ cm^2$

$D_f = 1.193\ cm$

$D_s = 0.21817\ cm$

$\Sigma_{a_{th}}\ (cm^{-1}) = 0.01743\ (1 - x) + 28.2381(x)$,

where x is the volume fraction of U^{235}. No correction was made for the presence of U^{238}.

The graphite constants selected were:

$\tau = 365\ cm^2$

$D_f = 1.1\ cm$

$L^2 = 2500\ cm^2$

$D_s = 0.903\ cm.$

APPENDIX C

SELF-LIMITATION OF EXCURSIONS IN ARGONAUT

Because of its high void coefficient, Argonaut exhibits the same tendency toward self-limitation as BORAX-I, II, or SPERT-I. As a result of its longer lifetime, a greater reactivity insertion can be handled in Argonaut without melting the fuel plates than in either SPERT-I or BORAX-I and II.[7]

The prompt neutron lifetime in Argonaut is calculated to be 1.9×10^{-4} sec. In BORAX, it is about 0.75×10^{-4} sec and in SPERT-I it is 0.5×10^{-4} sec. The void coefficient in Argonaut is found to be -0.25. In SPERT-I it is -0.2; in BORAX-I it is -0.2 and in BORAX-II it is -0.10. A brief calculation at the end of this Appendix shows that when Argonaut is on a fast rising period, the plate temperature at the center of the fuel plates is less than the center plate temperature in the SPERT-I-type element for the same over-all power and period. Moreover, SPERT-I tests show that, for subcooled excursions, both the maximum reactor power and the maximum fuel temperature are the same functions of reciprocal period as they are in BORAX-I. Hence a conservative estimate of the maximum permissible reciprocal period in Argonaut is just the value of the same quantity in SPERT-I.

Data from the previously cited report are reproduced here as Fig. 22. These data yield a limiting value of the reciprocal period of 250 sec^{-1} or a 4-millisecond period if the center is half again as hot as the surface; or of 400 sec^{-1} if only the surface is to be kept from melting. Taking the calculated value of the lifetime, 1.9×10^{-4} sec, and the more conservative limiting value of 250 sec^{-1}, it is seen that Argonaut will be self-limiting without fuel plate melting for instantaneous reactivity insertions up to 0.0475 k_{eff}. This would require the insertion of $>$190 gm U^{235} into the internal thermal column, or 712 gm into the annulus. In view of the start-up safety system, which would easily detect the large increase in multiplication resulting from such a reactivity addition, it is difficult to see how such an addition could cause an accident at start-up. During reactor operation, the large amount of uranium which must be added makes such an accident unlikely. Ramp rate tests on SPERT-I show that the same limitations apply there as in the instantaneous insertion case, the excursion being self-limiting so that the maximum period is the same as though the reactivity had been added instantaneously.

The mechanism by which shut down is attained is not understood in detail. If, for example, the temperature of the SPERT-I fuel plates is computed as a function of time during an excursion on the assumption that the

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[7] W. E. Nyer, et al, "Experimental Investigations of Reactor Transients," IDO-16285 (April 20, 1956).

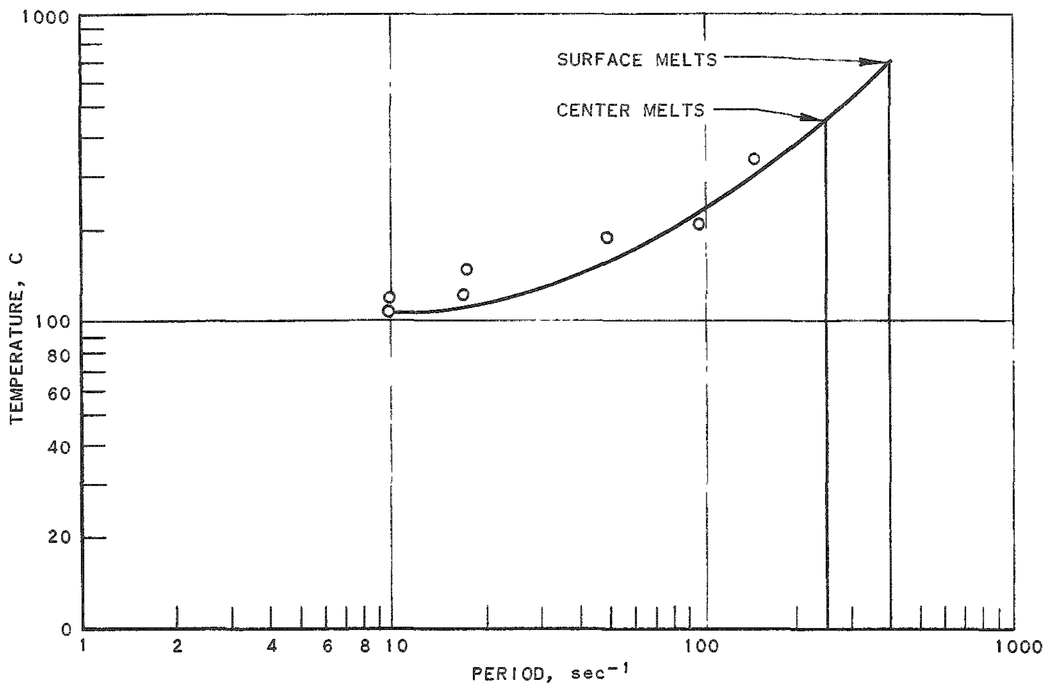


Fig. 22

MAXIMUM SURFACE TEMPERATURE OF SPERT-I AND BORAX-I FUEL PLATES VS. RECIPROCAL PERIOD

water is heated first by conduction and then by boiling heat transfer at constant heat flux, it is found that the plates will have melted long before the water has been heated up enough to shut the reactor down by boiling away water and thermal expansion. It is conjectured that the actual mechanism is that water next to the fuel plate is turned to steam in an iso-volumetric process; the rate of steam formation is governed by the heat flux, the pressure of the steam by the temperature at which it is formed. This steam is then assumed to expand adiabatically introducing voids by expelling a large portion of the water in each channel and substituting progressively lower and lower density steam in its place. Theoretical and experimental work to check this conjecture is planned.

If the foregoing conjecture is indeed the case, then it serves to demonstrate why the maximum safe excursion is governed largely by the period for reactors with a negative void coefficient. Briefly, the result of the iso-volumetric process is that whenever fuel plate temperature reaches a certain range, high-pressure steam is formed at a rapid rate, so rapidly that unless the void coefficient is quite small, or positive, the reactor is shut down in a rather short time. If the reactor period is long enough so that plate temperature does not increase substantially before shut down, then the excursion is safe. A hidden assumption here is that the water channels are not unusually wide. Another hidden assumption is that of subcooling, since at saturation conditions, other radiation-sensitive mechanisms may come into play. The central point is that the rate of void formation is very largely independent of plate temperature and its past history (constant heat flux into the water), and that the pressure at which the steam is formed depends upon the plate temperature in some simple fashion so that the dominating variable is the period.

In ANL-4951,[8] formulae are given for the temperature as a function of position in various types of plates and geometries when the neutron flux is increasing exponentially with time. On substituting in these formulae, it is found that the difference in center temperature of the Argonaut fuel plate and the MTR fuel plate is given by

$$\Delta T = 0.347(a/\alpha) - 0.297(a/\alpha)e^{\alpha t} \quad ,$$

where α is the reciprocal period and a is a material constant. ΔT is negative except for $t < 1/(6\alpha)$. For α of the order of a few hundred, this is less than one millisecond. The velocity of sound in water is 1461 meters/sec at 19C; thus, at a period of 4 ms, a pressure signal can be transmitted through 5.8 meters during one e-folding time. Since the characteristic dimension of the Argonaut core is 19 cm in the transverse direction, and 60 cm in the axial direction, it is clear that pressures equalize through the core before there is an appreciable pressure increase. Hence, a shock wave in the water will not occur. The larger dimensions of BORAX cores render it possible for a shock wave to occur.

[8] Reactor Engineering Division Quarterly Report, December, 1952.

APPENDIX D

AVIDAC CALCULATIONS OF RUNAWAY

Calculations have been made on the Argonne Electronic Computer, AVIDAC, of the flux and its instantaneous period as a function of time for a rate of reactivity insertion of 0.025%/sec. No shutdown mechanism was assumed.

Table II

AVIDAC CALCULATIONS OF RUNAWAY

Time, sec	Excess k	Flux, arbitrary units	Period, sec
0	0	1	10.87
5	0.00125	1.377	9.58
6	0.00150	1.518	5.9
10	0.00250	2.59	2.6
16	0.00400	11.95	1.37
20	0.00500	96.43	0.500
25	0.00625	37807.6	0.46
25.5	0.00638	107088.9	0.39
26.2	0.00658	670409.3	0.36
26.6	0.00668	1884056.4	

APPENDIX E

BLAST DAMAGE WITH CONTAINMENT OF THE REACTOR

An estimate is made of the energy release in the event of certain, highly unlikely, chemical reactions. Such excursions involve the burning of aluminum in water with subsequent recombination of the liberated hydrogen with atmospheric oxygen to yield a large chemical energy release. It is most difficult to conceive a means of bringing about such a situation in Argonaut. The reaction would have to be well contained and this would call not only for rendering ineffective all safety mechanisms, but for bringing in such additional structure as would be necessary to hold down the top plug long enough for the reaction to go to completion. Since the combustion of aluminum in water is similar to the burning of propellant powders in guns, it is useful to draw some conclusions from the theory of interior ballistics.

In the first place, in order for the flame front to be maintained, it is necessary for the aluminum to be finely dispersed. Secondly, a large portion (about 25%) of the blast energy goes into heating the container, and, since the burning rate is generally proportional to the pressure with an exponent a little greater than 1, carrying the reaction to completion requires a slow-burning powder or an extremely heavy container. In the case studied here, no mechanism is presented for dispersing the aluminum.

Two calculations are presented. In the first it is assumed that the explosion is contained only to the extent that a leaky gun is contained. In that case, the blast energy is about 25% of the total developable energy; an equal amount of energy (roughly) goes into heating and stressing the container. A sizable portion of the aluminum is not burned, and part of the energy will be expended in raising the top plug and surrounding structure. It will be shown that the total developable energy is similar to the release in an 8-inch gun, and hence there is small probability of excessive missile damage.[9]

The second set of calculations will assume that all the developable energy is released in the blast. It is not known how this can occur.

A. Incomplete Energy Release

The chemical reactions studied are:

$$2\ Al + 3\ H_2O \longrightarrow Al_2O_3 + 3\ H_2 + \Delta Q$$

$$6\ H_2 + 3\ O_2 \longrightarrow 6\ H_2O + \Delta Q'$$

,

[9]Comparisons with ballistic experience are taken from "Theory of Interior Ballistics of Guns," by John Corner (New York: J. Wiley and Sons, 1950).

for which ΔQ is 389×10^3 cal/mol of aluminum oxide, $\Delta Q'$ is 58×10^3 cal/mol of water. The energy to dissociate the water originally is developed through nuclear fission, which is also used to heat the water to steam. It is assumed also that nuclear energy is used to melt the aluminum; actually the aluminum must be further dispersed in fine particles; this may happen during the process of steam formation. The total chemical energy released by burning all the aluminum in the fuel plates and recombining the hydrogen with oxygen from the room is 2.63×10^{16} ergs. The mean molecular weight of the gas is 39 and the number of "mols" at this weight is 4.45×10^3. If the entire process takes place in the volume occupied by the core, the peak pressure is 10^{11} dynes/cm^2. The building volume is 9×10^8 cc. The recombination of the hydrogen with room oxygen reduces the room pressure to 0.945×10^6 dynes/cm^2. The burned gas expands adiabatically with an exponent of 1.2 (from ballistic experience).

If 25% of the total energy is released in the blast, the overpressure in the room when the room is completely filled is about 5 psi. Windows will be shattered by this pressure, particularly since they will have been earlier subjected to a shock wave of small, but appreciable, intensity. Doors will be blown open; it is not easily ascertainable that the building will withstand this loading. Blast damage outside the building confines will be negligible. In view of the massive side shield and of the necessity for holding down the top plug during the initial states of the excursion, missiles will be directed upwards and will probably land within the building confines after rising to heights of a few hundred feet at the most. The top plug may be blown through the roof.

The nuclear energy necessary to promote the explosion is 10^{16} ergs, requiring 3.33×10^{19} fissions. The approximate cloud height at night for energy releases of this order is given by the formula:[10]

$$H = \left(\frac{Q_h}{2\, c_p \rho (\pi)^{\frac{3}{2}} C^3 \theta'_a} \right)^{0.276}$$

where

Q_h = heat liberated (calories)

c_p = specific heat at constant pressure (0.25 calorie per gram per degree centigrade)

ρ = air density (grams per cubic meter)

θ'_a = gradient of potential temperature (degrees centigrade per meter)

C = diffusion coefficient, (meters)$^{\frac{1}{8}}$
C varies from 0.3 for stable to 0.6 for unstable conditions.

Under the conditions of the assumed explosion, the height would then be about 100 meters.

---

10 "Meteorology and Atomic Energy," AECU-3066 (July, 1955) p. 83.

B. Blast Totally Contained

If the blast is totally contained, the reaction goes to completion and then is released. The calculated overpressure based on all the energy going into the blast cloud is 3 atmospheres when the room is filled. The building will be destroyed, and blast damage will occur in a region not more than 30 meters from the reactor. Small missiles will be thrown a considerable distance beyond this. The number of fissions required to promote the process is the same.

APPENDIX F

HYDROLOGY AND SEISMOLOGY

A. Soil and Hydrology

1. Surface Characteristics and Drainage

Topographically, the DuPage site of Argonne National Laboratory is a rolling and partly rugged, partly forested plateau, rising quite sheerly from the Des Plaines River. The site is located on soil of a composition differing from the locality in general. Approximately 80% of the site is covered with yellow-gray silt loam (upland timber soil) and most of the remaining surface is exposed limestone, glacial river bottom, and river silt soils. The moraine overlies a Niagaran limestone formation to a depth varying from zero to 160 ft. Less than 5% of the soil is of the typical DuPage County composition, which is brown and black silt loams. There is very little precipitation penetration because, due to the type of soil, almost all rainfall is surface drained.

Bounding the DuPage site (elevation plus 750 ft) on the south is the Des Plaines River (elevation plus 590 ft), which flows southwesterly. The Des Plaines River, the Sanitary and Ship Canal, the Illinois and Michigan Canal, and the Sag Channel have all been interconnected by the time they reach Joliet, which lies about 14 miles southwest of the DuPage site (Fig. 23).

The water flow in the Des Plaines River just prior to Joliet varies between 10 and 100 cfs; the excess is diverted to the Sanitary Canal, at the point just south of Lemont, before reaching Joliet. The flow rate of the Sanitary Canal for 1944 and 1945 averaged about 3400 cfs; of this about 1600 cfs is water which has been diverted from Lake Michigan, and the balance is made up of domestic and industrial discharge from this district. Both the river and the canal flow approximately 20 miles per day. Any surface drainage, therefore, from the DuPage site would be diluted first by the river, bordering the site, and then further diluted by the canal within 14 miles, normally within 17 hours, unless such drainage occurred during a wet period when it would then be diluted more extensively and sooner.

Canal water is used prior to and in Joliet for some industrial uses, such as hydro-electric generators and condensers, as well as for irrigation at the state prison. After leaving Joliet, the Des Plaines River carries these waters southwest to a point approximately 14 miles further where the river is joined by the Kankakee River forming the Illinois River. The first use made of this water for drinking purposes is at Alton, Illinois, which is about 275 miles from the DuPage site and 10 miles downstream from the point where the Illinois River merges with the Mississippi River. Both Alton and East St. Louis treat about five million gallons per day of this Mississippi River water.

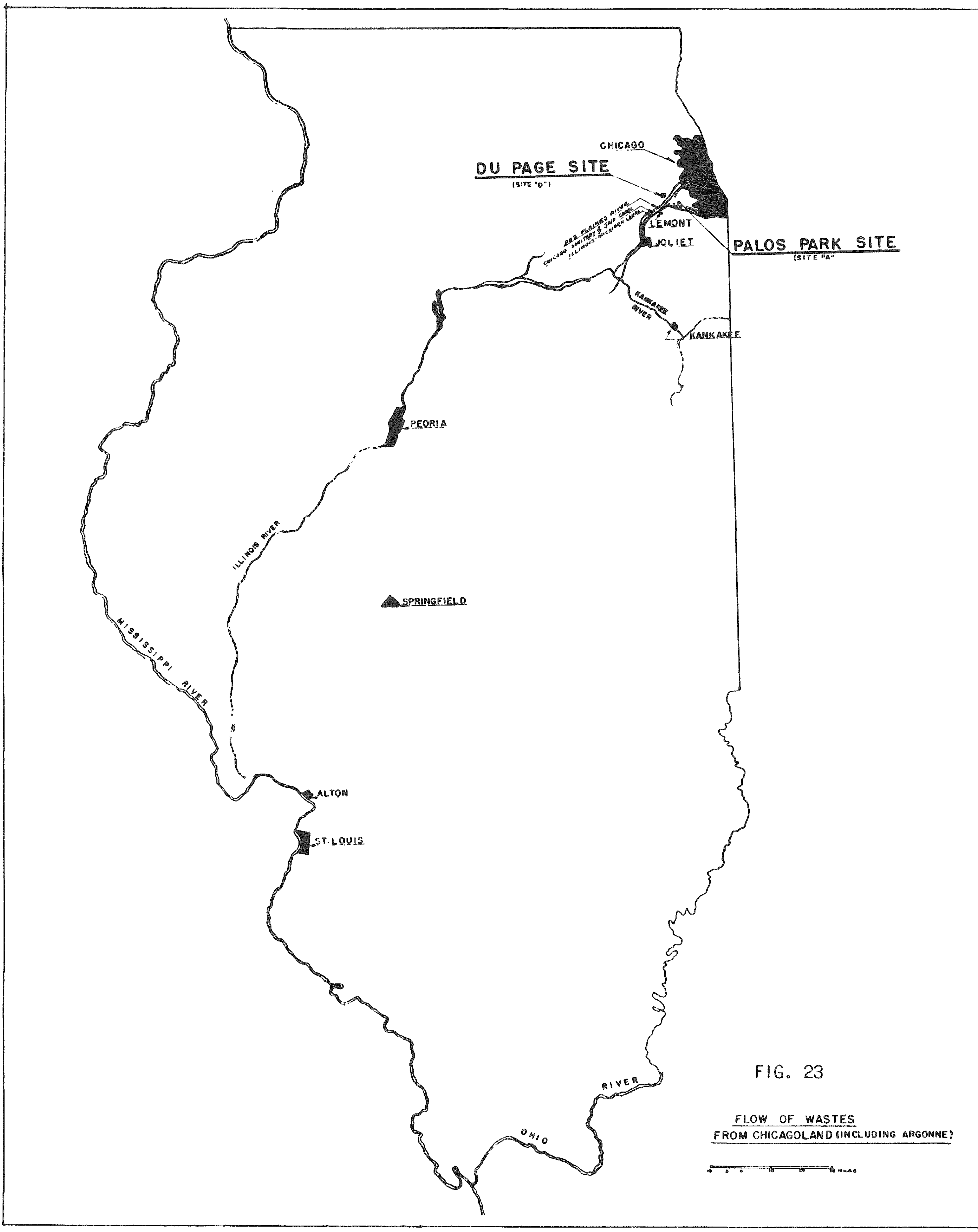


FIG. 23

FLOW OF WASTES FROM CHICAGOLAND (INCLUDING ARGONNE)

2. Sub-surface Water Conditions

The geology of the DuPage site including the sub-surface water conditions is described in a report entitled "Geology and Ground-Water Hydrology of the Argonne National Laboratory Area, DuPage County, Illinois" by Allen, Drescher and Foley, Consultants to the U. S. Atomic Energy Commission. Presumably, copies of this report are available for the AEC. The following statement concerning any possible hazard due to water-borne activity has been prepared by Dr. F. C. Foley, who is the senior author of the above-mentioned report.

Ground water in the Laboratory area is obtained from two principal aquifers, the Niagara dolomite and deeply buried Ordovician and Cambrian sandstones. The two shallow supply wells in the Laboratory area obtain water from the Niagara dolomite while the deep well is cased and sealed through the Niagara and gets its water from the deep sandstones. Only the Niagara dolomite needs to be considered in connection with possible contamination from an accidental spill of radioactive liquid, as the deep aquifers are separated from the surface by hundreds of feet of rock formations of which the Maquoketa shale is particularly impermeable.

The uppermost formation at the Laboratory site is glacial till of Late Wisconsin age, which overlies the Niagara dolomite. It covers the whole area except along the bluff on the valley of the Des Plaines River, Chicago Sanitary and Ship Canal and along Mill Creek below Bluff Road. The till has a maximum thickness of about 180 ft. It consists of clay and silty clay containing fragments of dolomite and other consolidated rock, and a few thin lenses of sand.

The glacial till is relatively impermeable and water moves through it very slowly. No experimental work has been done at the Laboratory site to determine the exact rate of movement, but such work is planned. At the site of the Argonne Research Reactor, the glacial till is about 110 ft thick. It is estimated that about one year would be required for water introduced near the surface to penetrate to the top of the Niagara dolomite. All the time, and even if it did, it would be diluted with normal ground water descending with it. Once it entered the Niagara it would move through open fissures down the hydraulic gradient, which is generally southeastward and not toward the present supply wells. The closest well in use is the meteorology station well. It might seep gradually into the Des Plaines River over an extended period of time. In view of the great thickness of relatively impermeable glacial till at the reactor site, and the direction of the hydraulic gradient in the Niagara dolomite, it is very doubtful that radioactive liquids would enter the Laboratory supply well or private wells. It is probable that such liquids would be extremely diluted by natural water.

B. Seismology

Realistic prediction regarding earthquakes or earthshocks, their frequency and severity, can only be based upon the seismic history of the area concerned. Apparently, new trouble areas seldom occur and this is particularly true of the United States. Insofar as the Argonne sites are concerned, it is expected that no building of sound construction on firm ground will suffer any damage as a result of the infrequent and small earthquakes which may occur anywhere within 150 miles from the sites. It is conceded that earthquakes occurring as far as 500 miles away may disturb sensitive laboratory apparatus.

APPENDIX G

MAKE-UP OF SURROUNDING AREA

The map of the territory surrounding the Reactor Site (see Fig. 24) is useful for orienting the DuPage site insofar as this region, in general, is concerned. It is evident that a higher density of population occurs, because of communities, in the directions starting northwest and moving clockwise to the southeast.

Table III below shows population distributions, using the DuPage site as a focal point, for areas up to 20 miles in diameter. Also, Fig. 24 shows various industrial installations worthy of note and the Hinsdale Sanitarium.

Table III

POPULATION DISTRIBUTION

(DuPage Site as Center)

Item No.	Region	Estimated** Population (1950 Census)	Area (Sq. Miles)	Density (Av. Population per Sq. Mile)
1	Total within 1-1/2-mile radius*	3,500	6.9	507
2	In the band between 1-1/2- and 5-mile radius	13,000	71.6	182
3	In the band between 5- and 10-mile radius	84,000	235.7	357
4	Total within the 5-mile radius	16,000	78.5	204
5	Total within the 10-mile radius	100,000	314.2	319

*During normal working hours.

**The population in this area is increasing at about 10% per year.

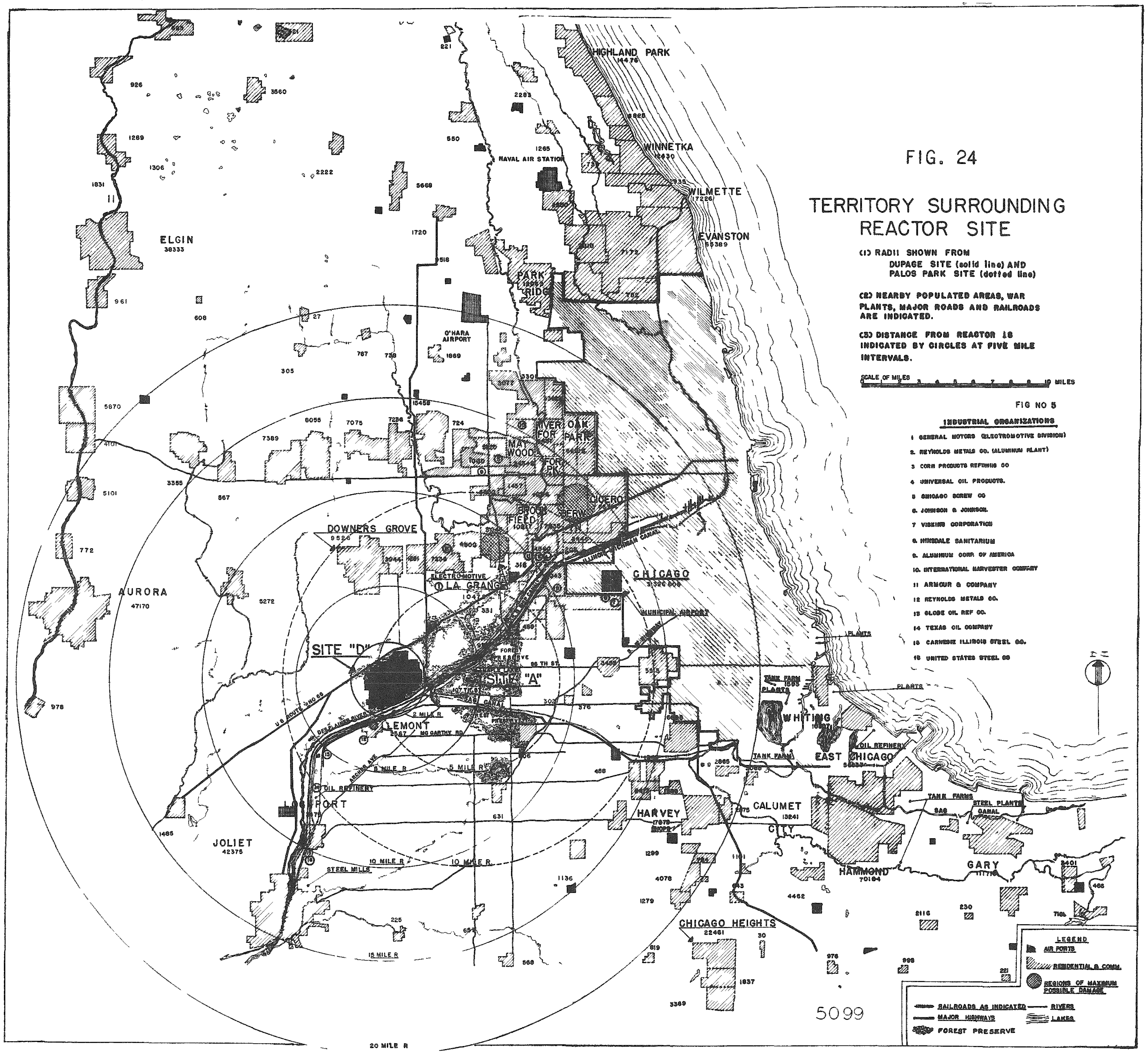


FIG. 24

TERRITORY SURROUNDING REACTOR SITE

(1) RADII SHOWN FROM DUPAGE SITE (solid line) AND PALOS PARK SITE (dotted line)

(2) NEARBY POPULATED AREAS, WAR PLANTS, MAJOR ROADS AND RAILROADS ARE INDICATED.

(3) DISTANCE FROM REACTOR IS INDICATED BY CIRCLES AT FIVE MILE INTERVALS.

APPENDIX H

CLIMATOLOGY (METEOROLOGY GROUP)

Annual climatological summaries based on measurements taken at the DuPage site of the Argonne National Laboratory have been prepared and published as reports ANL-4538, ANL-4793, ANL-4928, and ANL-5256. These reports cover the period beginning July 1949 and ending June 1953. As a supplement to the Argonne data, monthly weather summaries prepared by the United States Weather Bureau are included as appendices to these annual climatological reports.

I. Wind Measurements

Wind measurements taken by both the U. S. Weather Bureau and the Argonne National Laboratory are presented in this report. Although the wind measurements made at Argonne are more representative of this site, the Weather Bureau data are included since they represent the best available long series of measurements for this area. Upper air wind data obtained by the U. S. Weather Bureau are also presented here. No upper air measurements obtained with the aid of balloons are available for the Argonne site.

Surface wind roses based on 10 years of Weather Bureau data gathered at the Chicago Midway Airport are shown in Fig. 25. Figures 26 and 27 are upper air wind roses for this area.

Several wind studies based on data included in the four abovementioned ANL climatological reports and on data for an additional year have been made and are presented in Tables IV - VII. Table IV consists of a joint frequency distribution of wind speed and direction for the 5-year period July 1949 to June 1954. A similar study for a single year is shown in Table V. However, in this table the frequencies are given on a percentage basis.

To facilitate hazard evaluation, information on how long a given wind direction may persist is desirable. An investigation of the number of times the wind from a particular direction persisted for a given number of hours was made and the results are given in Table VI. Again these data are based on the 5-year period from July 1949 through June 1954. A similar study based on data from July 1949 through June 1950 is shown in Table VII.

II. Frequency of Turbulent and Stable Conditions

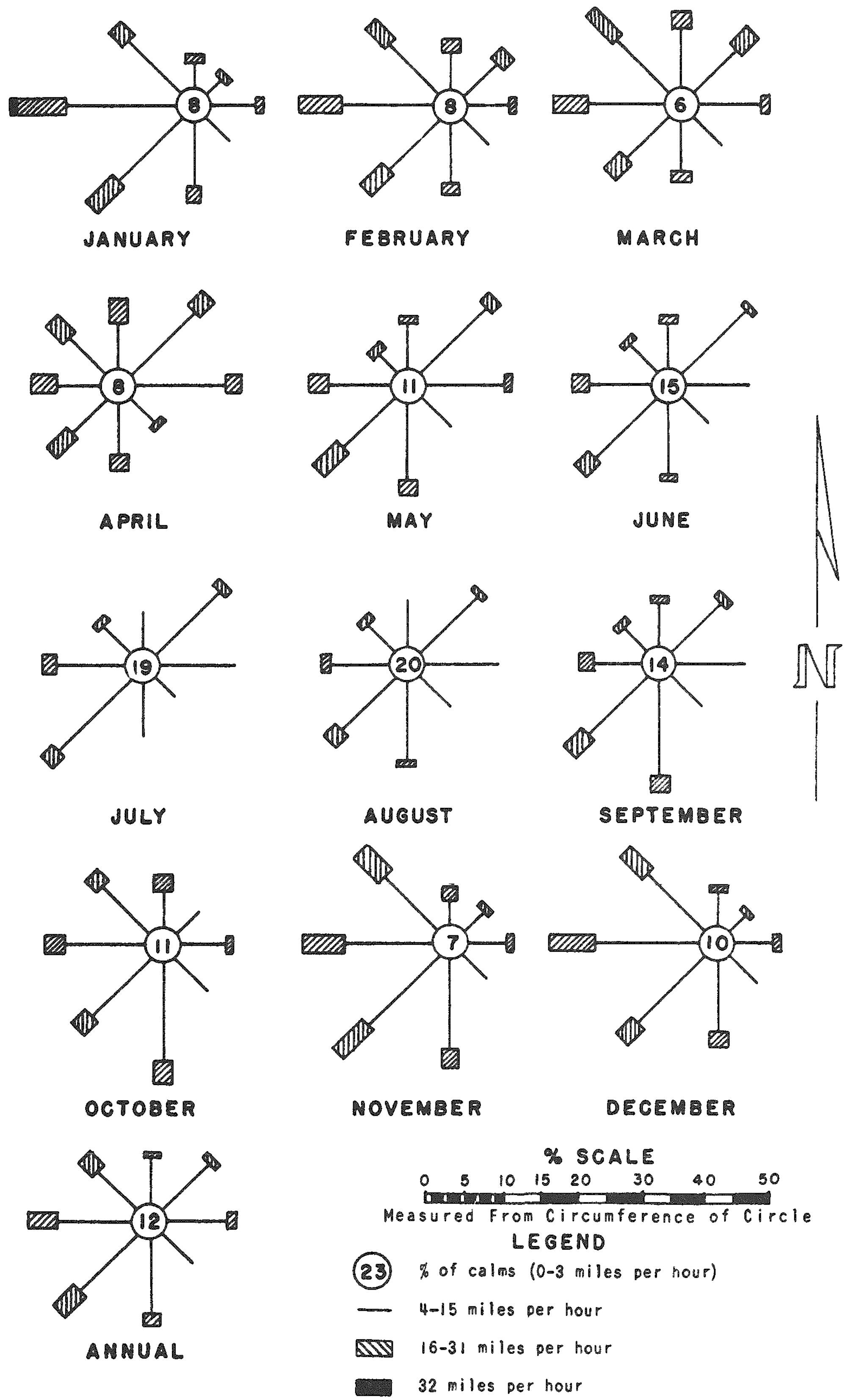
Several studies to determine the relative frequency of turbulence or periods of rapid diffusion have been made. One of these studies, based on

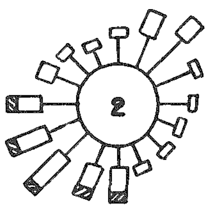
FIG. 25

SURFACE WIND ROSES

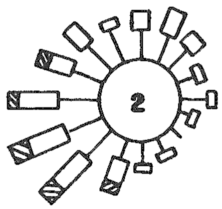
CHICAGO MIDWAY AIRPORT, CHICAGO, ILLINOIS

BASED ON 85,133 OBSERVATIONS COPIED FROM AIRWAY METEORLOGICAL ATLAS FOR THE UNITED STATES.
U. S. WEATHER BUREAU

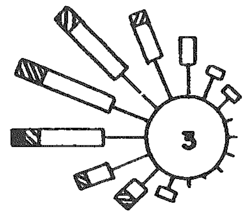




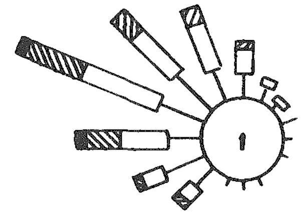
500 METERS
(4145 OBSERVATIONS)



1000 METERS
(4036 OBSERVATIONS)

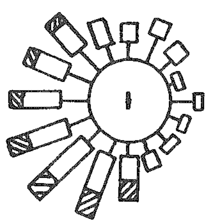


3000 METERS
(2233 OBSERVATIONS)

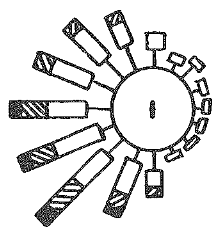


5000 METERS
(417 OBSERVATIONS)

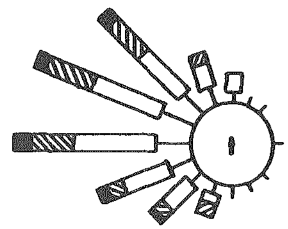
JUNE - JULY - AUGUST



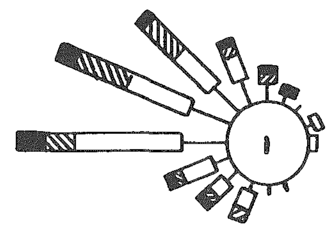
500 METERS
(3985 OBSERVATIONS)



1000 METERS
(3620 OBSERVATIONS)



3000 METERS
(1309 OBSERVATIONS)



5000 METERS
(205 OBSERVATIONS)

SEPTEMBER - OCTOBER - NOVEMBER

LEGEND

(23) % of calms (0-1 m.p.s.)
—— 2-7 meters per second
▭ 8-14 meters per second
▨ 15-21 meters per second
■ 22 meters per second & over

Indicated heights are above sea level.

N

% SCALE

0 5 10 15 20 30 40 50

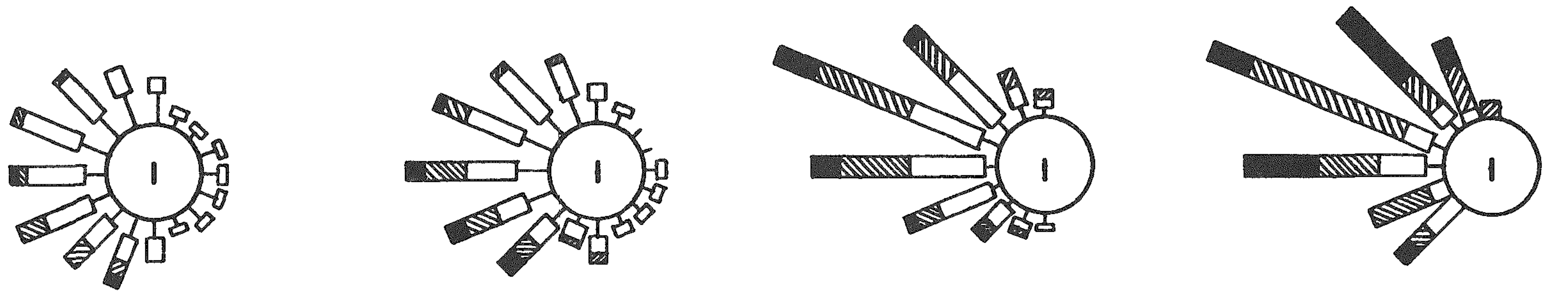
Measured From Circumference of Circle

FIG. 26

UPPER AIR WIND ROSES

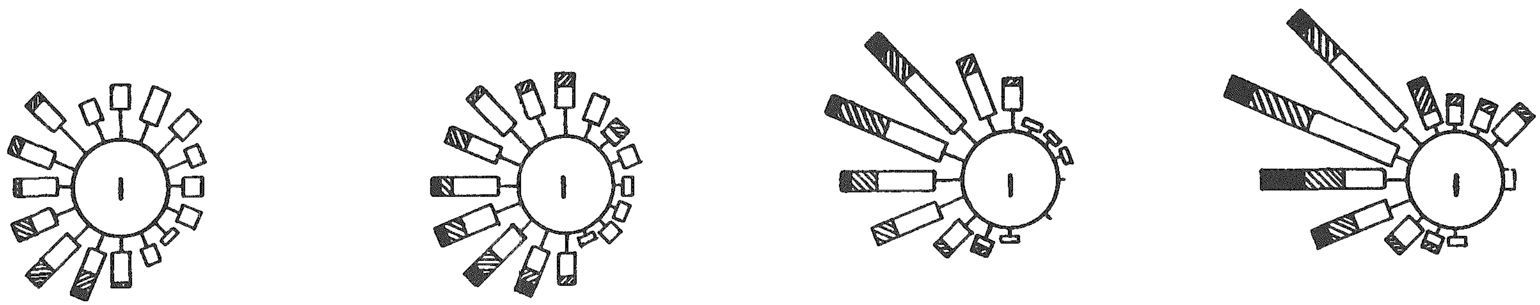
CHICAGO MIDWAY AIRPORT, CHICAGO, ILLINOIS

NOTE: THESE DATA WERE TAKEN FROM THE AIRWAY METEORLOGICAL ATLAS FOR THE UNITED STATES U.S. WEATHER BUREAU



500 METERS (3276 OBSERVATIONS) — **1000 METERS** (2698 OBSERVATIONS) — **3000 METERS** (631 OBSERVATIONS) — **5000 METERS** (58 OBSERVATIONS)

DECEMBER - JANUARY - FEBRUARY



500 METERS (3705 OBSERVATIONS) — **1000 METERS** (3428 OBSERVATIONS) — **3000 METERS** (1212 OBSERVATIONS) — **5000 METERS** (198 OBSERVATIONS)

MARCH - APRIL - MAY

LEGEND

- (23) % of calms (0-1 m.p.s.)
- ——— 2-7 meters per second
- ▭ 8-14 meters per second
- ▨ 15-21 meters per second
- ▬ 22 meters per second & over

Indicated heights are above sea level.

% SCALE

0 5 10 15 20 30 40 50

Measured From Circumference of Circle

FIG. 27

UPPER AIR WIND ROSES

CHICAGO MIDWAY AIRPORT, CHICAGO, ILLINOIS

NOTE: THESE DATA WERE TAKEN FROM THE AIRWAY METEORLOGICAL ATLAS FOR THE UNITED STATES U.S. WEATHER BUREAU

TABLE IV

Joint Frequency Distribution of Wind Direction and Wind Speed
July 1949 - June 1954

LEVEL	DIRECTION (16 POINTS)	WIND SPEED (MPH) CALM	1-3	4-7	8-12	13-18	19-24	25-31	32-38	39-46	> 46	MISSING	TOTAL	PER CENT
150 - FOOT	CALM	258	8									3	269	0.6
	NNE	2	82	272	892	696	212	50	1			2	2209	5.0
	NE		51	207	644	510	118	30	1			2	1563	3.6
	ENE	2	51	229	789	528	178	40	7			8	1832	4.2
	E	2	90	440	1290	516	120	33	2			4	2497	5.7
	ESE	1	65	247	681	365	54	3				4	1420	3.2
	SE	1	58	256	645	286	57	11	1			3	1318	3.0
	SSE		81	346	831	400	151	25	7			2	1843	4.2
	S	4	76	425	1452	1213	460	139	27	8		4	3806	8.7
	SSW		64	330	1193	1390	705	134	16	4		9	3845	8.8
	SW	1	61	265	960	1294	574	131	7	6		10	3309	7.6
	WSW	2	60	260	918	991	423	169	37	10		10	2880	6.6
	W		86	369	1245	1528	629	319	107	15	1	6	4305	9.8
	WNW	1	68	304	893	1142	422	154	20			9	3013	6.9
	NW	1	52	209	701	884	281	64	2	1		12	2207	5.0
	NNW		82	281	806	966	304	70	22	1		18	2550	5.8
	N	5	71	339	998	945	280	63	5			8	2714	6.2
	VARIABLE	13	134	93	20	6	5						271	0.6
	MISSING	8	61	241	774	379	65	5	3	2		435	1973	4.5
	TOTAL	301	1301	5111	15732	14039	5038	1440	265	47	1	549	43824	
	PER CENT	.7	3.0	11.7	35.9	32.0	11.5	3.3	.6	.1		1.3		
19 - FOOT	CALM	1115	73									1	1189	2.7
	NNE	8	454	972	788	231	38					21	2512	5.7
	NE	9	329	648	548	158	20	1				13	1726	3.9
	ENE	9	344	719	632	215	40	4				11	1974	4.5
	E	5	503	1047	568	210	22					7	2362	5.4
	ESE	5	431	521	345	72	1					6	1381	3.2
	SE	3	392	586	338	91	3					3	1416	3.2
	SSE	1	420	653	521	162	15	2				3	1777	4.1
	S	2	322	967	1134	564	99	17	1			6	3112	7.1
	SSW	2	358	1329	1382	723	69	12	1			9	3885	8.9
	SW	5	458	1208	1237	471	60	9				4	3452	7.9
	WSW	2	389	1055	902	444	131	25	1			2	2951	6.7
	W	2	422	1564	1380	774	282	54				7	4485	10.2
	WNW	2	219	971	911	467	123	14				3	2710	6.2
	NW	1	206	749	789	357	49	1					2152	4.9
	NNW	2	261	783	858	525	85	17				5	2536	5.8
	N	9	402	1036	924	397	50	7				12	2837	6.5
	VARIABLE	7	264	147	12							3	433	1.0
	MISSING	18	79	228	204	61	6	1				337	934	2.1
	TOTAL	1207	6326	15183	13473	5922	1093	164	3			453	43824	
	PER CENT	2.8	14.4	34.6	30.7	13.5	2.5	.4				1.0		

TABLE V

WIND DIRECTION AND SPEED - PER CENT OF TOTAL NUMBER OF HOURLY OCCURRENCES FOR EACH DIRECTION AND SPEED GROUP

(19-Foot Level - July 1949 to June, 1950)

Wind Speed in Miles Per Hour

	1	1-3	4-7	8-12	13-18	19-24	25-31	32-38	Miss-ing	Total %
CALM	2.8									2.8
NNE		1.1	2.0	1.5	.3				.2	5.0
NE		.6	1.6	1.2	.3				.1	4.0
ENE		.4	1.7	1.4	.7	.1			.1	4.4
E		.8	2.1	1.4	.6				.1	4.9
ESE		.6	.9	.8	.2				.1	2.5
SE		.6	1.2	.9	.3					3.0
SSE		.5	1.3	1.3	.3	.1				3.5
S		.6	2.5	3.1	2.0	.4	.1			8.8
SSW		.5	2.7	2.5	.9	.1				6.7
SW		.6	3.0	3.4	1.2	.2				8.5
WSW		.7	2.4	1.7	.9	.5	.1			6.2
W		.7	3.1	3.0	2.0	.7	.3		.1	9.9
WNW		.2	1.8	1.9	1.1	.6	.1			5.8
NW		.3	1.6	1.9	1.0	.2				5.0
NNW		.3	1.6	1.9	1.4	.2			.1	5.4
N		1.1	2.2	1.3	.5				.1	5.2
VARIABLE		.9	.5	.1						1.6
MISSING		.9	2.2	1.8	.6	.1				6.8
TOTAL %	2.8	11.4	34.4	31.1	14.3	3.2	.6		1.3	100.0

TABLE VI

Persistence of Wind Direction - 150-Foot Level
July 1949 - June 1954

HOURS	WIND DIRECTION (8 POINTS)											TOTAL FRE-QUENCY	TOTAL HOURS
	CALM	NE	E	SE	S	SW	W	NW	N	VARI-ABLE	MISSING		
1	163	511	428	422	552	653	668	586	560	168	41	4752	4752
2	29	220	193	216	240	277	299	282	243	21	8	2028	4056
3	7	128	107	134	137	182	188	199	129	10	5	1226	3678
4	3	87	90	85	106	130	120	101	87	5	4	818	3272
5		44	60	42	62	92	73	64	59	1	4	501	2505
6	1	33	34	42	74	64	66	44	32	1	5	396	2376
7		27	32	18	42	49	47	45	35		4	299	2093
8		24	14	19	36	41	40	35	23			232	1856
9	1	28	21	24	29	30	30	24	19		4	210	1890
10		14	22	12	27	40	26	14	12			167	1670
11		9	11	10	21	31	20	16	18		1	137	1507
12		5	8	6	14	29	18	12	10			102	1224
13		9	6	1	15	8	13	10	12			74	962
14		4	8	6	7	9	19	12	10		4	79	1106
15		6	5	3	11	10	12	4	10		1	62	930
16		7	4	1	8	12	8	9	3			52	832
17		7	4		6	9	9	3	1		1	40	680
18		2	6	1	10	8	5	9	2		1	44	792
19		5	3	1	9	5	7	5	2		1	38	722
20		2	4	1	8	3	4	4	2			28	560
21		2	1	1	4	6	5	2	1		2	24	504
22			2		2	4	1	1	4			14	308
23		1	1		1	1	2	1	2		1	10	230
24		1	1	1	3	2	3	1	2			14	336
25					1	3	4	1	2			11	275
26		1	1		1	1	3	1	3			11	286
27			1		2	2	4				1	10	270
28				1	2	3	2	2	2			12	336
29				1	3	1	1	1				7	203
30			1		3	1	2	1			1	9	270
31						2	2	1				5	155
32					2				2			4	128
33					1	1		1	2			5	165
34		1					1					2	68
35					1	1			1			3	105
36			1			2		1				4	144
37					1							1	37
38						1	1				1	3	114
39			1					2				3	117
40			1								1	2	80
41							1	1			1	3	123
42		1					1		1			3	126
43						1					1	2	86
44						1						1	44
46					1			1				2	92
47					1							1	47
48					1	2						3	144
49											1	1	49
51						1						1	51
54						1	1					2	108
58							1					1	58
61											1	1	61
63											1	1	63
72											1	1	72
302											1	1	302
380											1	1	380
424											1	1	424
												TOTAL	43824

TABLE VII

PER CENT OF TIME DURING ONE YEAR THAT WIND FROM A SPECIFIC DIRECTION PERSISTED, DISTRIBUTED ACCORDING TO WIND DIRECTION AND DURATION OF PERSISTENCE

(150-Foot Level, July 1949-June 1950)

Hours	Calm %	NE %	E %	SE %	S %	SW %	W %	NW %	N %	Variable %	Total %
1 hour or less	.26	1.97	2.05	1.89	2.73	3.38	3.23	2.74	2.24	.66	21.16
Longer than 1	.10	5.47	5.13	3.71	10.63	11.76	11.45	7.68	5.14	.36	61.59
Longer than 2	.02	4.31	3.94	2.63	8.83	9.58	9.37	5.87	3.90	.18	48.78
Longer than 3	.01	3.53	3.10	1.90	7.55	7.99	7.83	4.67	2.99	.07	39.79
Longer than 4	0	2.95	2.46	1.40	6.47	6.69	6.61	3.83	2.35	.02	32.92
Longer than 5		2.53	2.03	1.03	6.38	5.63	5.63	3.21	1.85	.01	27.62
Longer than 6		2.21	1.68	.72	5.56	4.82	4.76	2.68	1.46	0	23.22
Longer than 7		1.92	1.39	.50	4.86	4.14	4.10	2.22	1.12		19.59
Longer than 8		1.67	1.16	.29	4.26	3.56	3.54	1.88	.90		16.60
Longer than 9		1.48	.98	.14	3.75	3.05	3.08	1.62	.73		14.16
Longer than 10		1.32	.82	.07	3.33	2.64	2.70	1.39	.59		12.20
Longer than 11		1.17	.67	.02	2.95	2.33	2.35	1.17	.48		10.49
Longer than 12		1.04	.54	0	2.62	2.10	2.02	.96	.37		9.01
Longer than 13		.91	.43		2.32	1.89	1.75	.77	.28		7.71
Longer than 14		.81	.34		2.07	1.70	1.51	.61	.21		6.60
Longer than 15		.71	.25		1.84	1.51	1.33	.48	.16		5.63
Longer than 16		.62	.17		1.66	1.33	1.18	.35	.14		4.80
Longer than 17		.53	.10		1.51	1.20	1.05	.26	.12		4.13
Longer than 18		.46	.04		1.37	1.07	.95	.20	.10		3.56
Longer than 19		.40	.02		1.26	.97	.86	.15	.08		3.10
Longer than 20		.37	.01		1.19	.87	.79	.12	.06		2.76

data for the year July 1949 - June 1950, uses the wind data only, i.e., wind speed ratio is used as the criterion of turbulence. The wind speed ratio is obtained from readings at the 150-foot and 19-foot levels on the Meteorology Tower. This study is based on wind data only since temperature lapse rate data are unavailable for this period.

For the period July 1951 - June 1954 both wind data and temperature lapse rate data are available. A number of studies combining these parameters are shown below.

Wind ratios as a measure of turbulence have been used very successfully by the British Chemical Warfare Service. Also it is by means of the wind ratio expressed by the parameter n that Sutton varies the index of turbulence in his diffusion formula (see Section IV below). (Ministry of Supply-Rearmament Records of Research and Development, No. 9.400.)

The following relationship between wind ratio and n as presented by Sutton is a satisfactory first approximation:

$$\frac{u}{u_0} = \left(\frac{Z}{Z_0}\right)^{\frac{n}{2-n}}$$

u = Wind speed at upper level
u_0 = Wind speed at lower level
Z = Height of upper level
Z_0 = Height of lower level

The British found that the wind speed ratio was related to three meteorological quantities: wind speed, change of temperature with height, and surface roughness. They also found that it is a useful indicator for the degree of turbulent diffusion of gases (or particulate matter of less than 10μ) in the atmosphere. This is to be expected since the distribution of wind speed with height is a result of the transfer of momentum, and it is generally assumed that this transfer is accomplished by the same turbulent eddies which achieve the diffusion of gases (or particulate matter of less than 10μ) in the lower layers of the atmosphere.

The calculations of wind ratios at the DuPage site are made under different surface roughness conditions and over a different height interval than the British measurements, which were made at heights of 2 meters and 1 meter above the ground. Measurements of surface roughness have not been made at the DuPage site. However, a spot check of the data indicates that the contribution of the surface roughness to the ratio of wind speed at 150 feet to 19 feet is not as large as the contribution found by the British. This is, perhaps, because of the larger and more elevated height interval used at the DuPage site.

A comparison of the values of n computed from the Argonne wind ratios with the values of n obtained by the British, using time of day and wind speed to determine roughly the amount of turbulence present, indicates that the relationship between n and turbulence determined experimentally by the British can be applied to the Argonne data. The ranges of n adapted for the various stability limits differ slightly from those of the British and are shown in Table VIII.

TABLE VIII

NUMBER OF OCCURRENCES OF RATIO OF WIND SPEED AT 150 FEET TO WIND SPEED AT 19 FEET (R) FOR THREE GENERAL CLASSIFICATIONS OF TURBULENCE GROUPED ACCORDING TO WIND SPEED AT 19-FOOT LEVEL (JULY 1949 - JUNE 1950)

	Wind speed for 19-foot level in miles/hr											
	n	R	0	1-2	3-7	8-12	13-18	19-24	25-31	32-38	Total	%
Turbulent	-1.000-.273	0.50-1.39	14	61	498	940	695	189	44	1	2442	27.9
Neutral	.279 - .340	1.40-1.53	0	27	318	592	344	78	16	0	1375	15.7
Non-Turbulent	.344 - 1.000	1.54-8.00	103	446	2575	1105	198	6	0	0	4433	50.6
									Missing Data			5.8
											Total	100%

THEORETICALLY n SHOULD NOT BE NEGATIVE. THE FEW CASES OF R LESS THAN 1 APPEAR TO BE DUE TO LOCAL TERRAIN EFFECTS.

Since the biggest possibility of error lies in the boundaries of the neutral zone, between 0.300 and 0.335 according to the British, this neutral zone was expanded from 0.279 to 0.340 to include any doubtful cases of stable or unstable turbulence in the neutral or change-over zone. The use of only three categories for the whole range of conditions of turbulence is somewhat misleading. However, it is impossible to make a detailed breakdown without a more thorough investigation into the quantitative variation of wind ratio with both wind speed and the vertical distribution of temperature. This breakdown is sufficient for the type of calculations which can be made in this report.

In Table VIII, the cases where the wind speed at the 19-foot level was 0 had to be considered in a different manner, since the wind ratio would be infinite. Here the breakdown was accomplished by assuming stable conditions during the hours of darkness and unstable conditions with the hours of sunshine. Research since this breakdown was completed indicates that in some cases with a wind ratio of 1.54 - 1.69 the accompanying wind speed may create enough mechanical turbulence to place these cases in the unstable category. However, the possible error cannot exceed 5 or 6 per cent of the data and is on the side of safety.

A summary of the frequency of occurrence of atmospheric stability based on measurements taken at the DuPage site for the period July 1951 - June 1954 is presented in Table IX. The temperature differences were obtained by thermopiles which were well aspirated and shielded from solar radiation. One thermopile was mounted about 5 feet above the ground and the other on a tower at 144 feet.

Table IX

FREQUENCY DISTRIBUTION OF TEMPERATURE DIFFERENCES IN HEIGHT INTERVAL OF 42 METERS

July 1951 - June 1954

	Temperature Diff. °C (T_{top} minus T_{bottom}) Over Height Interval of 42 meters	No. of Cases July 1951 - June 1954
Unstable 26.3%	$\leqslant$-2.0	10
	-1.9 to -1.5	224
	-1.4 to -1.0	1615
	-0.9 to -0.5	4615
Near Neutral 28.3%	-0.4 to 0.0	6957
Stable 45.4%	0.1 to 0.5	3597
	0.6 to 1.0	1942
	1.1 to 1.5	1329
	1.6 to 2.0	1098
	2.1 to 2.5	793
	2.6 to 3.0	541
	> 3.0	1868

As a further aid in determining how often periods of rapid and slow diffusion may prevail the studies of Tables X - XIII are presented. In these studies the data were separated into two periods. The first period, 0800 - 1800, was chosen as representing the period of working hours or the period during which the population density onsite is high. The second period, 1900 - 0700, is considered the off-hour period.

In Tables X and XI are shown the relationship between lapse rate and wind speed and in Tables XII and XIII the relationship between lapse rate and wind ratio. It is evident from these tables that the parameters depend upon

TABLE X

JOINT FREQUENCY DISTRIBUTION OF VERTICAL TEMPERATURE DIFFERENCE VERSUS 19–FOOT WIND SPEED DURING THE HOURS 1900 THROUGH 0700 FOR THE PERIOD JULY 1951–JUNE 1953

Temperature Difference $T_{144} - T_{5.5}$ (°C)	19–foot Wind Speed (mph)										Total
	0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	⩾40	Missing	
⩽2.0											
−1.9 to −1.5	1	1		1	1						4
−1.4 to −1.0		1	4		2						7
−0.9 to −0.5	34	107	71	31	16	5	3				267
−0.4 to 0.0	270	881	764	251	87	14	4			2	2273
0.1 to 0.5	314	812	506	125	23	5	2			3	1790
0.6 to 1.0	328	553	159	9	4	1				3	1057
1.1 to 1.5	351	347	24	5							727
1.6 to 2.0	367	261	17							1	646
2.1 to 2.5	318	146	3		1					3	471
2.6 to 3.0	314	113	2		1					1	431
>3.0	899	255								1	1155
Missing	276	257	110	23	8	1					675
Total	3472	3734	1660	445	143	26	9			14	9503

TABLE XI

JOINT FREQUENCY DISTRIBUTION OF VERTICAL TEMPERATURE DIFFERENCE VERSUS 19–FOOT WIND SPEED DURING THE HOURS 0800 THROUGH 1800 FOR THE PERIOD JULY 1951–JUNE 1953

Temperature Difference $T_{144} - T_{5.5}$ (°C)	19–foot Wind Speed (mph)										Total
	0–4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	≥40	Missing	
⩽2.0			2	1	1						4
–1.9 to –1.5	6	32	57	30	5						130
–1.4 to –1.0	113	252	255	68	20	2					710
–0.9 to –0.5	437	913	809	236	61	4				1	2461
–0.4 to 0.0	266	890	876	339	113	25				3	2512
0.1 to 0.5	113	322	335	87	27	5					889
0.6 to 1.0	97	166	102	34	6	2					407
1.1 to 1.5	70	79	26	5	1						181
1.6 to 2.0	37	51	9								97
2.1 to 2.5	33	14	9	4							60
2.6 to 3.0	17	7		3							27
>3.0	26	6	1	1							34
Missing	124	206	133	50	15					1	529
Total	1339	2938	2614	858	249	38				5	8041

TABLE XII

JOINT FREQUENCY DISTRIBUTION OF VERTICAL TEMPERATURE DIFFERENCE VERSUS 150/19 FOOT WIND SPEED RATIO DURING THE HOURS 0800 THROUGH 1800 FOR THE PERIOD JULY 1951–JUNE 1953

Temperature Difference $T_{144} - T_{5.5}$ (°C)	Wind Speed Ratio (U_{150}/U_{19})									Total
	<1.0	1.0 – 1.2	1.3 – 1.5	1.6 – 1.8	1.9 – 2.1	2.2 – 2.4	2.5 – 2.9	⩾3.0	Missing	
⩽2.0		1	3							4
–1.9 to –1.5	5	64	51	3					7	130
–1.4 to –1.0	21	254	292	31	11	2			99	710
–0.9 to –0.5	33	680	1144	172	25	6	4	1	396	2461
–0.4 to 0.0	34	456	1324	364	84	17	10	8	215	2512
0.1 to 0.5	2	128	408	194	40	20	8	8	81	889
0.6 to 1.0	1	35	121	92	46	25	9	20	58	407
1.1 to 1.5		8	32	24	29	21	16	15	36	181
1.6 to 2.0			5	20	14	14	14	13	17	97
2.1 to 2.5		1	12	7	3	3	4	13	17	60
2.6 to 3.0			3	1	3	1	4	8	7	27
>3.0			3			2	4	9	16	34
Missing	8	83	187	85	20	14	5	12	115	529
Total	104	1710	3585	993	275	125	78	107	1064	8041

TABLE XIII

JOINT FREQUENCY DISTRIBUTION OF VERTICAL TEMPERATURE DIFFERENCE VERSUS 150/19 FOOT WIND SPEED RATIO DURING THE HOURS 1900 THROUGH 0700 FOR THE PERIOD JULY 1951–JUNE 1953

Temperature Difference $T_{144} - T_{5.5}$ (°C)	Wind Speed Ratio (U_{150}/U_{19})									Total
	<1.0	1.0 – 1.2	1.3 – 1.5	1.6 – 1.8	1.9 – 2.1	2.2 – 2.4	2.5 – 2.9	≥3.0	Missing	
≤2.0										
–1.9 to –1.5		1	1			1		1		4
–1.4 to –1.0		2	1	1	2	1				7
–0.9 to –0.5		48	130	48	9	2			30	267
–0.4 to 0.0	4	215	1060	533	139	56	21	29	216	2273
0.1 to 0.5	2	47	533	535	224	126	67	44	212	1790
0.6 to 1.0		8	90	219	249	138	77	96	180	1057
1.1 to 1.5		2	23	83	135	100	89	106	189	727
1.6 to 2.0			8	40	71	112	104	113	198	646
2.1 to 2.5		2	4	10	41	60	73	115	166	471
2.6 to 3.0			1	15	28	43	58	121	165	431
>3.0		3	7	27	42	86	132	260	598	1155
Missing	1	27	109	116	89	47	37	61	188	675
Total	7	355	1967	1627	1029	772	658	946	2142	9503

each other in a complicated fashion. However, it is clearly shown by these investigations that atmospheric conditions favoring rapid diffusion are likely to be present during working hours while conditions favoring slow diffusion are considerably more prevalent during off hours.

Data on the frequency with which stability conditions occur during each month and during the 6-hour periods 0100-0600, 0700-1200, 1300-1800, and 1900-2400 are presented in Tables XIV through XVII. This information is based on hourly observations of the temperature difference between the 144 foot level on the Meteorology Tower and 5.5 feet above ground during the period from July 1951 - June 1954.

III. Precipitation, Stability and Wind

Based on 75 years of Weather Bureau records the average monthly totals of precipitation range from 1.88 in. in February to 3.61 in. in May. During the spring and summer months the average monthly totals of precipitation are $1\frac{1}{2}$ to 2 times as large as those in the fall and winter months. A summary of precipitation and other climatological data prepared by the U. S. Weather Bureau is presented in Table XVIII.

Data showing the frequency of occurrence of combinations of wind speed and wind direction during precipitation are shown in Tables XIX and XX. The information in Table XIX is based on measurements by the U. S. Weather Bureau taken during the 8-year period, January 1934 - December 1941 at the Chicago Midway Airport. This material was taken from a study by Col. Benjamin G. Holzman of the USAF. Argonne data for the 5-year period, July 1949 - June 1954 are presented in Table XX.

It is interesting to note that there were 8198 hourly observations of precipitation or precipitation on 11.4% of the measurements, in the 8-year period of the Weather Bureau data. Precipitation occurred during only 8.3% of the observations during the period of the Argonne data. This difference may not be this large since the Argonne Weather Station is manned only 8 hours per day 5 days a week. Precipitation measurements at Argonne are made by a modified weighing type Bendix-Friez precipitation gauge. It is likely that some hours during which only a trace occurred were not detected by the precipitation gauge for periods when Argonne observers were off duty.

For the three-year period from July 1951 - June 1954 a study was made of the relationship between wind, precipitation and stability. Tables XXI and XXII summarize this investigation. Worthy of note is that in periods of no precipitation the atmosphere was stable in only 24% of the measurements. The undesirable combination of atmospheric stability and precipitation occurred on only 2.1% of the observations but the wind speed exceeded 7 miles per hour on over 3/4 of these cases.

TABLE XVI

Frequency Distribution of Temperature Difference Between 144-Foot and 5.5-Foot Level For Hours 1300 - 1800 July 1951 - June 1954

TEMPERATURE DIFFERENCE °C 144-FT. MINUS 5.5-FT. LEVEL	MONTH												TOTAL
	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	
< -2.0					1				1	6			8
-1.9 -- 1.5	5	8	3					12	30	22	15	2	97
-1.4 -- 1.0	54	41	48	50	34	28	7	56	53	80	67	38	556
-0.9 -- 0.5	141	150	136	139	126	135	89	160	150	160	171	151	1708
-0.4 – 0.0	137	181	128	134	188	155	259	166	203	148	158	173	2030
0.1 – 0.5	90	107	99	85	81	61	88	55	63	49	67	87	932
0.6 – 1.0	50	33	39	52	38	21	35	23	21	14	26	45	397
1.1 – 1.5	19	21	26	28	27	5	15	8	7	9	6	30	201
1.6 – 2.0	4	6	17	20	14	10	11	8	5	4	1	9	109
2.1 – 2.5	1	1	13	14	12	3	7	3	4	2		4	64
2.6 – 3.0		1	4	10	8	4	2	1				1	31
> 3.0		1	10	20	7	2	4	2			1		47
MISSING	57	8	17	6	4	134	41	16	21	46	46		396
TOTAL	558	558	540	558	540	558	558	510	558	540	558	540	6576

TABLE XV

Frequency Distribution of Temperature Difference Between 144-Foot and 5.5-Foot Level For Hours 0700 - 1200 July 1951 - June 1954

TEMPERATURE DIFFERENCE °C 144-FT. MINUS 5.5-FT. LEVEL	MONTH												TOTAL
	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	
< -2.0									1		1		2
-1.9 – -1.5	10	6	2		1	1		11	27	37	25	1	121
-1.4 – -1.0	133	89	79	93	64	35	17	88	88	127	153	86	1052
-0.9 – -0.5	198	267	247	240	216	178	139	160	193	210	232	292	2572
-0.4 – 0.0	115	148	142	136	167	131	235	177	151	106	94	111	1713
0.1 – 0.5	31	23	31	29	39	40	69	31	44	6	11	36	390
0.6 – 1.0	5	10	9	14	17	29	24	8	15	2	1	7	141
1.1 – 1.5	3	4	4	4	17	4	11	7	4	7	1	1	67
1.6 – 2.0	1	1	1	8	5	2	5	4	2		1		30
2.1 – 2.5		1	3	8	4	2	5	7	3				33
2.6 – 3.0			1	1			4						6
> 3.0			1	15	9	2	11	4	2				44
MISSING	62	9	20	10	1	134	38	13	28	45	39	6	405
TOTAL	558	558	540	558	540	558	558	510	558	540	558	540	6576

TABLE XVI

Frequency Distribution of Temperature Difference Between 144-Foot and 5.5-Foot Level For Hours 1300 - 1800 July 1951 - June 1954

TEMPERATURE DIFFERENCE °C 144-FT. MINUS 5.5-FT. LEVEL	MONTH												TOTAL
	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	
<-2.0					1				1	6			8
-1.9 — -1.5	5	8	3					12	30	22	15	2	97
-1.4 — -1.0	54	41	48	50	34	28	7	56	53	80	67	38	556
-0.9 — -0.5	141	150	136	139	126	135	89	160	150	160	171	151	1708
-0.4 — 0.0	137	181	128	134	188	155	259	166	203	148	158	173	2030
0.1 — 0.5	90	107	99	85	81	61	88	55	63	49	67	87	932
0.6 — 1.0	50	33	39	52	38	21	35	23	21	14	26	45	397
1.1 — 1.5	19	21	26	28	27	5	15	8	7	9	6	30	201
1.6 — 2.0	4	6	17	20	14	10	11	8	5	4	1	9	109
2.1 — 2.5	1	1	13	14	12	3	7	3	4	2		4	64
2.6 — 3.0		1	4	10	8	4	2	1				1	31
> 3.0		1	10	20	7	2	4	2			1		47
MISSING	57	8	17	6	4	134	41	16	21	46	46		396
TOTAL	558	558	540	558	540	558	558	510	558	540	558	540	6576

TABLE XVII

Frequency Distribution of Temperature Difference Between 144-Foot and 5.5-Foot Level For Hours 1900 - 2400 July 1951 - June 1954

TEMPERATURE DIFFERENCE °C 144-FT. MINUS 5.5-FT. LEVEL	MONTH												TOTAL
	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	
-1.9 – -1.5										6			6
-1.4 – -1.0					1					1			2
-0.9 – -0.5		1		1	19	46	15	9	22	18	5		136
-0.4 – 0.0	39	40	44	102	157	209	208	214	192	156	108	71	1540
0.1 – 0.5	77	65	77	73	119	66	134	107	94	102	91	95	1100
0.6 – 1.0	61	65	56	70	59	47	65	43	72	56	61	96	751
1.1 – 1.5	63	70	50	44	51	22	33	34	62	35	61	76	601
1.6 – 2.0	60	62	63	55	44	15	19	37	38	28	54	58	533
2.1 – 2.5	43	49	56	51	25	9	16	15	15	16	40	35	370
2.6 – 3.0	34	43	37	22	21	12	10	9	14	15	31	24	272
> 3.0	127	151	145	134	44	6	14	28	20	59	51	77	856
MISSING	54	12	12	6		126	44	14	29	48	56	8	409
TOTAL	558	558	540	558	540	558	558	510	558	540	558	540	6576

TABLE XVIII

METEOROLOGICAL DATA

(OFFICIAL RECORDINGS FROM THE CHICAGO WEATHER BUREAU)

	WIND		TEMPERATURE			PRECIPITATION	
	AVERAGE HOURLY VELOCITY	PREVAIL-ING DIREC-TION*	AVERAGE DAILY MAX.	AVERAGE DAILY MIN.	AVERAGE	AVERAGE RAIN-FALL	AVERAGE SNOW-FALL
NO. OF YEARS RECORDED	30	74	73	73	75	75	61
MONTH							
JANUARY	12	SW	31.8	17.9	24.9	1.92	9.2
FEBRUARY	12	W	33.7	20.0	26.9	1.88	8.5
MARCH	13	SW	43.0	29.2	36.1	2.66	6.0
APRIL	12	NE	54.4	39.6	47.1	2.80	1.0
MAY	11	NE	65.4	49.6	57.5	3.61	0.1
JUNE	10	NE	75.2	59.7	67.5	3.52	0.
JULY	9	SW	89.6	66.0	73.3	3.13	0.
AUGUST	9	NE	78.7	65.3	72.0	3.20	0.
SEPTEMBER	10	SW	72.5	58.3	65.3	3.21	0.
OCTOBER	11	SW	61.1	46.9	53.9	2.58	0.1
NOVEMBER	12	SW	47.0	33.8	40.2	2.37	1.8
DECEMBER	12	SW	35.6	23.4	29.2	1.93	6.7
ANNUAL AVERAGE	11	SW	56.6	42.5	49.5	32.81	33.4

* PREVAILING DIRECTION = DIRECTION FROM WHICH WIND BLOWS

The direction of the prevailing winds expressed in percentage of yearly time is recorded as follows:

North	6 %	Southeast	10 %	West	13 %
Northeast	17 %	South	13 %	Northwest	13 %
East	9 %	Southwest	19 %	Calm	0 %

The average weather conditions for this area follow:

Sunshine: Total hours per year...... 2,645
Percent of year............. 58

Average number of days per year:

Clear	117
Partly cloudy	120
Cloudy	128
Rain (over .01)	124
Snow	59
Thunder storms	38
Dense Fog	10

TABLE XIX

SURFACE WIND SUMMARY - FREQUENCY OF DIRECTION BY VELOCITY GROUPS DURING PRECIPITATION PERIODS CHICAGO AIRPORT, JANUARY 1934 - DECEMBER 1941

DATA OBTAINED FROM A STUDY BY
(COL. BENJAMIN G. HOLZMAN, USAF)

ANNUAL

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	29	400	446	36	4	-	885	10.7	913	11.1
NE	-	40	588	374	12	3	-	978	11.8	1018	12.4
E	-	67	691	310	2	-	-	1002	12.1	1070	13.0
SE	-	33	607	182	2	-	-	792	9.6	825	10.0
S	-	57	734	420	15	2	-	1170	14.1	1227	14.8
SW	-	35	570	388	26	10	-	995	12.0	1030	12.5
W	-	32	481	502	66	18	-	1066	12.9	1098	13.3
NW	-	24	461	489	34	7	1	993	12.0	1017	12.3
TOTAL	59	317	4532	3111	193	44	1	7881	-	8198	-
PER CENT	.7	3.8	54.9	37.7	2.3	.5	-	95.2	-	-	-

JANUARY

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	5	45	34	4	1	-	83	6.6	87	7.0
NE	-	10	84	32	4	3	-	124	9.9	134	10.7
E	-	20	132	43	-	-	-	175	13.9	196	15.6
SE	-	7	93	35	-	-	-	128	10.1	134	10.7
S	-	5	130	53	1	1	-	184	14.7	190	15.1
SW	-	-	92	66	2	3	-	162	12.9	162	12.9
W	-	-	85	100	19	5	-	211	16.8	211	16.8
NW	-	1	78	49	7	3	-	137	10.9	138	10.9
TOTAL	-	48	739	412	37	16	-	1204	-	1252	-
PER CENT	-	3.8	32.8	32.8	2.9	1.3	-	95.8	-	-	-

FEBRUARY

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	1	55	77	3	-	-	134	11.5	135	11.6
NE	-	7	91	90	-	-	-	182	15.5	189	16.1
E	-	8	95	64	-	-	-	159	13.5	167	14.2
SE	-	3	83	28	-	-	-	106	6.3	113	9.7
S	-	9	78	45	2	-	-	119	10.6	134	11.3
SW	-	5	37	43	4	-	-	85	7.1	89	7.6
W	-	3	40	63	14	8	-	123	10.5	127	10.8
NW	-	2	94	113	5	1	-	215	18.3	217	18.3
TOTAL	3	38	573	523	28	9	-	1133	-	1171	-
PER CENT	.3	3.2	48.8	44.5	2.4	.8	-	96.5	-	-	-

MARCH

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	1	48	75	4	-	-	126	15.8	128	16.0
NE	-	-	68	66	6	-	-	145	17.5	140	17.5
E	-	5	70	57	2	-	-	130	16.1	135	16.8
SE	-	2	24	20	-	-	-	44	5.5	46	5.7
S	-	1	43	34	2	-	-	78	9.6	79	9.9
SW	-	3	51	37	-	-	-	89	11.0	90	11.3
W	-	-	34	47	9	-	-	80	11.2	92	11.5
NW	-	1	36	46	4	-	-	86	10.4	86	10.7
TOTAL	5	13	374	382	27	-	-	778	-	796	-
PER CENT	.6	1.6	46.7	47.7	3.4	-	-	97.1	-	-	-

TABLE XIX (CONT'D)

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
APRIL											
N	-	3	27	61	7	1	-	96	13.5	99	14.0
NE	-	2	61	80	1	-	-	141	19.9	143	20.1
E	-	2	67	63	-	-	-	131	18.5	133	18.8
SE	-	2	43	20	-	-	-	63	8.8	65	9.1
S	-	4	48	24	3	-	-	74	10.5	78	11.1
SW	-	4	39	29	1	-	-	70	9.8	74	10.3
W	-	1	23	24	3	2	-	52	7.4	53	7.5
NW	-	2	10	42	4	1	-	57	8.1	59	8.3
TOTAL	5	20	318	343	19	4	-	684	-	704	-
PER CENT	.7	2.8	44.9	48.4	2.7	.6	-	96.5	-	-	-
MAY											
N	-	2	35	33	2	-	-	70	12.7	72	13.1
NE	-	3	58	18	-	-	-	75	13.6	78	14.1
E	-	9	38	24	-	-	-	63	11.3	72	12.9
SE	-	5	41	11	-	-	-	52	9.3	56	10.2
S	-	6	42	24	-	-	-	66	11.9	72	13.0
SW	-	4	29	23	1	-	-	53	9.7	58	10.4
W	-	4	30	47	1	-	-	78	14.0	82	14.8
NW	-	2	24	32	-	-	-	56	10.1	58	10.5
TOTAL	6	35	297	212	4	-	-	513	-	548	-
PER CENT	1.1	6.3	53.6	38.3	.7	-	-	92.6	-	-	100.0
JUNE											
N	-	1	35	17	-	1	-	52	10.9	53	11.1
NE	-	3	64	15	-	-	-	80	16.6	83	17.3
E	-	3	68	8	-	-	-	76	15.8	79	16.4
SE	-	5	24	3	-	-	-	27	5.7	32	6.7
S	-	5	46	16	-	-	-	62	12.9	67	14.0
SW	-	2	50	24	-	-	-	73	15.2	75	15.6
W	-	3	23	29	1	1	-	54	11.3	57	11.8
NW	-	2	18	8	1	-	-	28	5.7	30	6.2
TOTAL	5	24	328	120	2	2	-	452	-	476	-
PER CENT	1.0	5.0	68.2	24.9	.4	.4	-	94.1	-	-	-
JULY											
N	-	2	19	7	-	-	-	26	12.4	28	13.4
NE	-	3	19	2	-	-	-	21	10.4	23	11.5
E	-	-	15	-	-	-	-	15	7.6	16	7.8
SE	-	2	16	-	-	-	-	16	7.9	18	8.7
S	-	1	19	3	-	-	-	22	10.6	23	11.3
SW	-	2	30	6	2	-	-	37	18.1	39	19.1
W	-	4	21	6	-	-	-	28	14.0	32	16.0
NW	-	-	13	9	-	-	1	23	11.3	23	11.3
TOTAL	2	14	152	33	2	-	1	188	-	190	-
PER CENT	1.0	6.9	74.5	16.2	1.0	-	.5	92.3	-	-	-

TABLE XIX (CONT'D)

AUGUST

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	3	27	9	2	-	-	39	11.4	41	12.3
NE	-	4	26	7	-	-	-	33	9.8	37	10.9
E	-	4	32	5	-	-	-	37	11.0	42	12.4
SE	-	2	48	3	-	-	-	51	15.2	53	15.6
S	-	6	38	5	-	-	-	43	12.7	49	14.5
SW	-	-	29	15	-	-	-	44	13.2	44	13.2
W	-	2	18	6	1	-	-	24	7.0	26	7.5
NW	-	5	21	10	1	1	-	33	9.8	38	11.2
TOTAL	8	26	239	60	4	1	-	304	-	330	-
PER CENT	2.4	7.7	70.7	17.8	1.2	.3	-	90.1	-	-	-

SEPTEMBER

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	5	22	40	2	-	-	66	14.8	71	15.9
NE	-	3	37	11	-	-	-	47	10.6	50	11.1
E	-	5	59	1	-	-	-	60	13.5	65	14.6
SE	-	4	40	3	-	-	-	44	9.8	48	11.0
S	-	3	53	23	-	-	-	75	16.9	78	17.5
SW	-	1	38	19	-	-	-	57	12.7	58	13.0
W	-	4	17	18	1	-	-	37	8.2	41	9.1
NW	-	2	15	9	2	1	-	25	5.8	27	6.2
TOTAL	7	27	281	124	5	1	-	411	-	438	-
PER CENT	1.6	6.1	63.1	27.9	1.1	.2	-	92.3	-	-	-

OCTOBER

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	1	24	22	5	-	-	46	9.9	48	10.1
NE	-	2	11	7	-	-	-	19	4.1	21	4.6
E	-	4	17	14	-	-	-	31	6.6	35	7.4
SE	-	1	42	9	-	-	-	50	10.7	51	11.0
S	-	1	61	59	-	-	-	121	25.8	121	25.9
SW	-	2	51	27	1	1	-	79	17.1	82	17.5
W	-	2	34	16	-	-	-	50	10.7	52	11.1
NW	-	1	35	16	-	-	-	52	11.1	52	11.3
TOTAL	4	14	271	170	6	1	-	448	-	462	-
PER CENT	.9	3.0	58.2	36.5	1.3	.2	-	96.0	-	-	-

NOVEMBER

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
N	-	3	33	28	3	-	-	65	8.2	68	8.6
NE	-	4	41	42	-	-	-	82	10.4	86	11.0
E	-	3	34	17	-	-	-	51	6.4	54	6.8
SE	-	1	40	27	2	-	-	69	8.7	69	8.8
S	-	1	55	73	7	1	-	136	17.2	138	17.4
SW	-	6	45	40	11	6	-	102	13.0	108	13.7
W	-	4	49	77	5	1	-	133	16.8	137	17.4
NW	-	4	51	69	4	-	-	123	15.6	127	16.2
TOTAL	2	26	348	373	32	8	-	761	-	787	-
PER CENT	.3	3.3	44.1	47.3	4.1	1.0	-	96.3	-	-	-

TABLE XIX (CONT'D)

DIR/VEL	CALM	1-3	4-12	13-24	25-31	32-46	47 & OVER	TOTAL OBS.	4 MPH & OVER %	TOTAL OBS.	ALL OBS. %
					DECEMBER						
N	-	1	34	43	3	-	-	81	7.7	82	7.8
NE	-	-	29	5	-	-	-	33	3.2	33	3.2
E	-	3	61	13	-	-	-	75	7.2	78	7.5
SE	-	3	114	23	1	-	-	137	13.2	140	[illegible]
S	-	12	121	62	1	1	-	186	17.8	197	19.0
SW	-	7	81	58	5	-	-	144	13.9	152	14.6
W	-	4	105	69	10	1	-	185	17.8	189	18.1
NW	-	2	67	86	7	-	-	159	15.3	161	15.5
TOTAL	9	32	612	359	27	2	-	1000	-	1032	-
PER CENT	.9	3.1	58.8	34.5	2.6	.2	-	96.1	-	-	-

TABLE XX

Joint Frequency Distribution of Wind Direction and Wind Speed During Hours of Precipitation July 1949 - June 1954

LEVEL	DIRECTION (16 POINTS)	WIND SPEED (MPH) CALM	1 – 3	4 – 7	8 – 12	13 – 18	19 – 24	25 – 31	32 – 38	39 – 46	> 46	MISSING	TOTAL
150 - FOOT	CALM	14											14
	NNE		7	15	64	93	62	14					255
	NE		2	21	45	67	42	24	1				202
	ENE		1	24	53	82	54	21	4			7	248
	E		9	31	129	101	36	11	1			3	321
	ESE	1	6	27	77	50	19	3				3	186
	SE		6	23	50	43	21	7	1				151
	SSE		3	15	61	56	40	11	4			1	191
	S	1	6	48	105	89	54	27	8	3		1	342
	SSW		5	24	68	81	36	15	6	1			236
	SW		9	12	40	68	38	14	1	2		4	188
	WSW	1	2	19	54	62	24	5		4		2	173
	W		4	19	59	47	34	21	11	1	1	2	199
	WNW		6	17	41	51	22	9	4			2	152
	NW		2	10	33	52	20	6				1	124
	NNW		6	15	60	45	28	16					170
	N	1	6	27	75	127	77	31	3				347
	VARIABLE		6	13	2	2							23
	MISSING		2	18	33	21	15					37	126
	TOTAL	18	90	378	1049	1137	622	235	44	11	1	63	3648

TABLE XXI

Joint Frequency Distribution of Wind Direction and Wind Speed During Hours of Precipitation and Stability as Indicated 150-Foot Level July 1951 - June 1954

Stability	Direction (16 Points)	Wind Speed (MPH) Calm	1–3	4–7	8–12	13–18	19–24	25–31	32–38	39–46	> 46	Missing	Total
STABLE - TEMPERATURE CONSTANT OR INCREASING WITH HEIGHT	CALM	5											5
	NNE		1	5	12	7	7	4					36
	NE		2	2	7	3	1	2					17
	ENE			4	6	4	1	1					16
	E		3	6	22	6							37
	ESE		2	7	15	7	3						34
	SE		1	5	16	9	4	2					37
	SSE		2	2	15	9	9	1	1				39
	S			16	25	13	6	4		1			65
	SSW		2	6	15	27	5	4	2				61
	SW		1	4	7	11	10	1					34
	WSW			6	7	8	3						24
	W			2	12	1	1	2					18
	WNW			5	2	7	2						16
	NW			2	6	1	3	1					13
	NNW		1	2	9	6	2	2					22
	N		1	2	8	20	5	2					38
	VARIABLE		2	6	1	1							10
	MISSING											1	1
	TOTAL	5	18	82	185	140	62	26	3	1		1	523
UNSTABLE - TEMPERATURE DECREASING WITH HEIGHT	CALM	4											4
	NNE		3	6	40	57	39	6					151
	NE			10	24	40	29	13					116
	ENE		1	10	25	41	33	10					120
	E		2	14	50	51	16	6	1				140
	ESE		4	10	38	26	6	1				3	88
	SE		3	9	16	19	11	4	1				63
	SSE		1	6	27	24	21	7	3			1	90
	S		2	13	31	42	16	9	5	1		1	120
	SSW		2	10	22	22	13	4	2	1			76
	SW		2	2	12	30	18	4		2		4	74
	WSW			5	21	33	16	4		4		2	85
	W		3	7	25	25	21	7	4	1	1		94
	WNW		3	4	20	23	11	3	3				67
	NW		1	4	17	34	9	2					67
	NNW		3	8	25	22	21	9					88
	N			13	38	69	41	20	3				184
	VARIABLE		3	5	1								9
	MISSING			1								2	3
	TOTAL	4	33	137	432	558	321	109	22	9	1	13	1639

TABLE XXII

Joint Frequency Distribution of Wind Direction and Wind Speed During Hours of No-Precipitation and Stability as Indicated 150-Foot Level July 1951 - June 1954

DIRECTION (16 POINTS)	WIND SPEED (MPH)										MISSING	TOTAL
	CALM	1 – 3	4 – 7	8 – 12	13 – 18	19 – 24	25 – 31	32 – 38	39 – 46	> 46		
STABLE - TEMPERATURE CONSTANT OR INCREASING WITH HEIGHT												
CALM	105											105
NNE		19	65	242	153	6	2					487
NE		14	56	181	85	3	2					341
ENE		15	77	295	72	5	1	1				466
E		18	115	457	93	5						688
ESE		15	59	289	75	5						443
SE		11	66	281	91	11					2	462
SSE		14	88	339	110	25	5	2			1	584
S		16	110	569	387	75	26	2	2		2	1189
SSW		11	87	463	544	247	35	3	1		2	1393
SW		8	63	315	424	168	13				3	994
WSW		15	63	313	352	102	9	1			2	857
W		17	77	319	428	97	37	8				983
WNW		15	86	300	404	110	10	1				926
NW		11	56	171	258	34	7					537
NNW		14	56	215	247	26	4	2				564
N		17	69	251	280	21	5					643
VARIABLE		2		3		1						6
MISSING		5	2	14	7	1					12	41
TOTAL	105	237	1195	5017	4010	942	156	20	3		24	11709
UNSTABLE - TEMPERATURE DECREASING WITH HEIGHT												
CALM	51										2	53
NNE		31	98	290	181	50	11					661
NE		15	56	137	102	14	1					325
ENE		17	55	211	164	55	7	2				511
E		26	90	212	115	46	20	1				510
ESE		17	62	105	101	20						305
SE		20	84	119	68	12					1	304
SSE		40	123	170	92	37	2					464
S		23	107	236	256	122	36	6	2			788
SSW		26	118	247	252	180	32	3	2		3	863
SW		19	74	212	216	141	50	5	2		2	721
WSW		24	80	222	244	144	84	22	3		6	829
W		19	86	242	264	139	45	3			1	799
WNW		30	122	358	434	213	98	38	7		1	1301
NW		15	62	162	219	97	13					568
NNW		31	102	222	260	124	23	5			1	768
N		23	99	334	216	94	21	2				789
VARIABLE	1	72	42	5	1	1						122
MISSING		2	3	8	2	1					20	36
TOTAL	52	450	1463	3492	3187	1490	443	87	16		37	10717

The direction of the prevailing winds expressed in percentage of yearly time is recorded as follows:

North	6%	Southeast	10%	West	13%
Northeast	17%	South	13%	Northwest	13%
East	9%	Southwest	19%	Calm	0%

The average weather conditions for this area follow:

Sunshine:	Total hours per year	2,645
	Percent of year	58

Average number of days per year:

Clear	117
Partly cloudy	120
Cloudy	128
Rain (over .01)	124
Snow	59
Thunder storms	38
Dense fog	10

The data indicate that when precipitation is occurring there are appreciable differences in the distribution of wind speeds and wind direction at 150 ft. during periods of stable and unstable conditions. For example, with precipitation there is a substantially higher proportion of winds from the northeast sector during unstable conditions. Also, the wind speeds average higher during unstable conditions.

IV. Atmospheric Dispersion of Noxious Gases (or Particulate Matter of Less than 10μ) from a Point Ground Source.

Table XXIII presents ground concentrations in units per cubic meter for a continuous point source located at the ground emitting 1 unit per second. These calculations are based on the equation developed by Sir Oliver Graham Sutton of England which follows:

$$\psi(x,y) = \frac{2Q}{\pi C_y C_z u x^{2-n}} e^{-\left(\frac{y^2}{x^{2-n} C_y^2}\right)}$$

ψ = concentration in units per cubic meter
Q = source strength in units per second
C_y = horizontal diffusion coefficient
C_z = vertical diffusion coefficient
u = wind speed in meters per second
x = distance in meters from source along plume of axis
n = turbulence index ($0 < n < 1$).

TABLE XXIII

CONCENTRATION IN UNITS PER CUBIC METER FOR A GROUND SOURCE EMITTING ONE UNIT PER SECOND AT VARIOUS DISTANCES DOWNWIND. HEIGHT AND WIDTH OF CLOUD WHERE CONCENTRATION EQUALS ONE-TENTH OF PEAK AXIAL CONCENTRATION ARE ALSO GIVEN. FROM THIS TABLE ESTIMATES CAN BE MADE OF DISTRIBUTION DOWNWIND OF CONTAMINATION

Distance downwind from source	32.8 ft	82 ft	164 ft	328 ft	656 ft	1312 ft	1640 ft	2460 ft	3280 ft	4100 ft	1 mile	5 miles	10 miles	15 miles	20 miles	25 miles
TURBULENT CASE WINDSPEED = 5 mps																
Concentration in units/cubic meter	2.6×10^{-2}	5.0×10^{-3}	1.4×10^{-3}	4.2×10^{-4}	1.2×10^{-4}	3.5×10^{-5}	2.3×10^{-5}	1.1×10^{-5}	6.7×10^{-6}	4.5×10^{-6}	2.8×10^{-6}	1.7×10^{-7}	4.5×10^{-8}	2.2×10^{-8}	1.3×10^{-8}	8.6×10^{-9}
Width of cloud in feet	29.2	66.6	124.6	232.2	433.6	809.2	989.2	1424.8	1845.9	2556.3	2832.6	12057	22500	32409	41987	51327
Height of cloud in feet	8.3	18.9	35.3	66	123	229	281	404	524	640	804	3422	6385	9197	11915	14565
STABLE CASE WINDSPEED = 2 mps																
Concentration in units/cubic meter	1.7	4.1×10^{-1}	1.4×10^{-1}	5.1×10^{-2}	1.8×10^{-2}	6.3×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.6×10^{-3}	1.1×10^{-3}	7.8×10^{-4}	7.0×10^{-5}	2.5×10^{-5}	1.3×10^{-5}	8.7×10^{-6}	6.3×10^{-6}
Width of cloud in feet	5.6	11.2	18.7	31.5	52.8	88.9	105.3	142.7	177.1	209.3	252.9	845.6	1422.2	1927.7	2392.1	2827.7
Height of cloud in feet	1.7	3.4	5.6	9.5	15.9	26.7	31.6	42.8	53.1	62.8	75.9	253.7	427	578.3	718	848

Calculations of concentrations were made for values of the diffusion coefficients and the turbulence index prevailing under stable and unstable conditions. The parameters used were as follows:

	C_y	C_z	n
Stable	0.10	0.06	0.5
Unstable	0.37	0.21	0.2

These values have not been definitely determined for the atmosphere under the various meteorological conditions and must be estimated. Also, there is some question as to how valid the equation is over long distances. Measurements have been made at distances up to 14 miles and were within the same order of magnitude as calculated. The equation assumes that the wind direction remains constant throughout the time it takes for the cloud to reach the distance from the source in question. The calculated values will, therefore, be too high except in the case of a persistent stable regime. Also, the concentrations and cloud widths are given for a 3-minute mean. Instantaneous concentrations will be higher and cloud widths smaller. Because of the various possibilities of error, it is felt that the calculations of the above values from Sutton's equation can only be correct to a factor of ten.

Estimates for width and height of the cloud at various distances downwind are also presented, calculated from the same equation. The width is defined as the distance between points on the skirts of the cross-wind concentration curve at which the concentration is 1/10 of the peak value. Similarly, the height is the distance from the ground at which the concentration is 1/10 of the value on the ground.

This equation must be used with some caution. It has been carefully checked with observations under average weather conditions at distances close to the source. However, the concentration and width of cloud depend upon the values chosen for the diffusion coefficients and turbulent index.