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SAFETY ANALYSIS

Reactor Site Description

The reactor site is located in the Engineering Building on the campus of Michigan State University. The campus is located in the southern area of the city of East Lansing, in Ingham County, in the state of Michigan. Reference to the floor plans (Figures 5,6,7 and 8) (Appendix 1) of the Engineering Building will provide an adequate description of the building layout.

The site within the Engineering Building is on the southern edge of the main campus. University farm lands and few agricultural research laboratories occupy the area to the south to a distance of four to five miles. These areas are sparsely populated.

Classrooms, offices, and student residence halls lie to the north, east, and west of the site. Outside the campus area in a northerly direction is the city of East Lansing. Some areas of the city also lie to the east and west of the site. The city is approximately 3/4 to 1 mile from the site.

East Lansing is primarily a residential community composed of year around residents and students of the university. Most of the business are retail stores.

To the west and southwest of the main campus (which is bounded on the west by Harrison Road) are university apartments for married students.

The population of the city of East Lansing, is approximately 51,000. This includes students who live as residents of the city. The number of students attending the university varies somewhat from season to season, but the peak student population is approximately 44,000. Of this number about 15,500 are on-campus residents in residence halls. A significant number of students commute to the campus from places of residence outside the East Lansing area. A map of the East Lansing area (Figure 1) is included in this report in order to provide a physical representation of the area. To represent the resident population, Table 1 is included with census tract numbers used to identify population districts. Approximations of peak population densities (i.e. during the academic year on week days between 8 a.m. and 5 p.m.) are as follows: 0-1/2 mile - 3400 people; 1/2 mile to 1 mile - 21,000; 1 mile to 1 1/2 miles - 11,700; and 1 1/2 to 2 miles 7200. These approximations are derived from 1980 census statistics, Michigan State University personnel and on campus housing departments statistics.

In addition to the students living on campus there are approximately 8,500 people working 8 hours per day on the campus in such capacities as professors, administrative personnel, clerical-technical personnel, and labor people. The

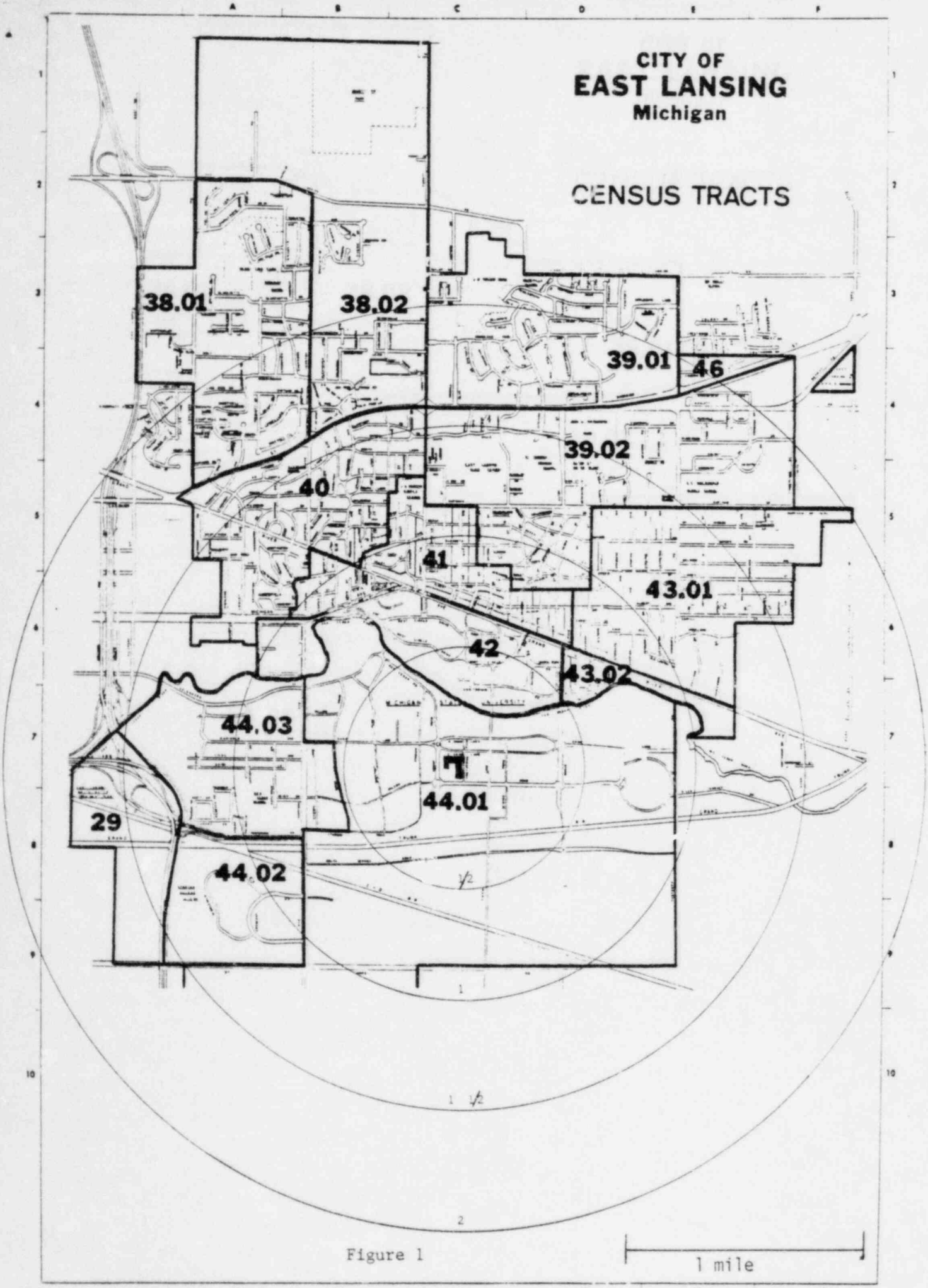

CITY OF
EAST LANSING
Michigan
CENSUS TRACTS
38.01
38.02
39.01
46
39.02
40
41
43.01
42
43.02
44.03
44.01
29
44.02
1/2
1
1 1/2
2
1 mile

Figure 1

Table 1

EAST LANSING POPULATION CHARACTERISTICS

CENSUS TRACT	TOTAL POPULATION	MALE	FEMALE	PERSONS AGE 60 AND OVER	%	PERSONS AGE 17 AND UNDER	%
29.01	14	6	8	2	14.3	6	42.9
38.01	3,648	1,800	1,848	211	5.8	1,204	33.0
38.02	2,002	896	1,106	323	16.1	376	18.8
39.01	1,791	854	937	316	17.6	432	24.1
39.02	3,989	1,928	2,061	447	11.2	707	17.7
40	3,766	1,820	1,946	577	15.3	766	20.3
41	4,882	2,449	2,433	210	4.3	162	3.3
42	5,656	2,590	3,066	1	0.0	47	0.8
43.01	4,253	2,136	2,117	338	7.9	608	14.3
43.02	2,877	1,347	1,530	6	0.2	11	0.4
44.01	11,400	5,894	5,506	3	0.0	53	0.5
44.02	3,852	1,879	1,973	14	0.4	1,002	26.0
44.03	2,993	1,492	1,501	119	4.0	711	23.8
46	269	131	138	8	3.0	58	21.6
Citywide	51,392	25,222	26,170	2,575	5.0	6,143	12.0

Source: 1980 Census Tape STF 1A

majority of these people work within 1 mile of the reactor site. The portion of the students of the university not residing on campus spend varying amounts of time per day on the campus. They are a highly mobile group and cannot be said to be in any one campus building for a significant amount of time. These people as well as the university employees could easily be moved from the area if a dangerous situation was caused by a reactor accident.

A map of the campus has been included in this report (Figure 2). It shows the location of the reactor site in relation to the rest of the campus. Campus buildings with appropriate identification are shown. In addition, it shows new construction on the campus.

Meteorological, Geological, and Hydrological Data

(1) Meteorological Data

Meteorological Data for the site were obtained from the Department of Commerce's Agricultural Services Office at 1405 S. Harrison Road, East Lansing, Michigan. The data were recorded at Capital City Airport which is located approximately 6 miles from the reactor site. Since the terrain between the site and the airport is flat with no major hills or valleys, the data are expected to be representative of the site.

Figure 3 is a wind rose showing wind direction, speed and the percentage of time the wind blows in any one direction.

Temperature and precipitation data are given in Table 2.

Table 2. Temperature and Precipitation Data of the Reactor Site (1943-1982).

Annual average temperature	46.8°F
Coldest month	February
Hottest month	July
Annual total precipitation	30.65
Wettest month	June
Driest month	February

There is a history of tornados occurring in Michigan. According to the United States Weather Bureau, Office of the State Climatologist's bulletin "Michigan Tornado Fact Sheet," Michigan lies at the north-eastern edge of the

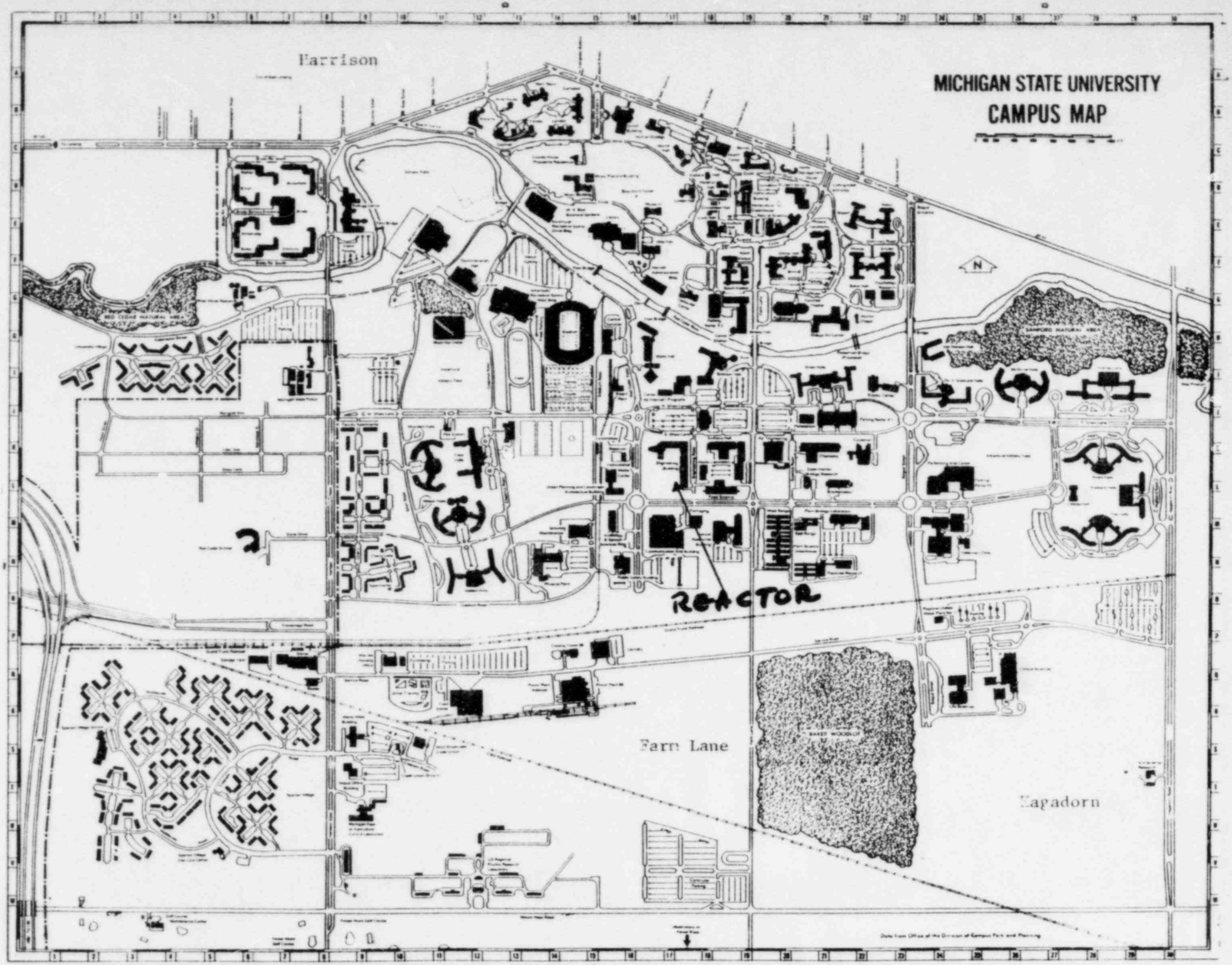
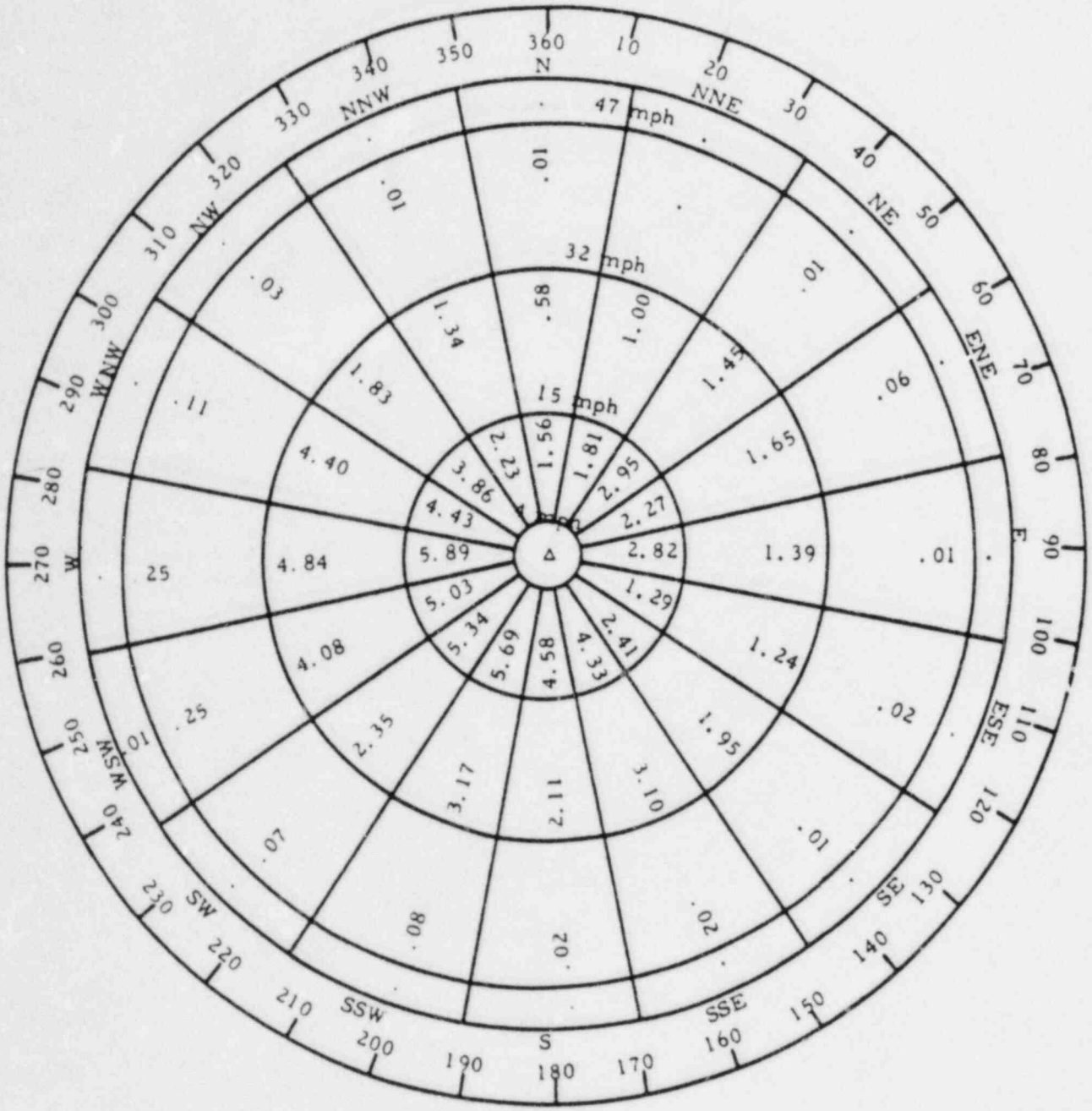

Harrison
MICHIGAN STATE UNIVERSITY
CAMPUS MAP
N
REACTOR
Farm Lane
Kapadorn

Figure 2



Δ = 6.06% calms, 0-3 miles per hour period of observation, 5 years

Numbers shown are percentages of time in direction and velocity indicated

Figure 3. Wind Rose Recorded in Lansing Michigan

nation's maximum frequency belt for tornados. In Michigan for the 58-year period of 1918-1975, June has produced the greatest frequency of tornados, tornado days, and number of deaths due to tornados. The month of December has never produced a verified tornado. February has produced only two. Michigan, during the 1956-1974 period has averaged 13 tornados per year. This can be compared to data from the surrounding states: Illinois 30, Indiana 23, Ohio 15, Wisconsin 20, and Minnesota 17. About 80 percent of the Michigan tornados occur in the southern one-half of the lower peninsula.

The general area around the site is also susceptible to damaging windstorms. A review of weather bureau data on damaging windstorms (excluding tornados) shows a total of 27 windstorms creating damage in excess of $500,000 since 1900. Of these storms, only 8 are listed as having winds in excess of 75 miles per hour. These windstorms had accompanying rain, freezing rain, hail, or snow.

(b) Geological Data -

Data received from T.T. Fujita at the University of Chicago indicates that although East Lansing is in the Southern half of Michigan's lower peninsula (the area of highest tornado frequency in the state), East Lansing has been historically free of tornados. Between 1930 and 1974 all tornados passed to the North and West of the reactor site or South and East. East Lansing lies within a pocket of relative quiet. The storms to the North West have all been of the F_2 or F_3 intensity on the Fujita scale. One storm (about 10 miles North of the reactor site) of the F_4 or F_5 intensity was recorded between 1940 and 1949.

Geology

The northwestern corner of Ingham County lies near the center of the Michigan Basin, an intracratonic basin developed on Precambrian crust. The basin is filled with primarily Paleozoic sedimentary rocks approximately 15,000 feet thick.

In the Lansing area, bedrock, which consists of shales and sandstones of the Saginaw formation of Pennsylvanian age, are covered with a layer of glacial drift approximately 75' thick. Bedrock is essentially undeformed and faults do not offset the younger formations.

Figure 4 shows the earth profile in the immediate area of the reactor site. This well log was taken before reactor tank installation.

Seismology

Some 16 events have been reported in southern Michigan since 1870. The most destructive of these had an intensity of VI on the modified Mercalli scale, i.e., "felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight." Quantitatively, this probably translates to Richter magnitude of about 4.0.

Of the 16 events, four are attributed to the Detroit and down-river region and are almost certainly small earthquakes of unknown cause that occurred in Lake Erie. Of the others, the 4 February, 1983 event listed for the Kalamazoo area is really a rail accident in LaPorte, Indiana (Sleep, 1981). The 19 May, 1906 Grand Rapids event is a powder mill explosion in Kenosha, WI.

The remaining ten events are listed below:

Wenona	43.7°N	83.9°W	6 February, 1872	8AM	IV (Intensity)
Port Huron	43.0°N	82.5°W	16 March, 1922		III
Morrice	42.8°N	84.2°W	22 February, 1918		IV
Niles	41.8°N	86.3°W	31 October, 1897		?
St. Joseph	42.1°N	86.5°W	10 October, 1988		IV
Kalamazoo	42.0°N	85.5°W	25 November, 1982		?
Coldwater	42.0°N	85.0°W	9 August, 1947		VI
Adrian	41.9°N	84.1°W	27 January, 1876		?
Lansing	42.8°N	84.6°W	2 February, 1967	1AM	IV 2 events

The first three events are all in the spring and may be due to ice break-up in Lake Huron. The Wenona events(s) may also be misreported earthquakes from Ohio. There is no information on the Niles, St. Joseph and Adrian events.

The Kalamazoo and Coldwater events were instrumentally recorded and are real. The Coldwater event is the largest event reported in Michigan and was felt at intensity IV in the Lansing area. These two events probably lie on some fault line and could produce earthquakes of magnitude 4 or so in size. Intensity IV is defined as "during the day felt indoors disturbed, walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked violently."

The Lansing events are enigmantic. The source for this report is not known, and the only reference made to it derives from the 1967 edition of United States Earthquakes. The Lansing State Journal reports nothing on this date or the several thereafter. This date is just after the major snowfall of 1967 and it is

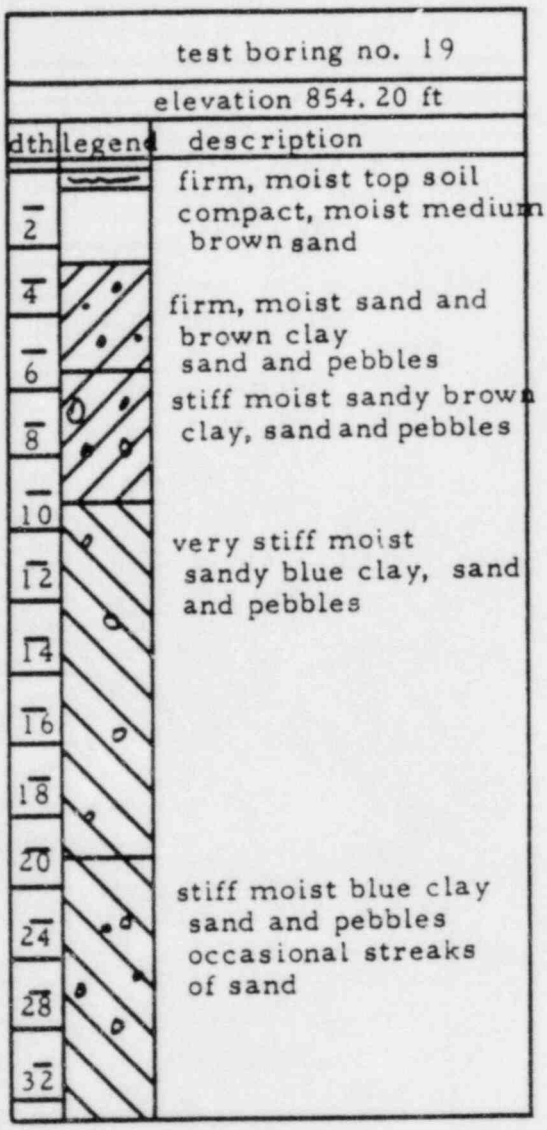


Figure 4. Earth Profile in Immediate Area of Reactor Site

possible that a large amount of snow fell off of a roof and awakened some people. It would seem likely that any other phenomena would have made it into the local paper. However, this is only speculation.

More likely is the detection or feeling of out-state earthquakes. On 27 July, 1980, a magnitude 5.2 earthquake occurred near Maysville, Kentucky. This was felt at intensity V in Detroit (mainly at Tiger Stadium) and with an intensity of II or III in Lansing. On 19 September, 1884, a moderate earthquake occurred near Colombus, Ohio and in March, 1937, several earthquakes occurred near Anna, Ohio. Maximum intensity was around VII or VIII (magnitude 5.5?). In the Lansing area, this was probably felt with an intensity of IV to V.

Thus, from local earthquakes the maximum intensity that would be felt in the Lansing area is probably about IV. From external (out-state) earthquakes, however, there is the possibility of intensities of up to VI in the region.

Hydrology

The reactor site area is drained by the Red Cedar River (1400 feet North) an the Grand River (4 miles West). Ground water is found approximately 12' below the surface of the reactor room floor. Ground water in this area moves very slowly through the components of the glacial drift. It is estimated that the ground water moves above 0.01 in/hour through the sand gravel/blue clay mixture found in the area of the reactor pool.

Surface water outside the Engineering Building is directed into the University storm sewer system. The University storm sewer system is directed to the Red Cedar River. Water in the Red Cedar River is periodically monitored by the Office of Radiation, Chemical and Biological Safety. The Red Cedar River is not used as source for human consumption.

Facility Description

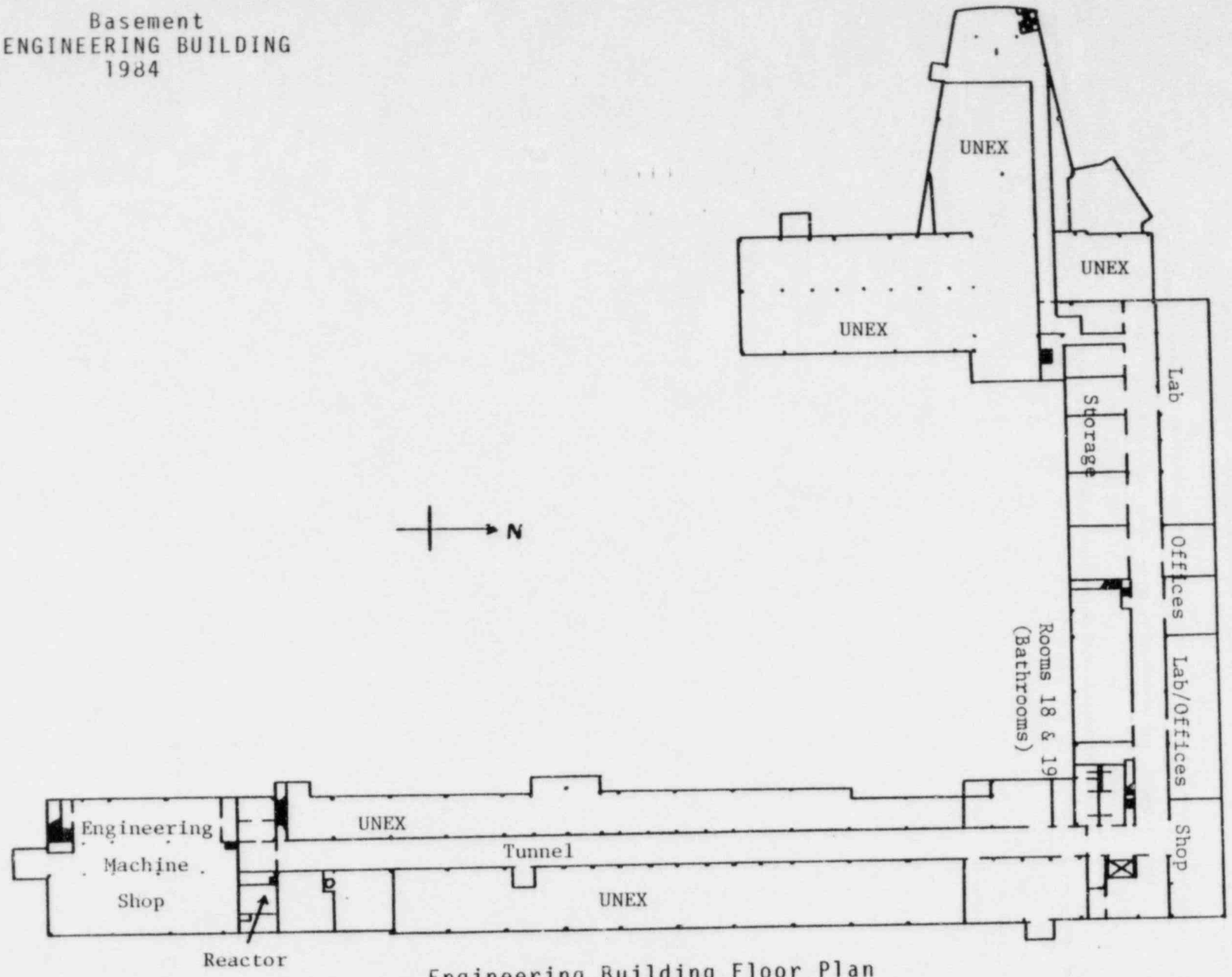
The Mark I Triga reactor is housed in Room 184 of the Michigan State University Engineering Building. This structure is a 3 floor concrete structure with block walls covered with brick veneer and was constructed in 1960-1962. The building is used for faculty and administrative offices, as well as instruction and research and is of essentially fire proof construction. Room 184, the reactor room, is located on the first floor in the southeast corner of the building. The attached floor plans (Figures 5,6,7,8 and 9) show the room location in relation to rooms in the same wing of the Engineering Building. Adjacent to the room are

undergraduate teaching laboratories on the north and south sides: a hall separates the room from faculty offices on the west side and the east side of the room is an exterior wall which faces a parking lot and street. There is no basement beneath the north half of Room 184 and it is here that the reactor well located. The south end of the room covers a machine shop in the basement (Fig. 10) and sufficient distance is maintained between the reactor core and this area to be equivalent to a minimum of 10 feet of concrete. Thus the shop is not a radiation area (radiation levels are less than 0.25 mr/hr). The second floor over the reactor areas is a classroom (Room 284) and the reactor pit has been deepened from the usual 21.5 feet to 24 feet 8 inches to insure that the radiation levels in this room are sufficiently low to permit free occupancy of the area. Thus the design of the facility is such that only Room 184 is a restricted operational area.

Room 184 (Figure 11) is a 25 x 30 foot area with 3 painted block walls, one painted brick wall, and concrete floor and ceiling (12-feet high). The outside wall of the room contains a continuous row of five foot high windows. Four 16-inch x 42-inch sections of the windows can be opened but would normally be closed during reactor operation. The opposite side of the room has fixed sash windows 4 x 12 feet into the hall and a 6 x 6-foot door. Adjacent to and entering into the room are three small rooms. Room 184A is a chemistry laboratory used for chemical preparation and radio-chemical separation. Room 184B is an instrument room used for sample counting. Room 190 is the office of the reactor supervisor.

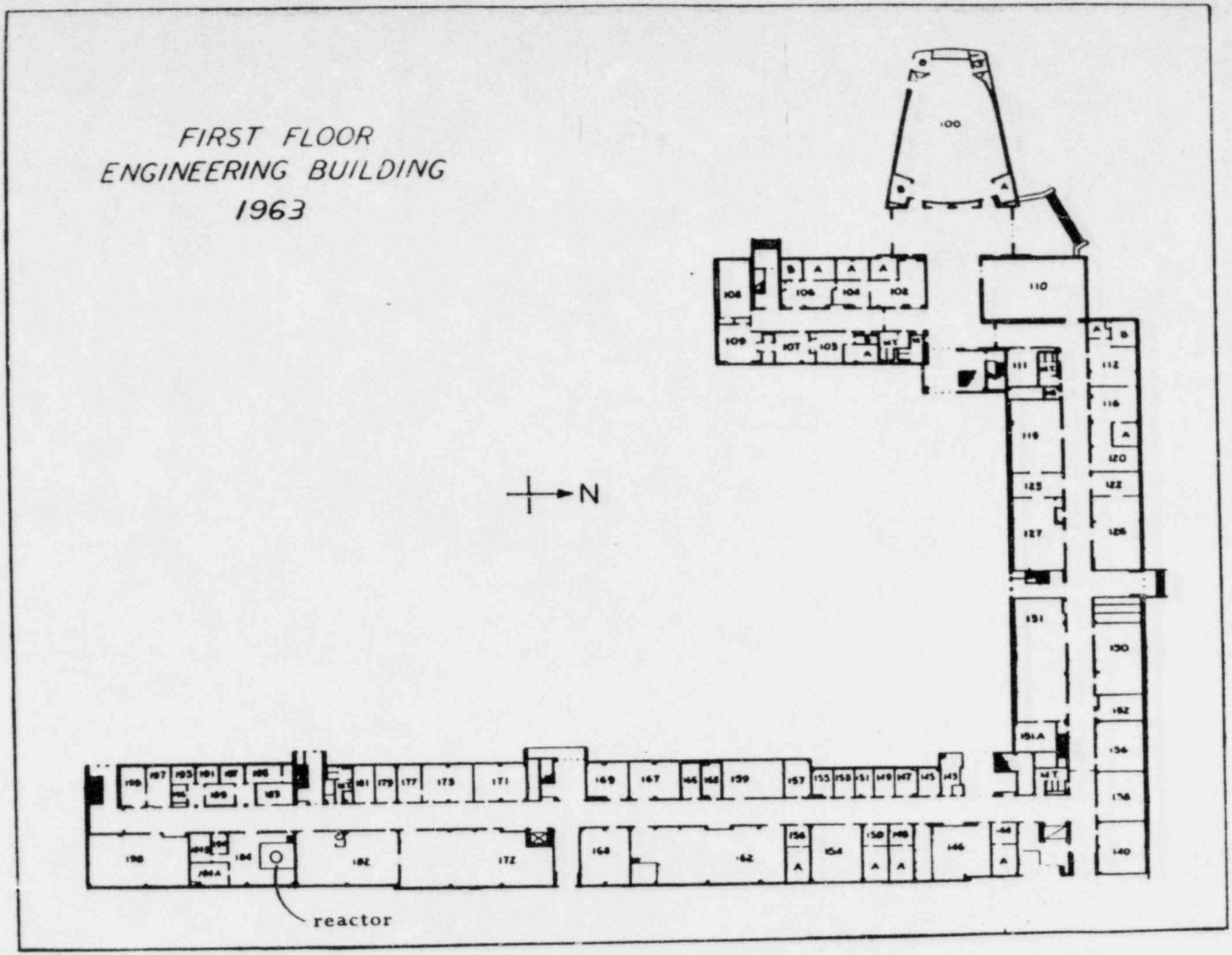
A 9 x 15 foot control room is located at the end of the interior hall leading to Rooms 184B and 190. The reactor console is housed in this room which has glass windows to permit viewing of the reactor area.

Ventilation into the facility is derived from two sources. A unit ventilator installed in the wall of Room 184 draws fresh air from the outside, heats it to the desired temperature and exhausts into the room. In addition, fresh air from the building air supply enters Rooms 184B and 190 at 200 cfm through ceiling ventilators. This air is dumped into Room 184 through a pneumatically operated damper in the control room wall. All air in Room 184 is exhausted through a continuously operating chemical hood located in Room 184A. Exhaust from this unit (at approximately 700 cfm) is through a duct to the building roof. All ventilation is designed to be closed in case of emergency and exhaust from the room in that instance would take place through an absolute filter system (in Room 184A) to the building roof, maintaining a negative pressure on the reactor room (184).



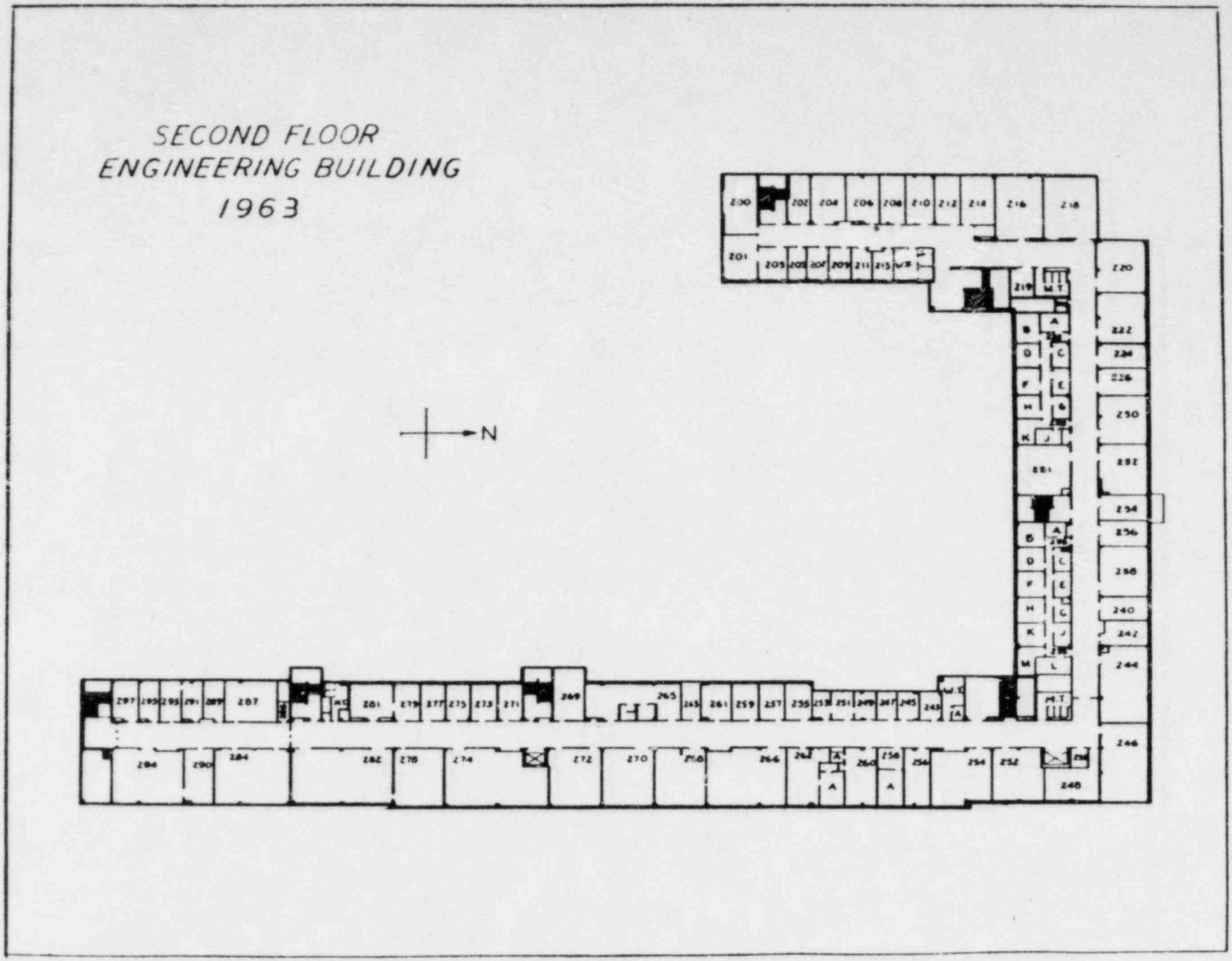
Engineering Building Floor Plan

Figure 5.



Engineering Building Floor Plan

Figure 6.



Engineering Building Floor Plan
Figure 7,

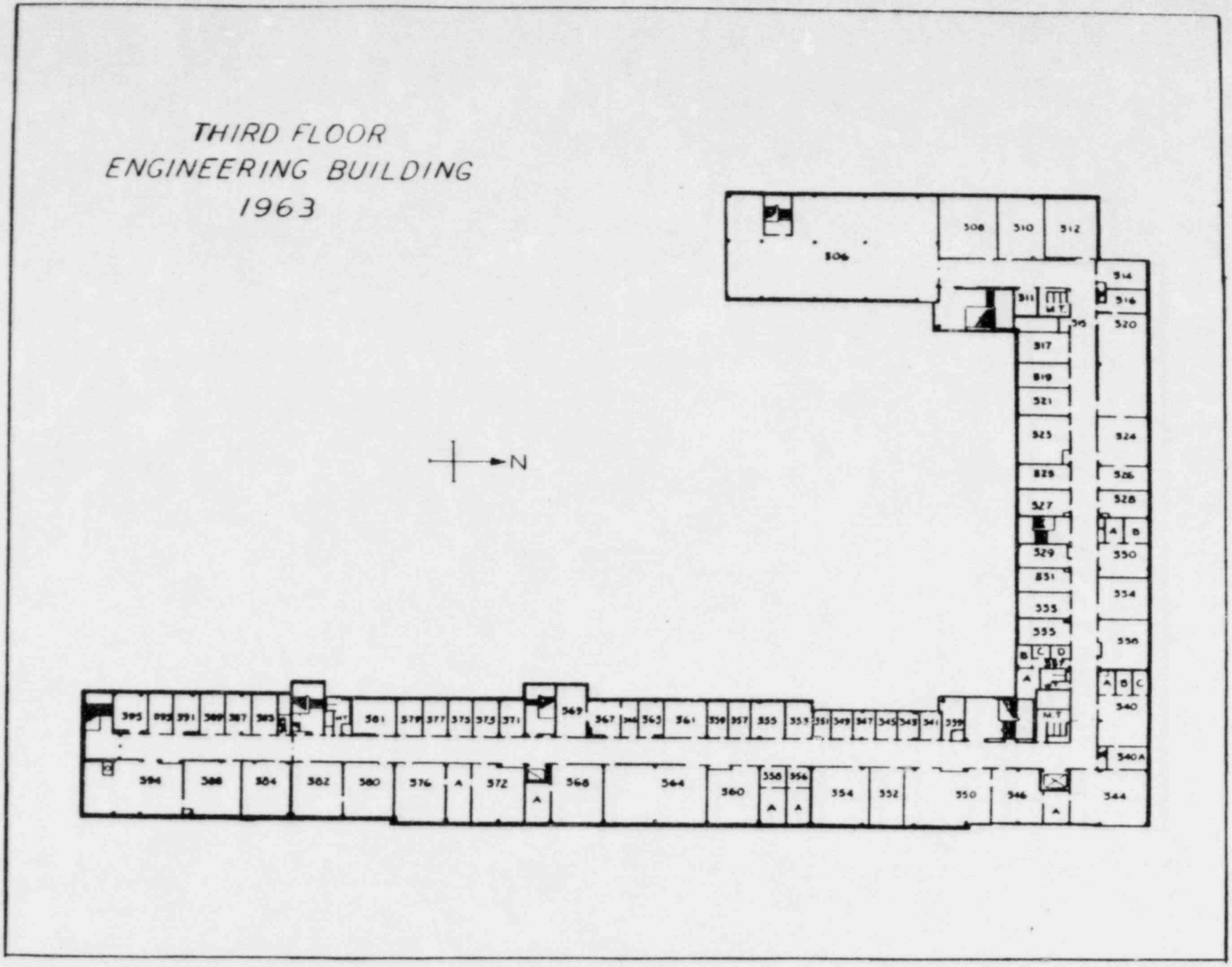
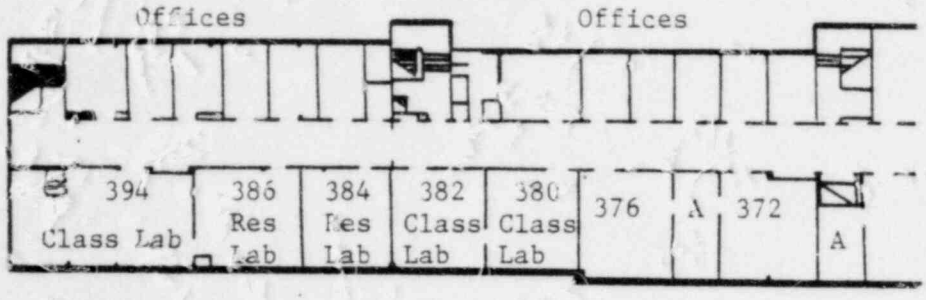
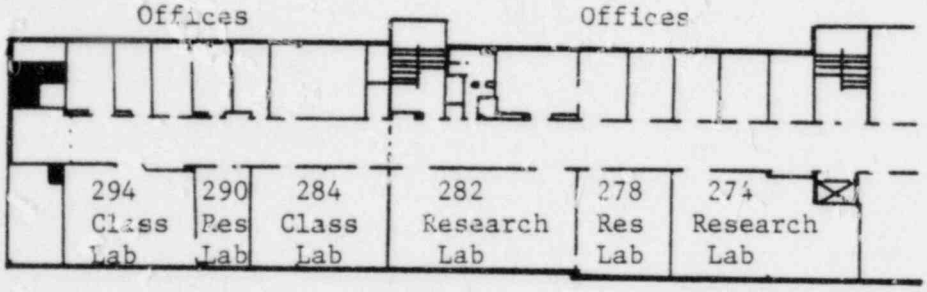


Figure 8. Engineering Building Floor Plan

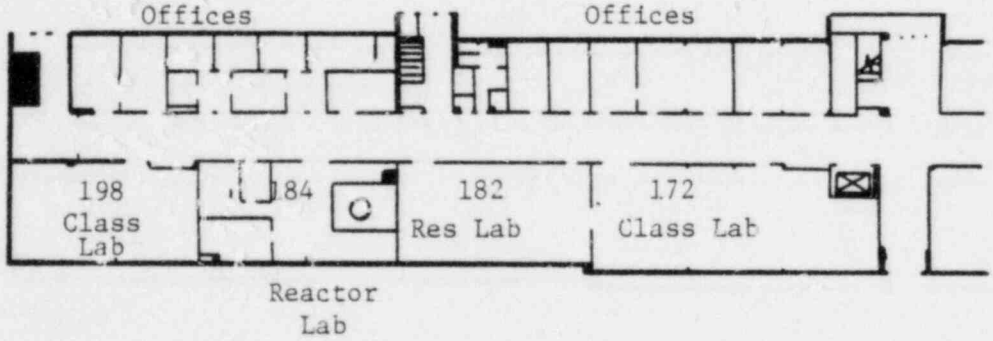
MSU Engineering Building (Southeast Wing)



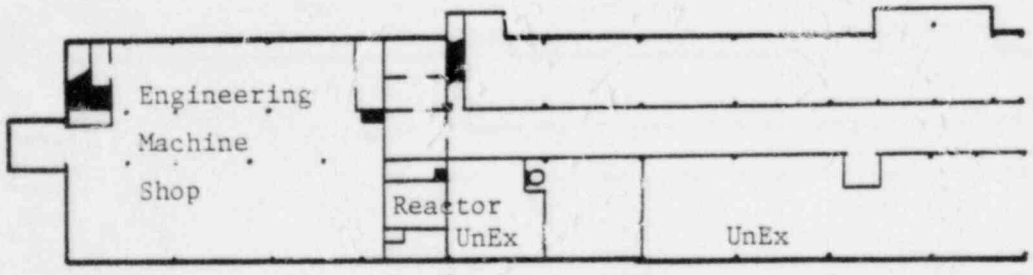
3rd Floor



2nd Floor



1st Floor



Basement

Figure 9.

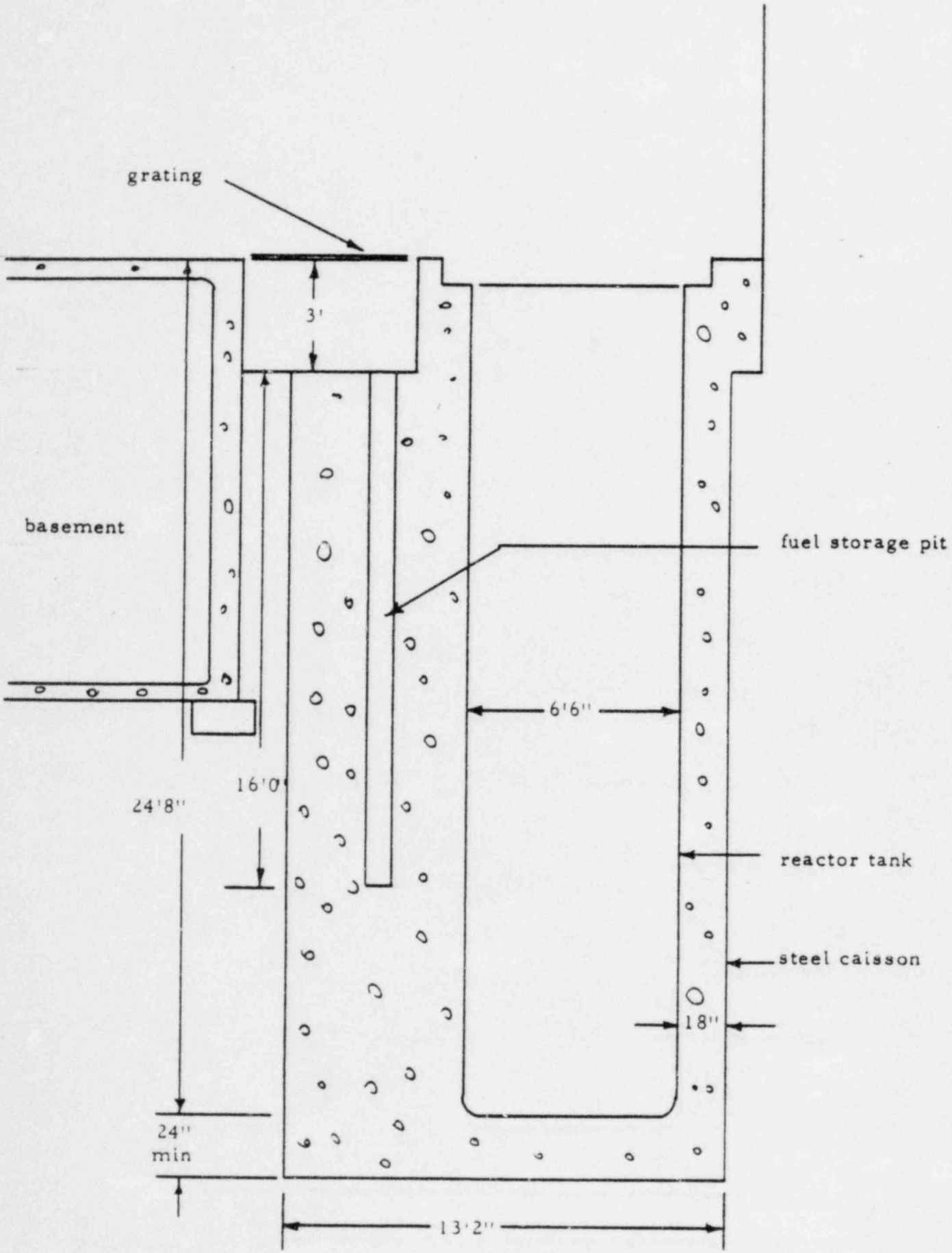


Figure 10. North-South Section through Reactor Pit

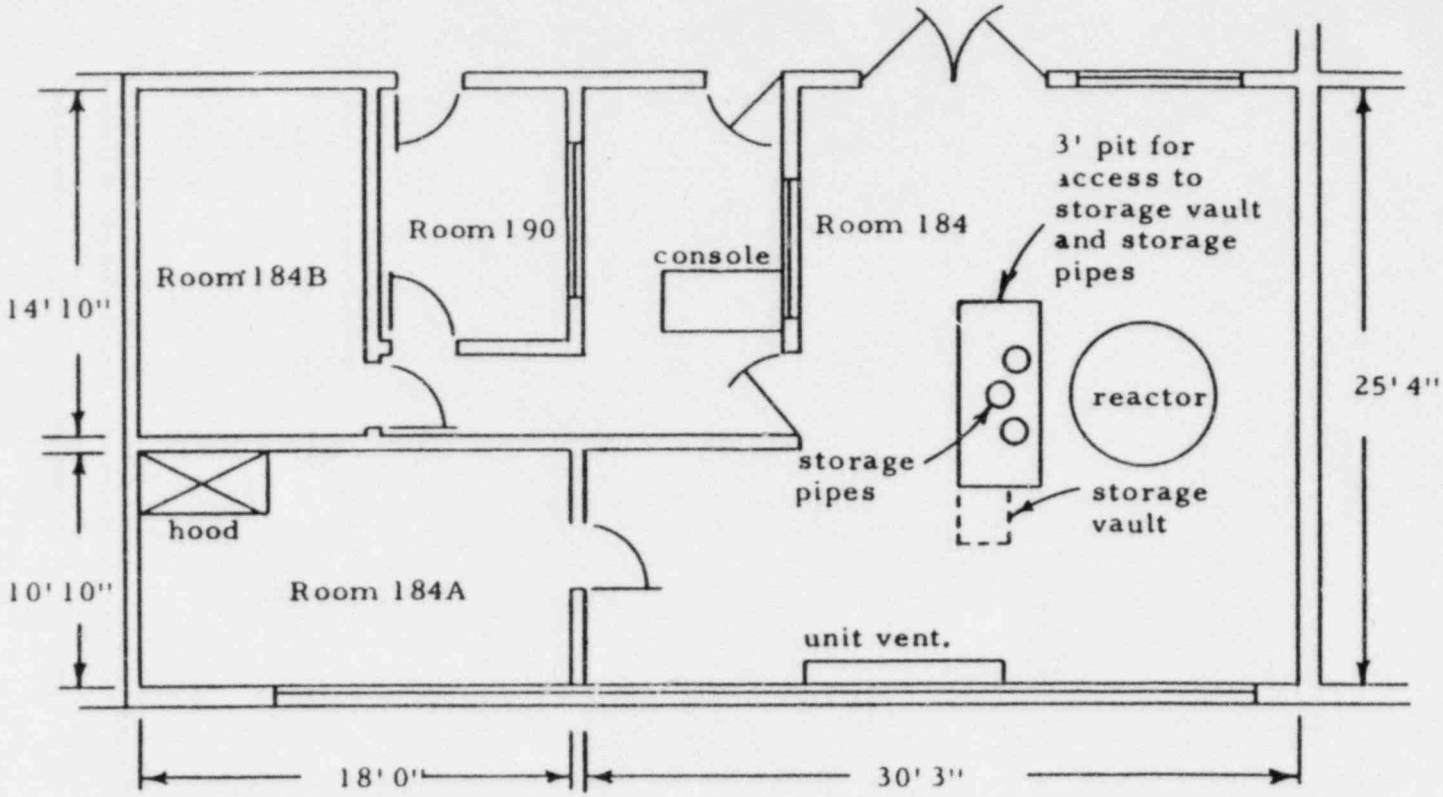


Figure 11. Floor Plan for Reactor Room, scale 1/8" = 1 foot.

The reactor core is located in a 6 1/2-foot diameter by 25-foot deep open pool in the north central area of Room 184 as shown on the enclosed sketch (Figure 12). No pneumatic transfer system is present.

Design Bases

(a) Reactor power: 250 KW steady state

$$250{,}000 \text{ KW } (1.4\% \frac{\delta K}{K}) \text{ pulsing.}$$

(b) Reactor water temperature: 122°F or 50°C maximum

(c) Restricted areas: all areas of the building except room 184, are unrestricted (i.e., radiation levels less than 0.25 mrem/hr). Further, the exterior of the building is an unrestricted area.

(d) Room ventilation: 2 air changes per hour minimum (700 cfm).

(e) Shielding surrounding core and tank:

(1) 1 1/2-foot concrete around tank to reduce ground activity to permissible levels

(2) 10-foot concrete (equivalent) from core to unrestricted access areas

(f) Emergency ventilation: doors and windows weather stripped. Capability of closing inlet air sources and diverting exhaust air through absolute filter in case of emergency. Air exhaust 150 cfm through this filter.

(g) Reactor fuel temperature: 500°C maximum.

Design Details

(a) Reactor

(1) Introduction

The TRIGA[1] reactor was developed by General Atomic Division of General Dynamics Corporation for use by universities and research institutions as a general-purpose research and training facility. Using U-$ZrH_{1.7}$ fuel, the reactor is designed for steady-state operation at a power level of 250 kw (thermal) and for routine pulsed operation. The total loading of this TRIGA reactor core is a maximum of 2.25% δk/k ($3.00) excess reactivity above a cold, critical, compact condition. Pulsed operation is limited to rapid insertions of up to 1.4% δk/k. As used in this document, a pulse is defined as a step insertion of an amount of

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[1] TRIGA trademark registered in U.S. Patent Office.

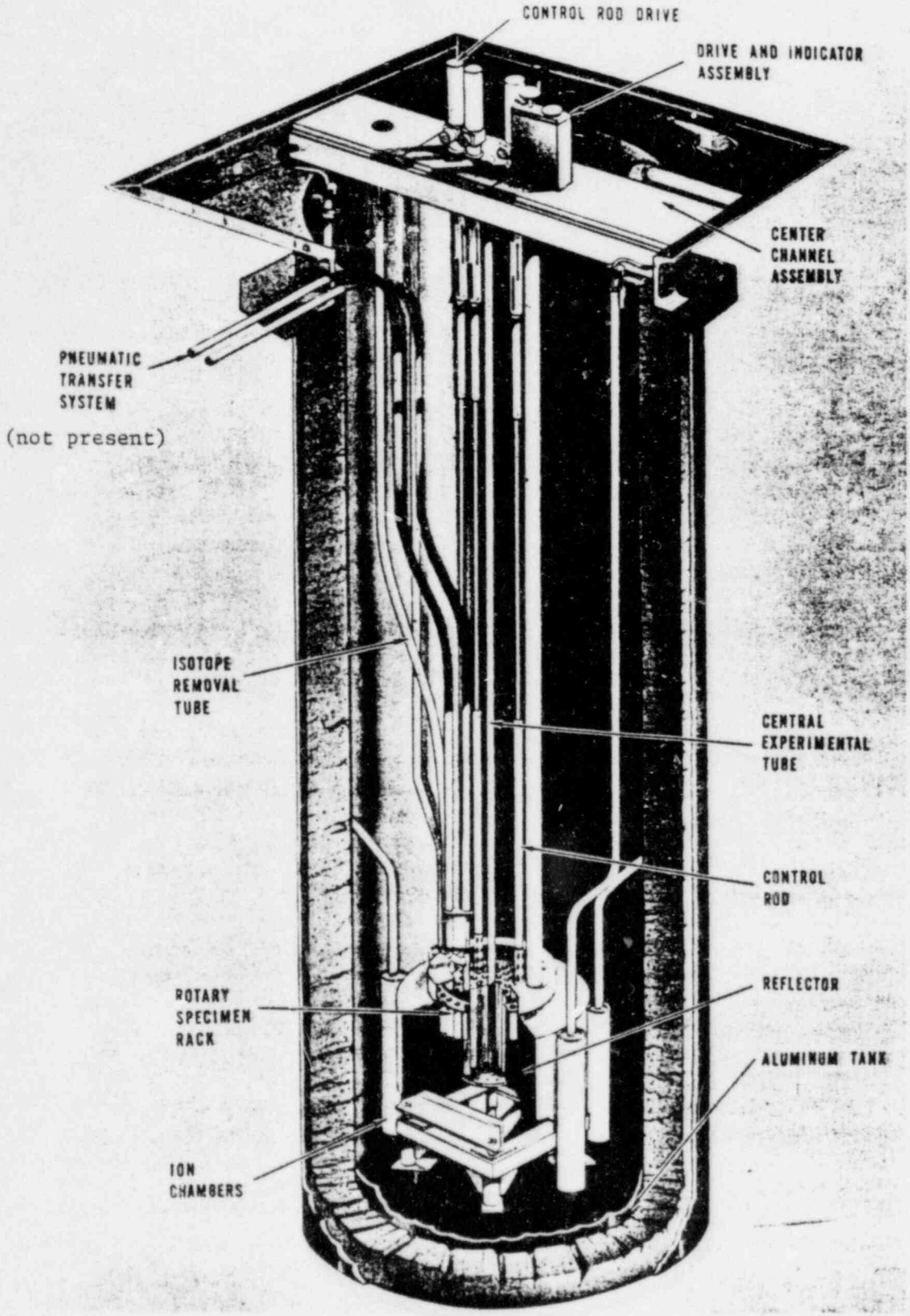


Figure 12. TRIGA Mark I reactor

excess reactivity between 0.75% and 1.4% δk/k. A 1.4% δk/k pulse yields a burse having a prompt energy release of about 8 Mw-sec, a peak power not to exceed 300 MW and a pulse width at half maximum of about 30 msec.

The safety of the TRIGA reactor lies in the large prompt negative temperature coefficient that is an inherent characteristic of the uranium zirconium hydride fuel-moderator material. Thus, even when large sudden reactivity insertions are made and the reactor power rises in a short period, the excess reactivity is compensated for automatically because the fuel temperature rises simultaneously so that the system returns quickly to a normal power level before any heat is transferred to the cooling water.

The inherent prompt shutdown mechanism of TRIGA reactors has been demonstrated extensively during many thousands of transient tests conducted at the two prototype TRIGA reactors in General Atomic' laboratories in San Diego. These tests, using aluminum-clad, U-$ZrH_{1.0}$ elements, involved step insertions of reactivity of up to 3.1% δk/k. This demonstrated safety has permitted the location of TRIGA reactors in urban areas for other research reactors of similar power level and excess reactivity.

This reactor core consists of a lattice of cylindrial stainless steel clad U-$ZrH_{1.7}$ fuel-moderator elements and graphite (dummy) elements. Twenty percent enriched uranium is used. A 1-foot-thick graphite radial reflector surrounds the core and is supported on an aluminum stand at the bottom of the tank. Water occupies about one-third of the core volume.

The power level of the pulsing TRIGA reactor is accurately controlled with three control rods: a regulating rod, a shim rod, and a safety-transient rod.

Four instrumentation channels monitor and indicate the neutron flux and power level and their rate of change.

The prototype TRIGA reactor attained criticality at General Atomic's John Jay Hopkins Laboratory for Pure and Applied Science in San Diego, California, on May 3, 1958.

Reactor Description

TRIGA Mark I Structure

The TRIGA Mark I reactor core assembly is located near the bottom of an aluminum tank placed in the ground and surrounded externally by concrete. Figure 7 has shown a typical Mark I installation.

Reactor Tank

The rector tank for the Mark I reactor is welded aluminum vessel with 1/4-inch-thick walls, surrounded externally by steel-encased concrete. The tank has an outside diameter of approximately 6.5 feet and an overall length of approximately 25 feet. The tank is waterproofed by continuous welded joints. The integrity of the joints is verified by radiographic testing, dye-penetrant checking, and leak-testing. The outside of the tank is coated for corrosion protection. An aluminum channel, used for mounting the ion chambers, fuel storage racks, underwater lights, and other equipment, is welded around the top of the tank.

Demineralized water in the tank provides approximately 20 feet of shielding water above the core.

Center Channel Assembly and Reactor Tank Covers

The center channel assembly across the top of the reactor tank provides support for the drive-and-indicator assembly for the isotope production facility, control rod drive assemblies, and tank covers.

The top, or a portion of the top, of the reactor tank is closed by aluminum grating tank covers that are hinged and installed flush with the floor. A sheet of Lucite plastic attached to the bottom of each grating section prevents foreign matter from entering the tank but still permits visual observation.

Basic Reactor Components

a) Reflector Assembly

The reactor core and reflector assembly (see Figure 13) form a cylinder approximately 43 inches in diameter and 23 inches high. The core consists principally of a lattice of fuel-moderator elements, graphite dummy elements, and control rods surrounded by the graphite reflector.

The reflector is a ring-shaped block of graphite that surrounds the core. It is 12 inches thick radially, with an inside diameter of 18 inches and a height of 22 inches. The reflector is encased in a leak-tight, welded aluminum can to prevent water penetration of the graphite. A "well" in the top of the graphite reflector is provided for the rotary specimen rack. The reflector assembly, which is supported by an aluminum platform, provides support for the two grid plates (Figure 13).

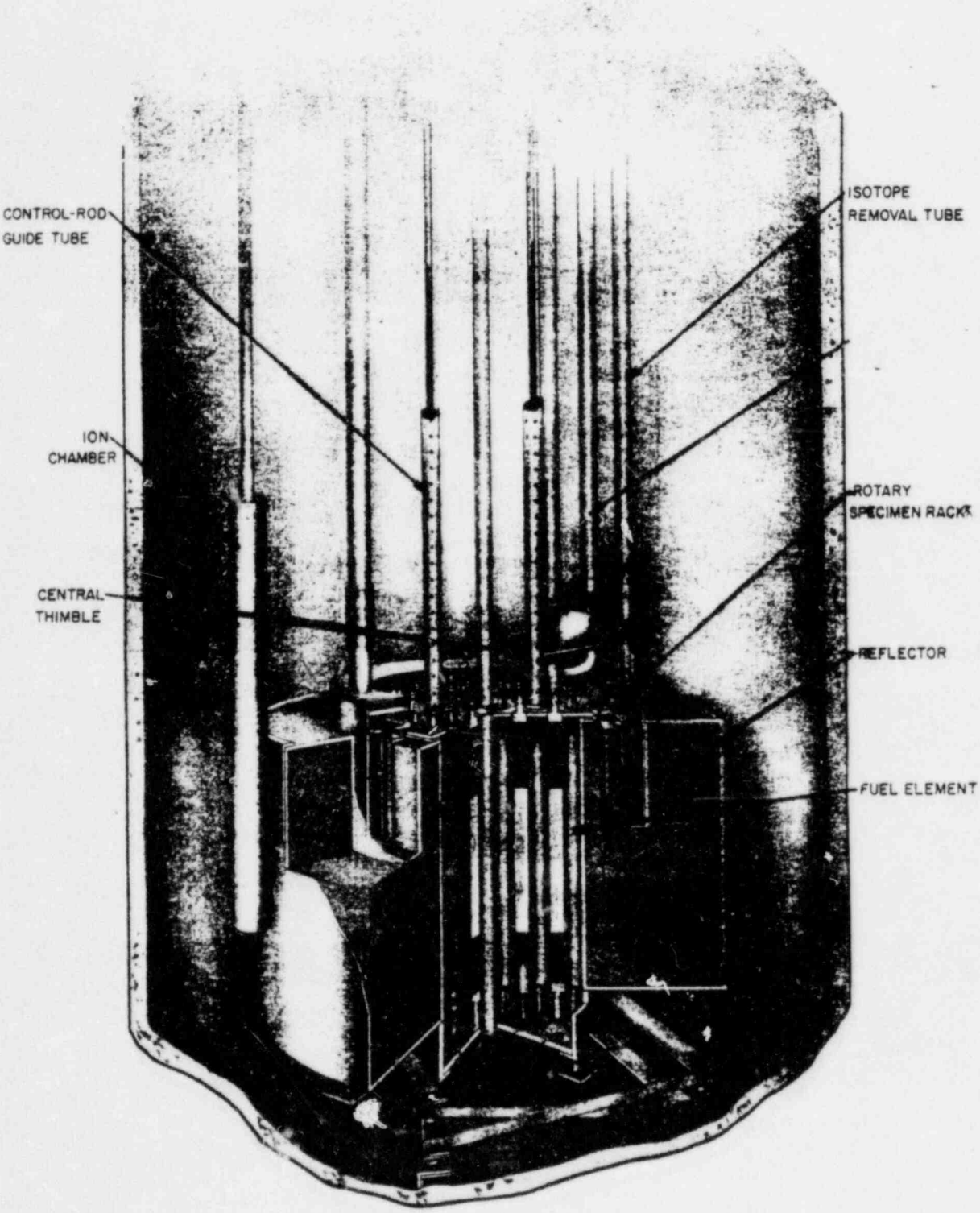


Fig. 13. Cutaway view of core and reflector assembly

The reflector obtained from the University of Illinois has several penetrations corresponding to the location of beam ports. These represent "holes" in the graphite and are not filled. The one penetrating beam port in the reflector was capped and sealed before installation.

Four vertical tubes attached to the reflector assembly permit accurate and reproducible positioning of the three ion chambers and the fission chamber.

The top grid plate provides lateral positioning of the core components. It is made of anodized aluminum and contains 91 holes approximately 1.5 inches in diameter; these holes are distributed in five circular rings about a center hole.

An anodized aluminum bottom grid plate, in addition to providing lateral spacing between the fuel-moderator elements, supports the entire weight of the core.

b) Fuel-Moderator Elements

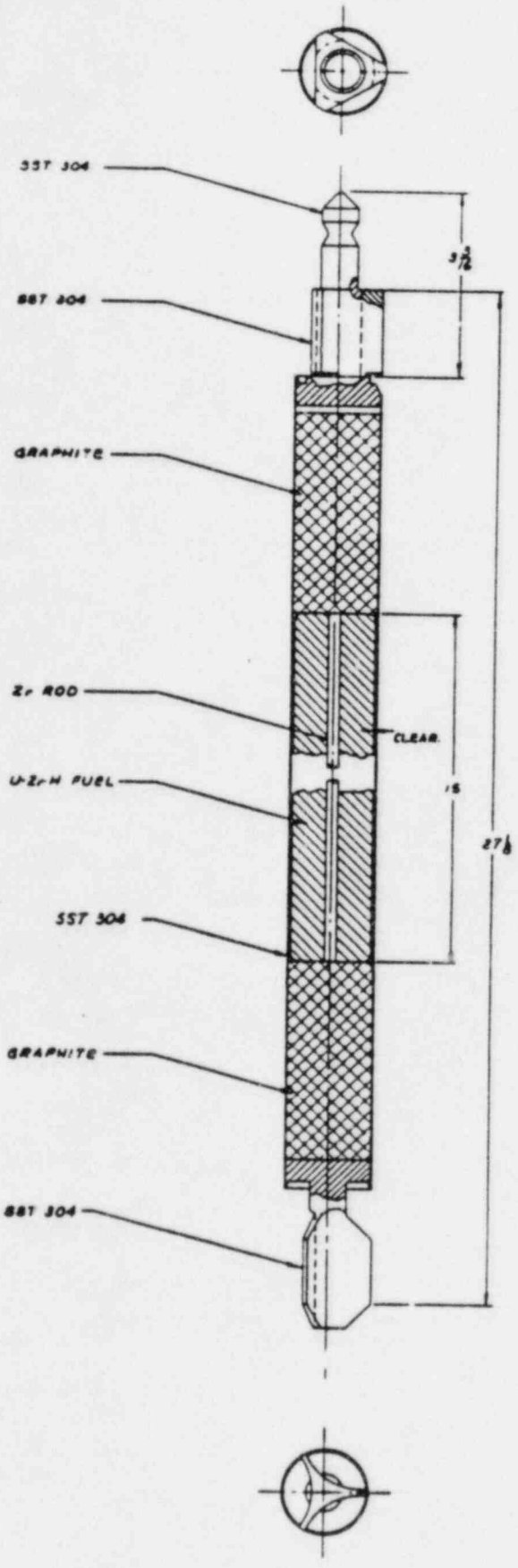
The active part of each fuel-moderator element, shown in Figure 14, is approximately 11.4 inches in diameter and 14 inches long. The fuel is a solid, homogeneous mixture of uranium-zirconium hydride alloy containing 8.5% by weight of uranium enriched to 20% U^{235}. Currently eight 12% by weight elements are also in the core. The hydrogen to-zirconium atom ratio is approximately 1.7 each element contains about 33 grams of U^{235}.

Each element is sealed in a 0.020 inch-thick stainless steel cladding and all closures are made by heliarc welding. Two 4-inch section of graphite inserted in the can, one above, and one below the fuel, to serve as top bottom reflectors for the core. Stainless steel and fixtures are attached to both ends of the can, making the overall length of the fuel-moderator element approximately 28.5 inches. The fuel element cladding is stainless steel to retard wear and corrosion.

The lower end fixture supports the fuel-moderator element on the bottom grid plate. The upper end fixture consists of a knob for attachment of the fuel-handling tool and a triangular spacer, which permits cooling water to flow through the upper gird plate. The weight of a fuel element is about 6.5 pounds.

c) Instrumented fuel-moderator elements

Instrumented fuel-moderator elements, shown in Figure 15, are provided with the core of each TRIGA pulsing reactor. These instrumented elements have the same dimensions and fuel material as standard elements, but they contain three chromel-alumel thermocouples embedded halfway between the outer edge of the element and



LC45755

EL-1249

Fig. 15. Typical TRIGA fuel element

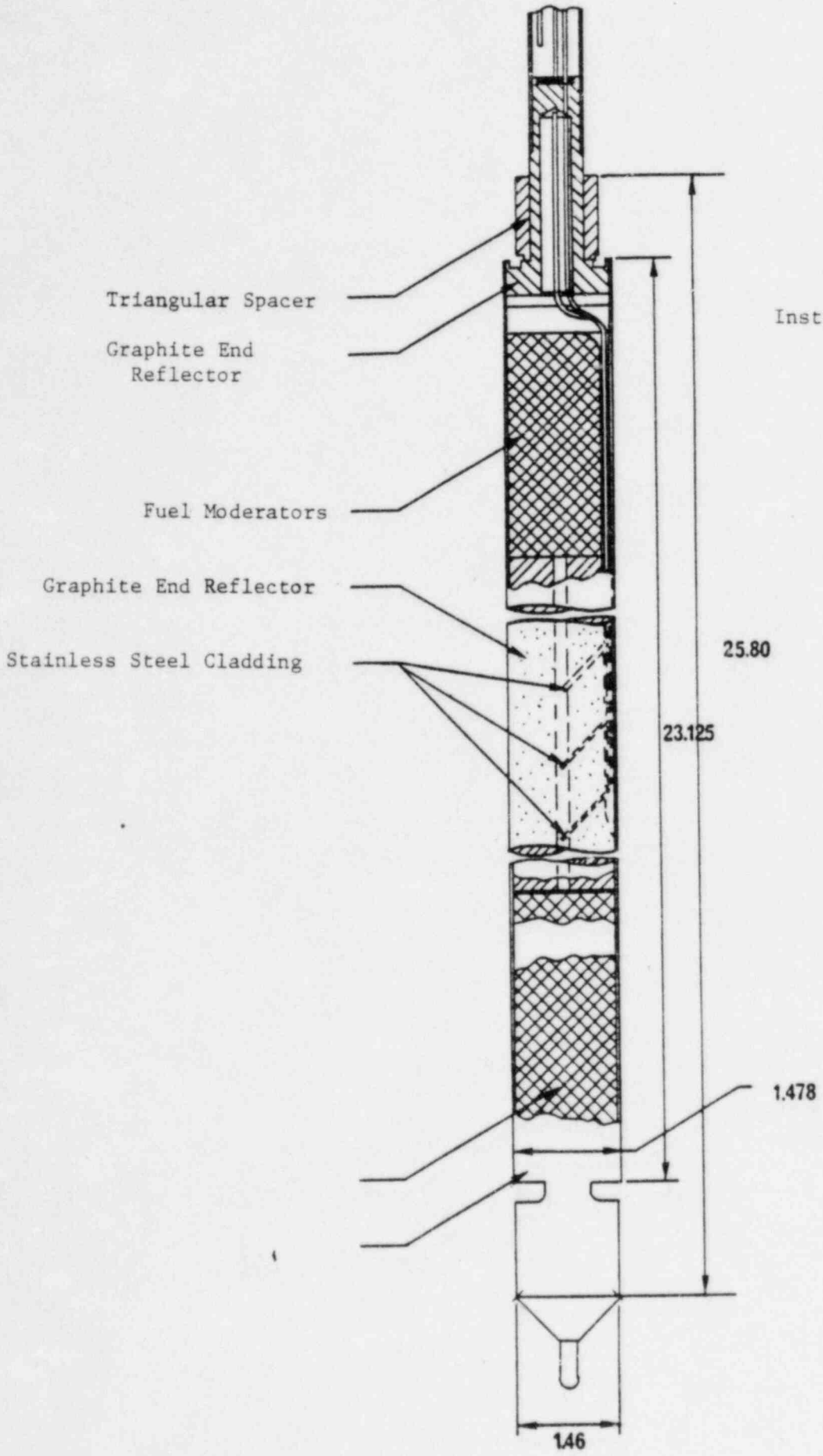


Figure 15.

Instrumented Fuel Element

its vertical centerline. They are located 1 inch above, and 1 inch below and at the horizontal centerline of the fuel. The tube that leads from the fuel element is sealed with an aluminum plug containing holes for the thermocouple wires. Soft solder flowed in on top of the plug seals the holes around the wires and between the plug and the tube. The wires lead from the fuel element to the water in aluminum tubing.

d) Graphite Dummy Elements

Graphite dummy elements are used to fill grid positions not filled by the fuel-moderator elements or other core components. They are of the same general dimensions and construction as the fuel-moderator elements, but are filled entirely with graphite.

e) Neutron Source

The neutron source consists of a mixture of Americum and Beryllium, double encapsulated to ensure leak-tightness. Initial strength at manufacture was 3 curies. This source has a nominal outside diameter of approximately 0.7 inch and a height of 0.7 inch. The neutron source holder (see Figure 16), is the same general size and shape as a fuel element: thus, it can be placed in any vacant fuel or graphite element location. The upper and lower portions of the holder are screwed together to enclose a cavity that contains the source. A shoulder a the upper end of the neutron source holder supports the assembly on the upper grid plate. The current source is 1.88 ci.

g) Experimental and Irradiation Facilities

A rotary specimen rack, (Figure 17) located in a well in the top of the graphite reflector, provides for the large-scale production of radioisotopes and for the activation and irradiation of small specimens in a dry atmosphere. All 40 positions in this rack are exposed to neutron fluxes of comparable intensity. Samples are loaded from the top of the reactor through a water tight tube into the rotary rack using a specimen lifting device (essentially a fishing pole with a grapple mechanism on the end of a power cord). The rotary rack can be turned manually or by using a motor drive located on the center channel assembly.

The TRIGA reactor is equipped with a central thimble (see Figure 12) for conducting experiments or irradiating small samples in the core at the point of maximum flux. It consists of a 1.5-inch OD aluminum tube that fits through the

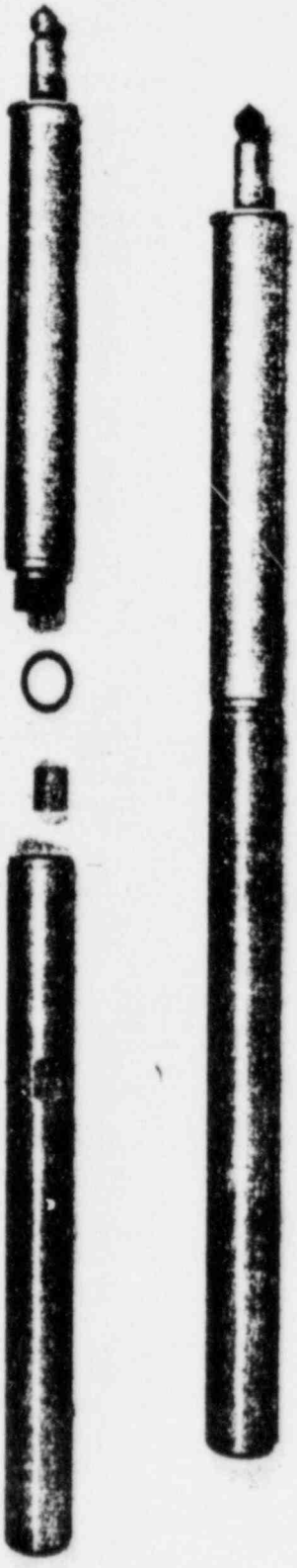


Fig. 16. Neutron source holder

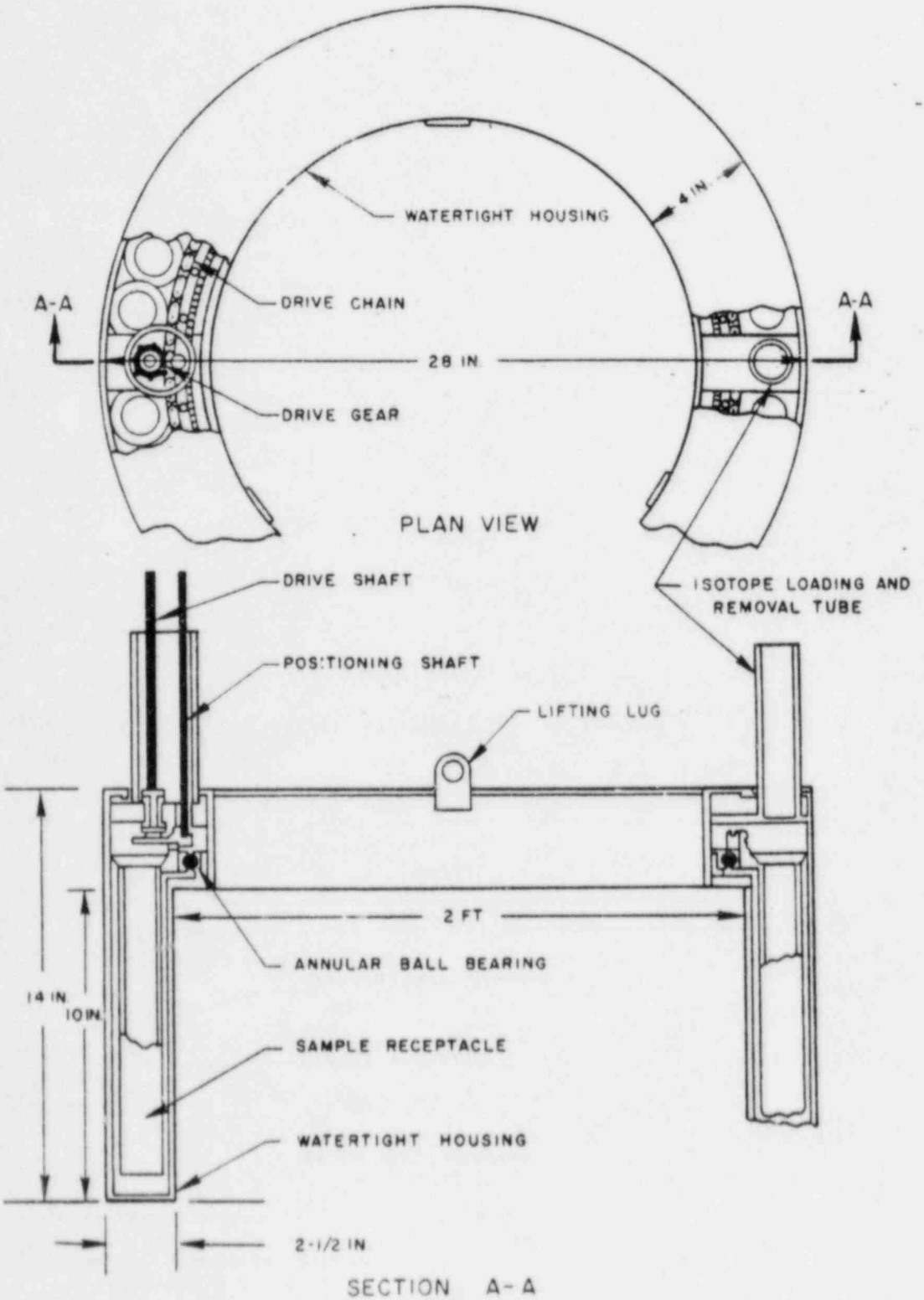


Fig. 17. Rotary specimen rack schematic

center hole of the top and bottom grid plates. Holes in the tube assure that it is normally filled with water; however, a special cap may be attached to the top end, compressed air applied, and the water column removed to obtain a well-collimated beam of neutrons.

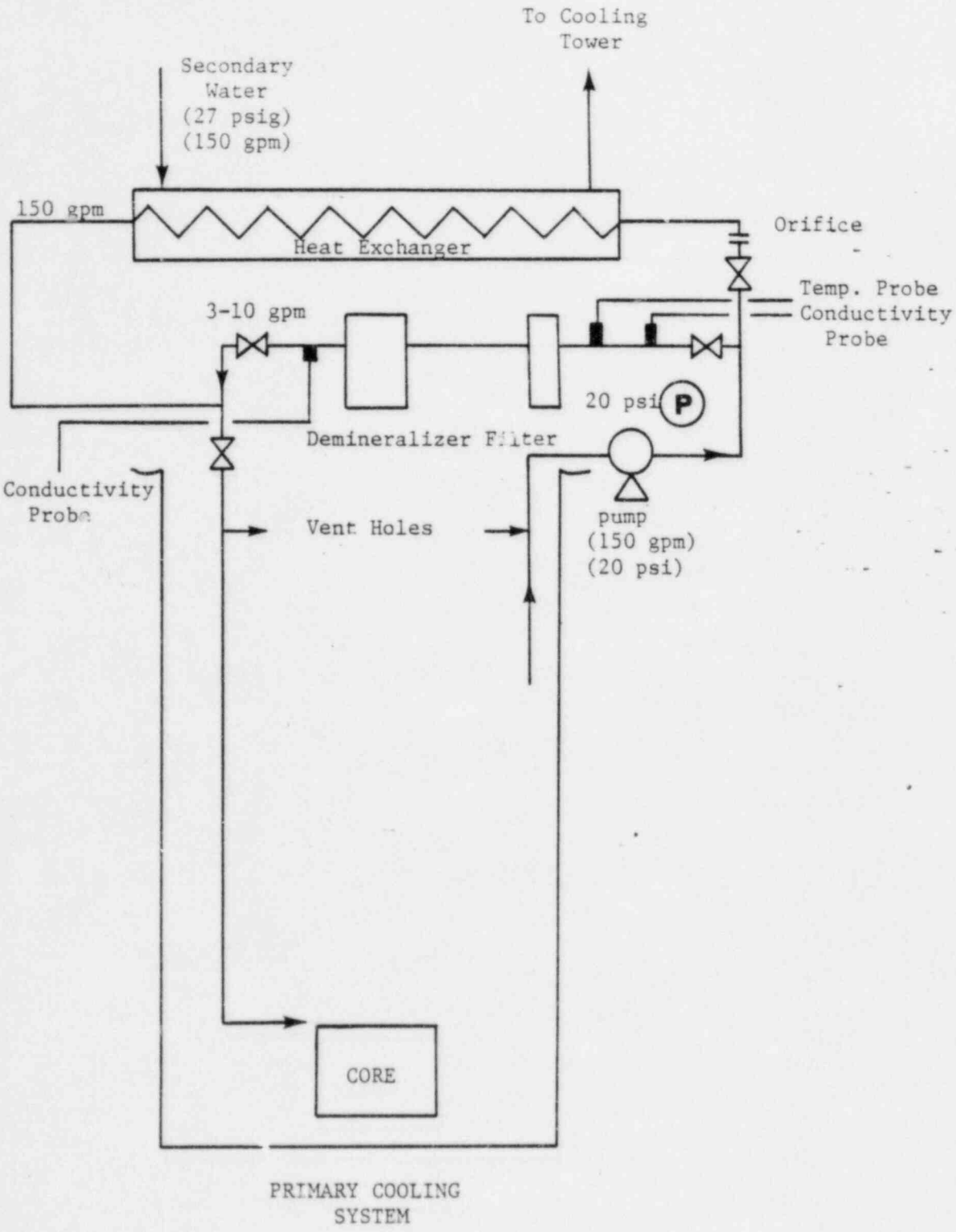
f) Reactor Water Cooling and Purification System (Figure 18)

The water system provided with the TRIGA reactor serves five functions it:

1. Maintains low conductivity of the water to minimize corrosion of all reactor components, particularly the fuel elements.
2. Reduces radioactivity in the water by removing nearly all particulate and soluble impurities.
3. Maintains the optical clarity of the water.
4. Provides a means of dissipating the heat generated in the reactor.
5. Reduces the radiation level due to nitrogen-16 at the top of the reactor because the vertical convective core water currents are deflected by the downward slanted discharge of water through a diffuser nozzle on the water system's tank inlet.

The system consists principally of a pump, fiber cartridge filter, a mixed-bed type of demineralizer, a flow meter, and a heat exchanger connected by suitable aluminum piping and valving. A surface skimmer is provided to assist in maintaining the cleanliness of the rector-tank water surface. Probes are provided for measuring the temperature and conductivity of the water as it passes through the system.

Reactor heat is removed by circulation of pool water from the reactor pool through the tube side of a stainless steel heat exchanger. The pump and exchanger for this operation is located along the north wall of the reactor room. Piping for the pool water is threaded aluminum and is provided with vacuum-breaking holes to prevent siphoning the pool water in case of line rupture. A fraction of the water flow is directed through a mixed bed ion exchange column for purification and then back to the reactor tank. The temperature of the pool water outlet as well as the electrical conductivity of the water is measured and displayed at the reactor console. The ion exchange unit is located in Room 184 to permit local shielding and controlled access in case the radioactivity on the bed becomes excessive.



PRIMARY COOLING
SYSTEM

Figure 18.

Secondary heat removal is accomplished by circulation of water through the shell of the heat exchanger up to a forced convection cooling tower located the penthouse on the building roof. The circulation pump for this stream is located in the basement pipe tunnel. Motor switches and indicator lights are provided at the control console to insure the operation of the cooling system.

g) Control Rods

Each of the three control rods operates in a perforated aluminum guide tube. The shim and regulating rods are sealed aluminum tubes containing boron carbide (in powdered form) as a neutron poison. The upper end of each control rod screws into a control-rod-drive-assembly extension tube. Each control rod is approximately 20 inches long. The regulating, shim, and safety-transient rods are 1.25-inch-OD; the vertical travel of the control rods is approximately 15 inches.

The safety-transient rod, which is completely out of the core during normal steady-state operation, is worth approximately 1.36% $\delta k/k$. The reg and shim rod worths are 1.30 and 2.12% $\Delta k/k$ respectively. The total excess reactivity in the core does not exceed 2.25% $\delta k/k$. The maximum possible reactivity insertion rate associated with the withdrawal of any rod except the transient rod shall not exceed 0.2% $\delta k/k$ sec or 28¢ per second.

h) Rack-and-Pinion Rod Drives

Rack-and-pinion rod drives, shown in Figure 19, are used to position the shim and safety rods. Each drive consists of a single-phase, reversible motor; a magnet rod-coupler, and a rack-and-pinion-gear system. The pinion gear engages a rack attached to a draw tube supporting an electromagnet. The magnet engages an iron armature attached above the water level to the end of a long connecting rod that terminates at its lower end in the poison rod. The magnet, its draw tube, the armature, and the upper portion of the connecting rod, are housed in a tubular barrel. The barrel extends below the reactor water level with the lower end of the barrel serving as a mechanical stop to limit the downward travel of the control rod assembly. Part-way down the upper portion of the connecting rod, i.e., just below the armature, is a piston that travels within the barrel assembly. Since the upper portion of the barrel is well-ventilated by large slotted openings, the piston moves freely in this range; but when the piston is within 2 inches of the bottom of its travel, its movement is restrained by the dash pot action of the grated vents in the lower end.

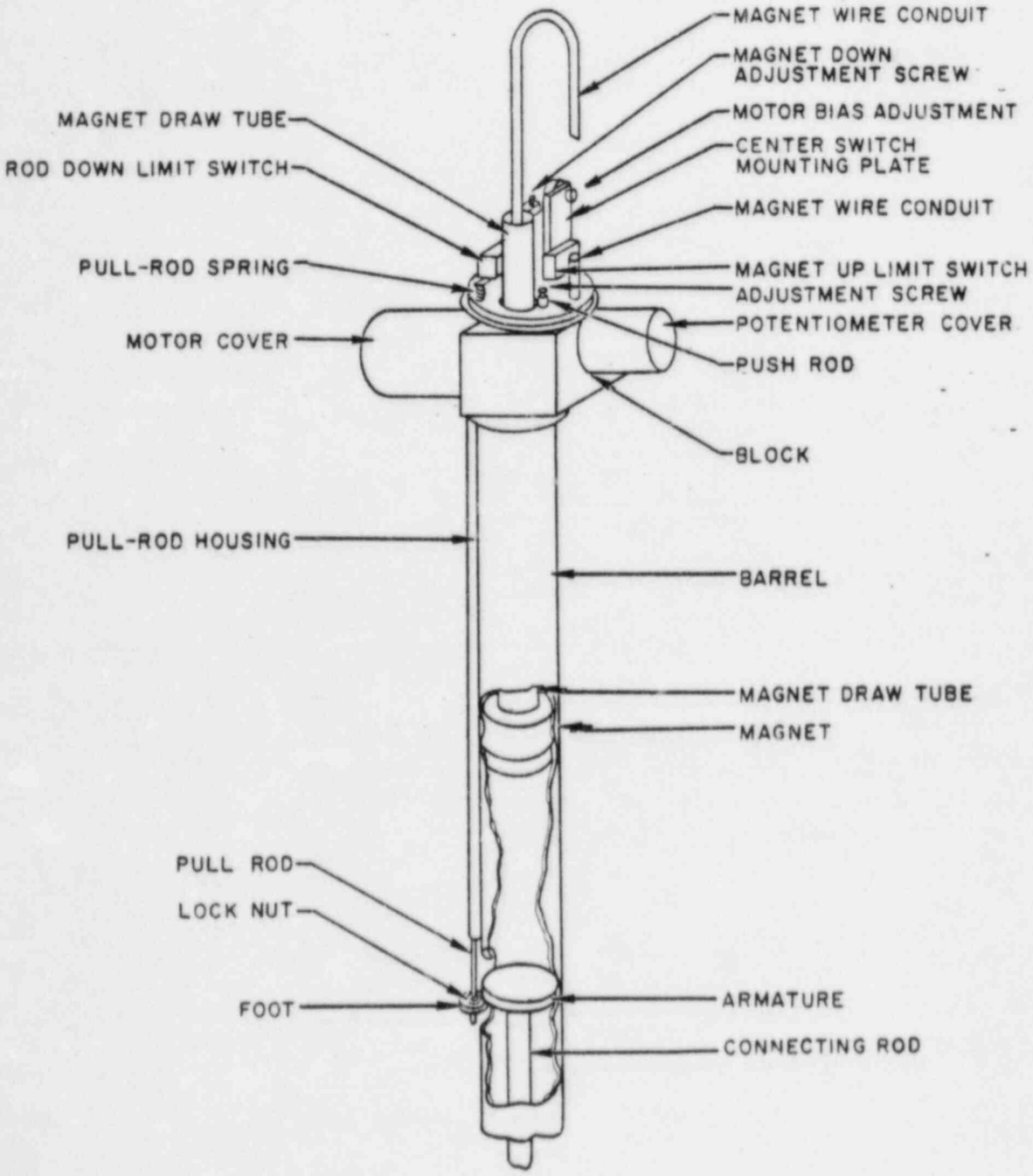


Fig. 19. -Rod drive mechanism, showing components and adjustment locations

Controls and Instrumentation

a) General

The pulsing TRIGA reactor is capable of operating in two standard modes:

Mode 1 Steady-state operation at power levels up to 250 kw thermal.

Mode 2 Pulsed operation produced by rapid transient rod withdrawal that results in a step insertion of reactivity of up to 1.4% δk/k ($2.00).

The reactor is operated from a console (see Figure 20) that displays all pertinent reactor operating conditions.

The control system consists of four power-measuring channels utilizing three ion chambers and one fission counter as well as monitors for fuel temperature, cooling water outlet temperatures, and water conductivity. Test circuits and calibration signals are provided for the log count-rate, log-n, and linear power-level channels. The rack-and-pinion control-rod drives and the pneumatic safety-transient rod drive are controlled from the console. Manual scram is possible for the control rods individually or as a group. A helipot is used on the regulating and shim rod drives to provide indication of the control rod position on the console.

A selector switch is provided for steady-state and pulsing modes of operation.

b) Modes of Operation

1) Steady-State Operation. For steady-state operation, the control rod are withdrawn slowly by manual control until the desired power level is reached. A diagram of the TRIGA reactor control system is given for steady-state operation in Figure 21.

The count-rate channel, using a fission counter and log count-rate chassis, provides power indication over 4 decades from below source level. This channel is provided with a source interlock that prevents rod withdrawal unless source level is above a preset level. Operating ranges for the various detectors is presented in Figure 22.

A log-n channel using a compensated ion chamber covers the power range from less than 10 watts to above full power, and is read and recorded by one pen of the 11-inch, dual-channel recorder. A period circuit indicates reactor period from -40 to ∞ to +7 seconds.

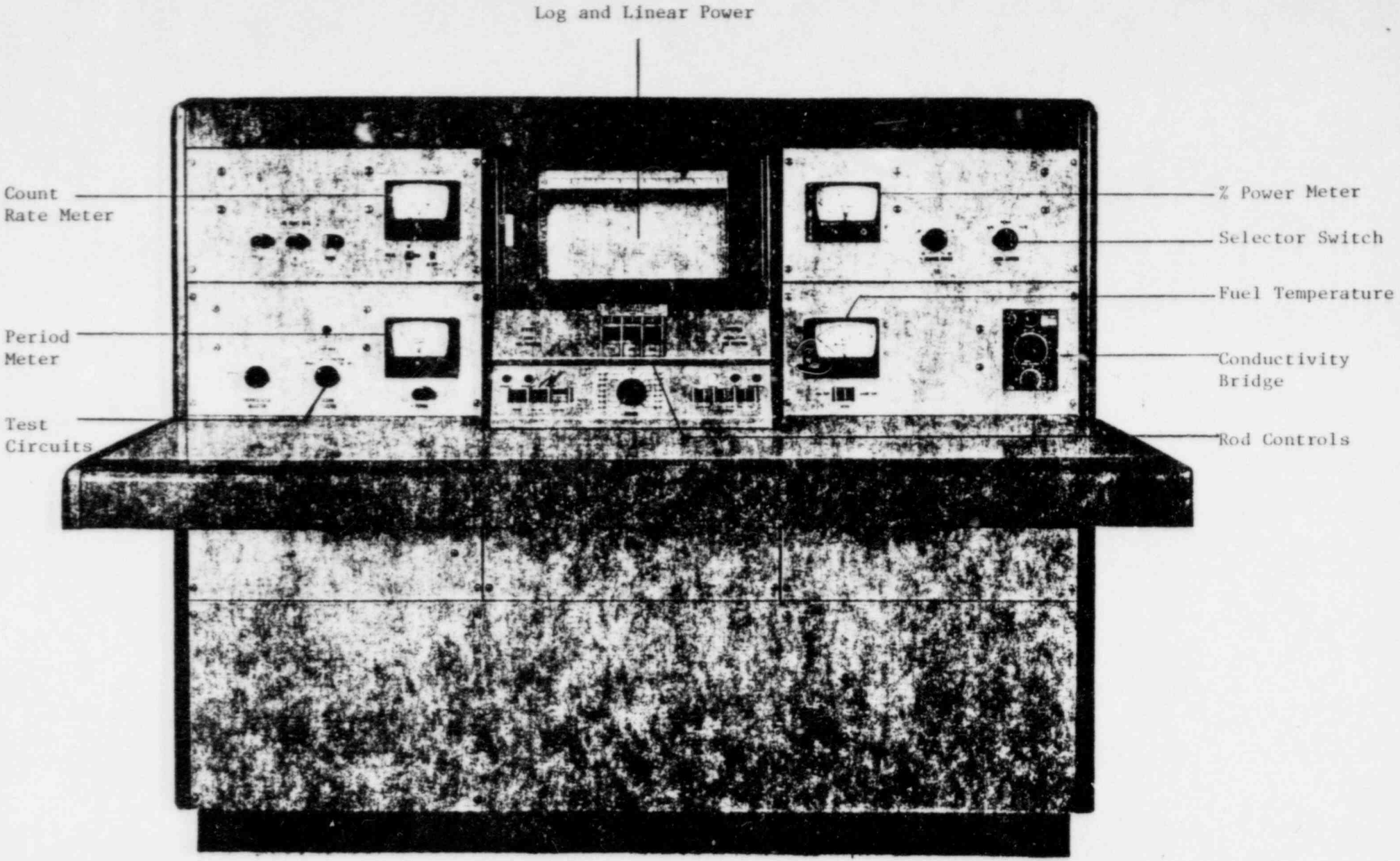


Fig. 20 TRIGA control console, front view

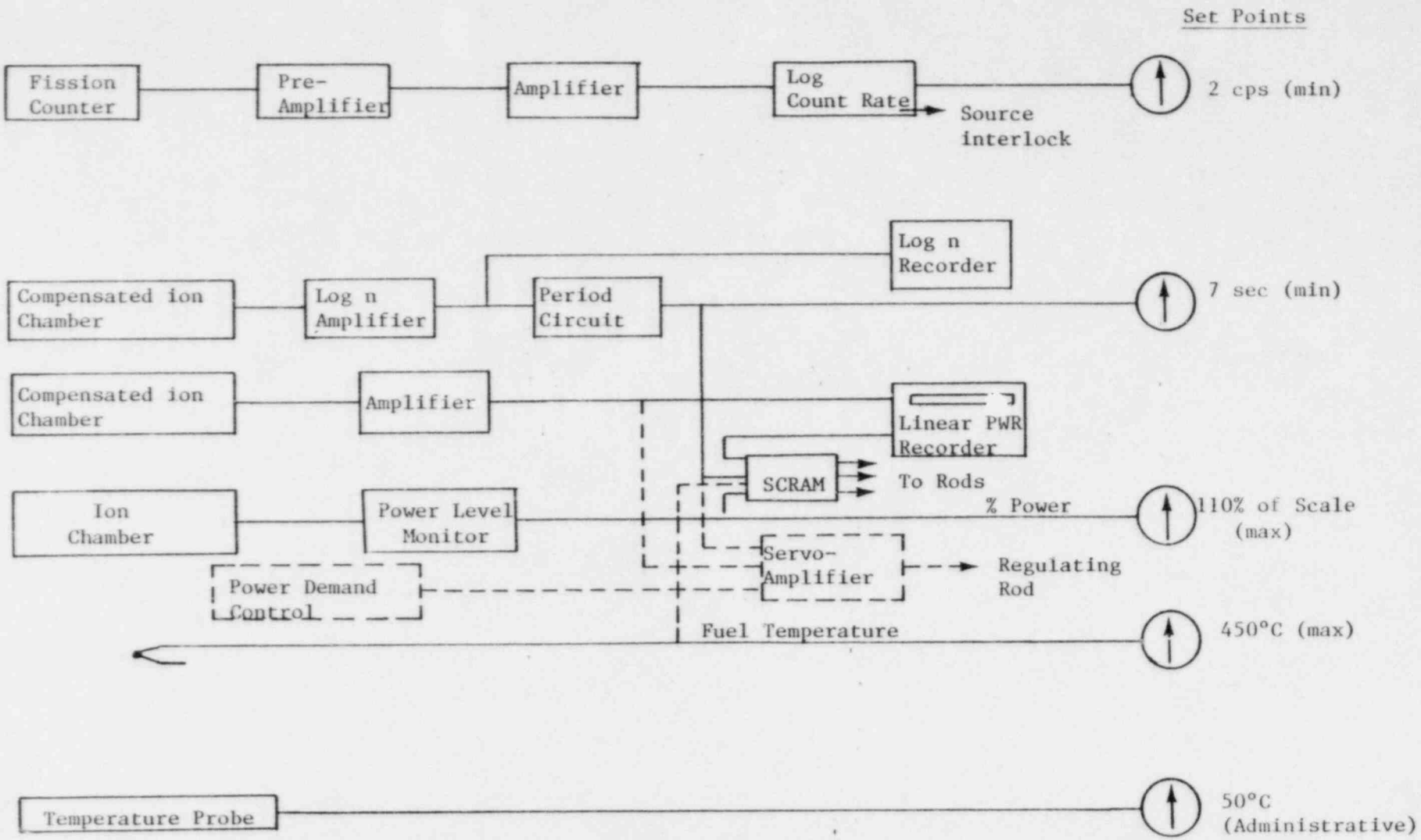


Figure 21. Block Diagram of Reactor Instrumentation for Steady-State Operation

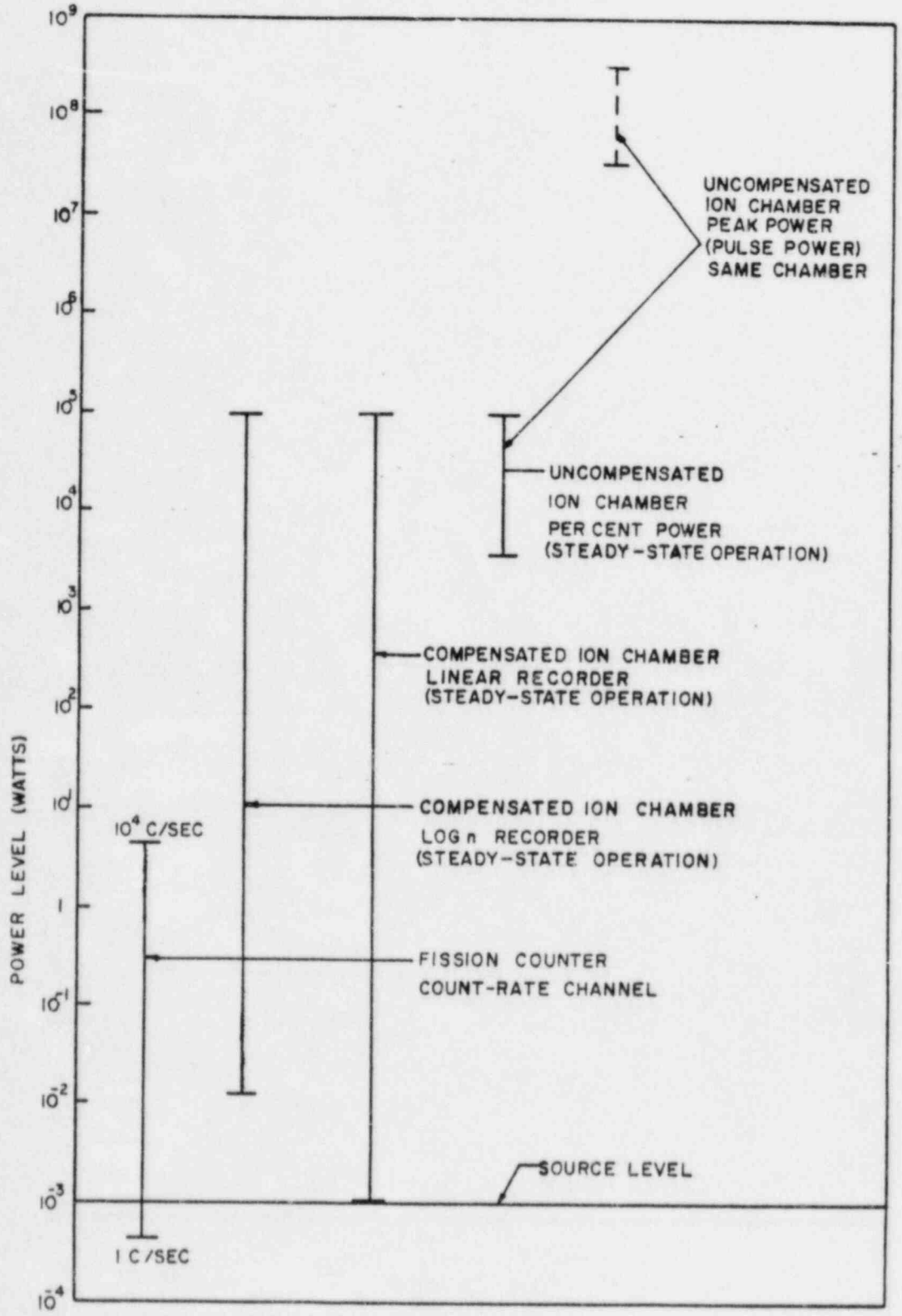


Figure 22. Detector Ranges

A linear micromicroammeter channel provides a power level measurement from about 0.001 watt to full power, with a range switch having two ranges per decade so that measurement of the compensated ion chamber current may be made accurately. The output is indicated and recorded by the second pen of the recorder. A linear channel scram at 110% of full scale is provided on all ranges.

A percent-power-level channel operating from an ion chamber indicates power in the range from a few percent to 110% of full power. This circuit provides for an adjustable-level scram within this range.

Fuel temperature and cooling water outlet temperatures can be read by means of a meter. At the console a manually operated water conductivity bridge is provided with two probes to read conductivity at the demineralizer inlet and outlet; the bridge is located on the console.

2) Pulsing Operation. After a power level of less than 1000 watts in the steady-state operating mode is reached, the mode switch is changed to the pulse mode so that the reactor can be pulsed. When the switch is turned to the pulse mode, the normal neutron channels are disconnected and a high-level pulsing chamber is connected to red out the peak power of the pulse. The peak power is then displayed on the recorder several seconds after the pulse is completed. Also, changing the mode switch to pulse removes an interlock that prevents application of air to the safety-transient rod unless the safety-transient rod cylinder is in the full "in" position and thus allows pulsing to take place. Furthermore, only the safety-transient rod can be moved during pulsing mode operation. In this mode, a scram is caused by excessive peak power or excessive integrated power. In addition, fuel temperature is recorded during pulsing. Fuel temperature can also unitiate a scram. These channels are indicated in Figure 23.

3) Detector Ranges. Operating ranges for the detectors using in the reactor are outlined graphically in Figure 22.

c) Rod Control

At the console the two standard rod drives and the safety-transient rod drive are controlled by switch-light pushbuttons, which not only control the up or down motion of the rods but also annunciate their extreme positions. In addition,

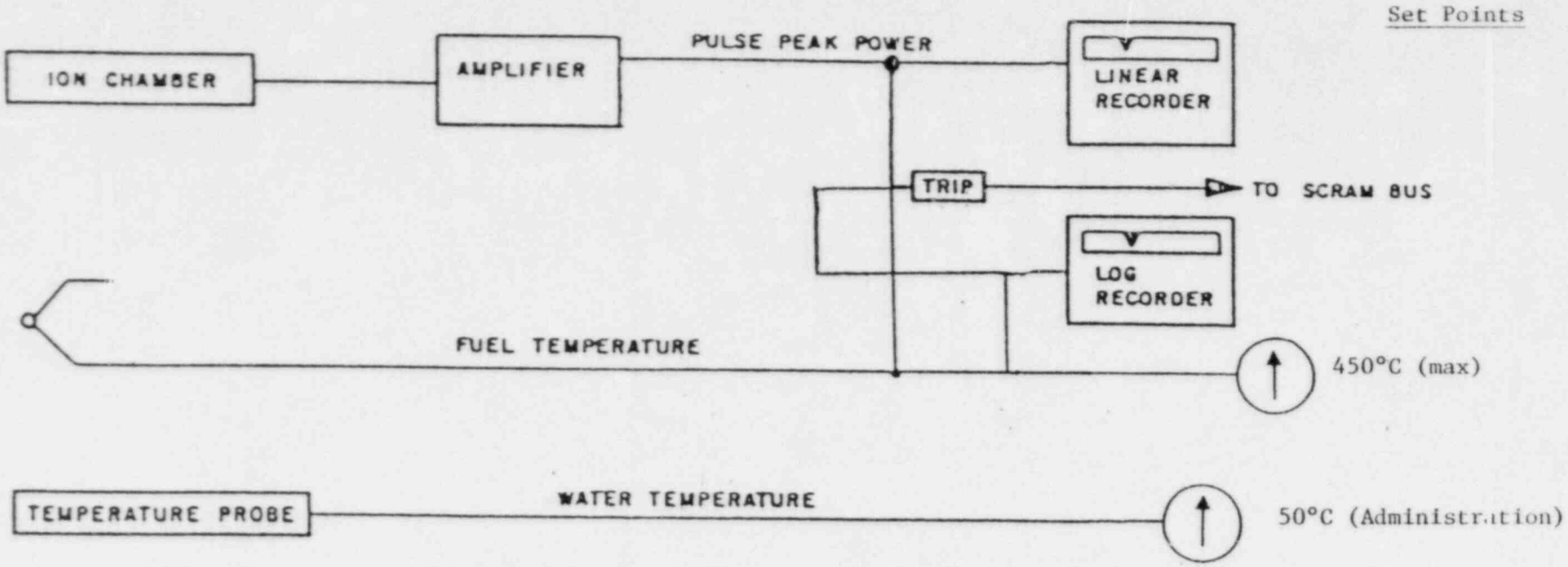


Figure 23. Block Diagram of Reactor Instrumentation for Pulsing Operation

position indicators with digital readout accurate to 0.2% are provided for the regulating rod and the shim rod. Following a scram, automatic rod drive. Down is provided for all drives except the safety-transient rod drive.

Safety Devices

Scrams:

1. Power level channel, compensated ion chamber micromicroammeter.
2. Power level channel, ion chamber, adjusted by operator from 2 to 110% of full power
3. Reactor period adjustable period scram between ∞ and -7 seconds
4. Manual
5. Ion-chamber power supply failure
6. Console power circuit failure
7. Peak power and integrated power in pulsing mode
8. Fuel temperature.

Interlocks are provided to

1. Assure minimum source strength before control rods can be withdrawn.
2. Prevent withdrawl of two control rods simultaneously on manual control.
3. Prevent movement of any rod except the safety-transient rod in pulsing mode.

Ventilation

There are two sources of ventilation air and one air outlet for Room 184. A unit ventilator located along the outside wall draws air from outside, filters and tempers it and circulates it within the room. The second source of air is the building ventilation which supplies Rooms 190 and 184B. The air from these rooms flows into Room 184 through a pneumatically operated grille in the control room wall. Both the unit ventilator and the grille are equipped with pneumatic dampers which can be remotely closed from console in case it should become necessary to close off the room. In addition, at that time, the ventilator fan is turned off. The doors and windows to room 184 from the hall, outside and control room are weather stripped to permit isolation of the room in case of emergency. Air discharge from the room is accomplished through the laboratory hood in Room 184A. This hood is operated at all times and moves sufficient air (700 cfm) to insure at least two air changes per hour through the reactor room. Discharge is to the roof

of the building at a distance of about 60 feet from the building ventilation inlet. This exhaust duct is equipped with a by-pass filtration system in Room 184A which can be dampered into operation remotely from the reactor console. It provides a continuous filtered exhaust from the room in case of emergency and maintain rooms 184 and 184A under slight vacuum. The flow rate under filtering conditions is about 150 cfm versus the 700 cfm normally experienced. The pneumatic dampers, ventilator fan switch and by-pass dampers are all actuated by a single switch at the console.

Radioactive Material Generation, Storage and Disposal

The total quantity of radioactive by-product material generated within the reactor (exclusive of radioactivity contained in the reactor fuel) has not exceeded the permissible amounts as specified in the NRC license 21-0021-29. There are two locations available in the facility for storage of these materials:

1. A storage vault approximately 3 1/2 x 4 x 2 feet in size is located beneath the floor in the unexcavated region of the room. Access to this vault is provided by are movable door in the pit area adjacent to the reactor. A 6-inch concrete shield door is provided to further shield the vault if necessary. The vault itself is constructed of concrete has 12 inches of concrete on the roof and south wall. The other walls face into the unexcavated portion of the building.
2. Three 10-inch diameter by 16-feet deep fuel storage pits are cast into the concrete adjacent to the reactor pit (see Figure). These pipes can be filled with water and used for high radiation isotope storage or for storage of fuel removed from the reactor. The pits are covered with steel plates and padlocks can be provided to prevent unauthorized removal of the contents. The pits are galvanized steel with Amercoat interior coating.

Radioisotopes generated by the reactor operation plus any other radioactive material are disposed of following he procedures outlined in the Michigan State University broad license NRC 21-00021-29 and 10CFR Part 20.

Monitoring Facilities

In addition to the safety monitoring facilities described in the description of the reactor, the following items are also used:

1. Airborne particulate monitor. This continuously monitors the radioactivity filtered from the room air by a fixed paper filter. The filter is changed bi weekly. A suitable alarm system is preset to correspond to a radioactive material concentration less than the permissible content specified in Title 10CFR Part 20. Output from the monitor is recorded on a recorder in the control room.
2. A remote reading gamma monitor is located at the reactor console with the sensing element mounted at the ceiling above the reactor pool. An alarm system is included to identify the existence of an abnormally high radiation level.
3. A second wall mounted gamma monitor is located on the wall adjacent at the reactor pool. It has a dial readout and both audible and visual alarms.
4. Several ionization and Geiger-Muller survey meters (both self contained and lien operated) are available for monitoring the radiation levels in the area around the reactor and storage vaults.
5. Geiger-Muller survey meters with thin windows are used to monitor the contamination levels of all equipment and areas in the laboratory as well as to monitor the personnel and materials leaving the facility.

Radiation Dose Rates Around Reactor

Complete gamma dose measurements have been taken around the MSU TRIGA reactor during 250-kw steady-state operation. Typical measurements are listed below. No neutron leakage has been detected from operating TRIGA reactors except for a thermal neutron dose of 0.03 mrem/hr (15 neutronscm^2-sec) measured above the rotary specimen rack drive shaft tube during 100-kw operation.

As indicated below, the measured radiation dose rates are low enough to allow operating personnel to perform experiments at the edge of the reactor tank during full power operation.

Table 3. Gamma Dose Rates Around Triga Reactor During 250-KW Steady-State Operation

Location of Instrument	Dose Rate (mrem/hr) Steady-State Operation
1. Surface of reactor tank water	1.0
2. 1 ft. above surface of the pool (floor level)	0.8
3. At handrail adjacent to reactor tank	0.1
4. At ceiling directly above reactor pool	0.2 to 0.3

Dose rates apply when the reactor cooling system is in operation. These doses are given in milliroentgens (mr). Since only gamma radiation was measurable, mr is the same as mrem in this case. The roentgen equivalent man (rem) is defined as the dose of any ionizing radiation that will produce the same biological effect as that produced by 1 roentgen of x-ray or gamma-radiation. The radiation levels produced at the floor level in the classroom over the reactor are less than the permissible levels for non-radiation worker as specified in Title 10, CFR Part 20 as measured by film badges located in the classroom and on the ceiling of the reactor room.

C - Safety Reviews

Several possible hazard conditions have been assessed with regard to the reactor. It has been concluded that operation of the reactor will not endanger the public health and safety. Among the analyses performed the following the pertinent:

1. Loss of coolant accident.
2. Fuel element failure in air.
3. Reactivity insertion
4. Mechanical rearrangement of fuel.

1. Loss of Coolant Accident

The MSTR operates at a maximum of 250 KW_{th} and the present core contains 70 elements. The average power density, thus, is 250/70 = 3.57 KW_{th} per element. A portion of the fuel contains 12 wt% uranium and, thus, is operated at a 41% higher power density than the remaining 8.5% uranium fuel. Thus, the maximum power density would be 3.57 x 1.41 or 5.03 KW_{th} per element. Under conditions speculated to involve the complete loss of power operation, it is estimated that the fuel temperature would reach approximately 225°C (see Fig. LCA-1). Under such conditions the estimated stress imposed on the cladding by internal gas is approximately 1200 psi (see Fig. LCA-2). This stress is considerably less than the approximately 37,000 psi yield stress for the stainless steel fuel cladding. It is, therefore, concluded that the loss of coolant would not result in the failure of the fuel cladding and that the fission product containment would not be lost.

Radiation Levels from Loss of Coolant

If it is assumed that the reactor water is suddenly lost, the radiation emitted from the contained fission products would potentially pose a threat to personnel in the reactor room and in Room 284 directly over the reactor. The operating floor of the MSTR is 20 feet above the reactor core and the estimated radiation levels from both direct radiation and scattered from the concrete room ceiling are given below for various decay times immediately following full power operation.

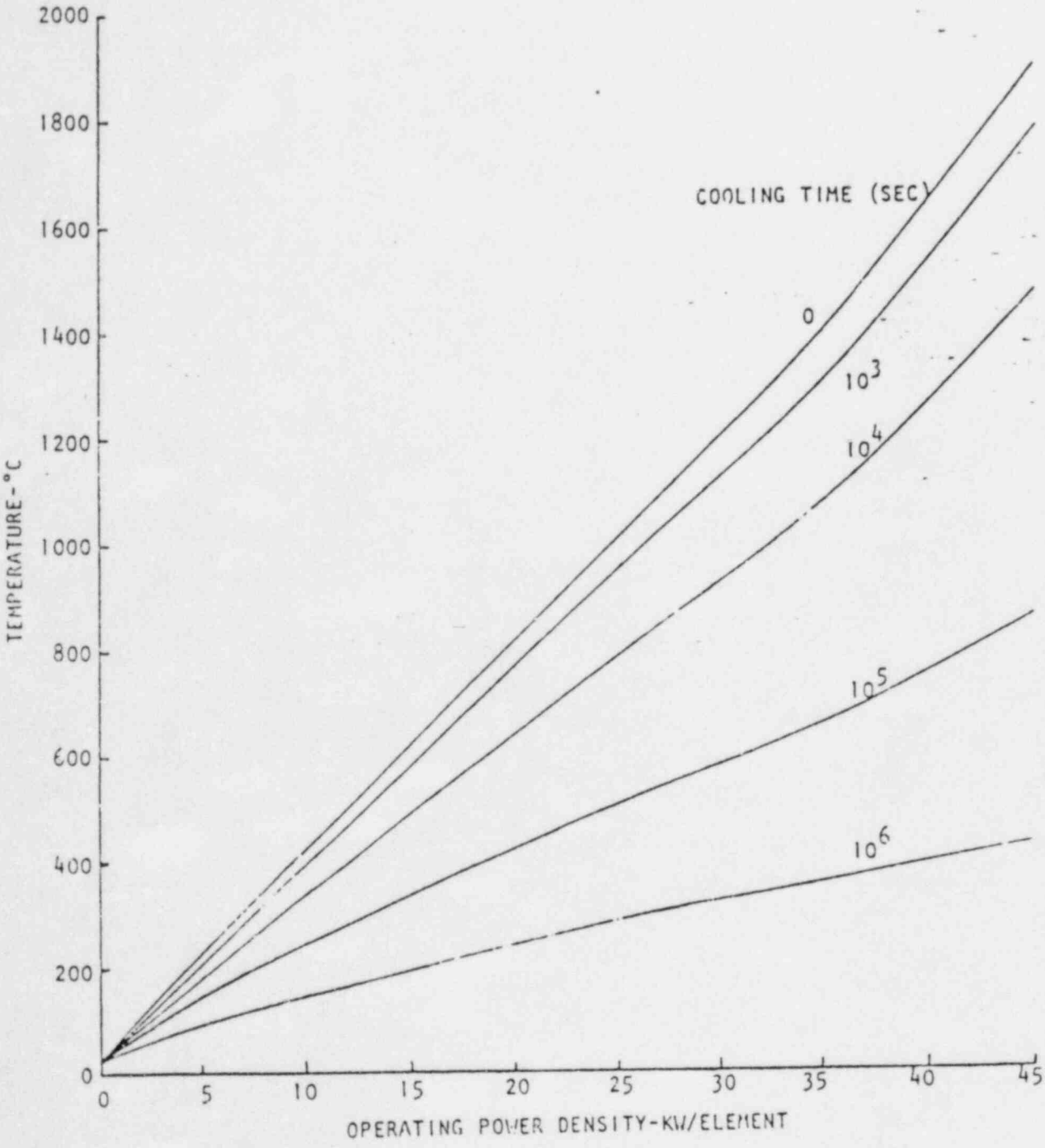


Fig. LCA-1. Maximum fuel temperature versus power density after loss of coolant for various cooling times between reactor shutdown and coolant loss.

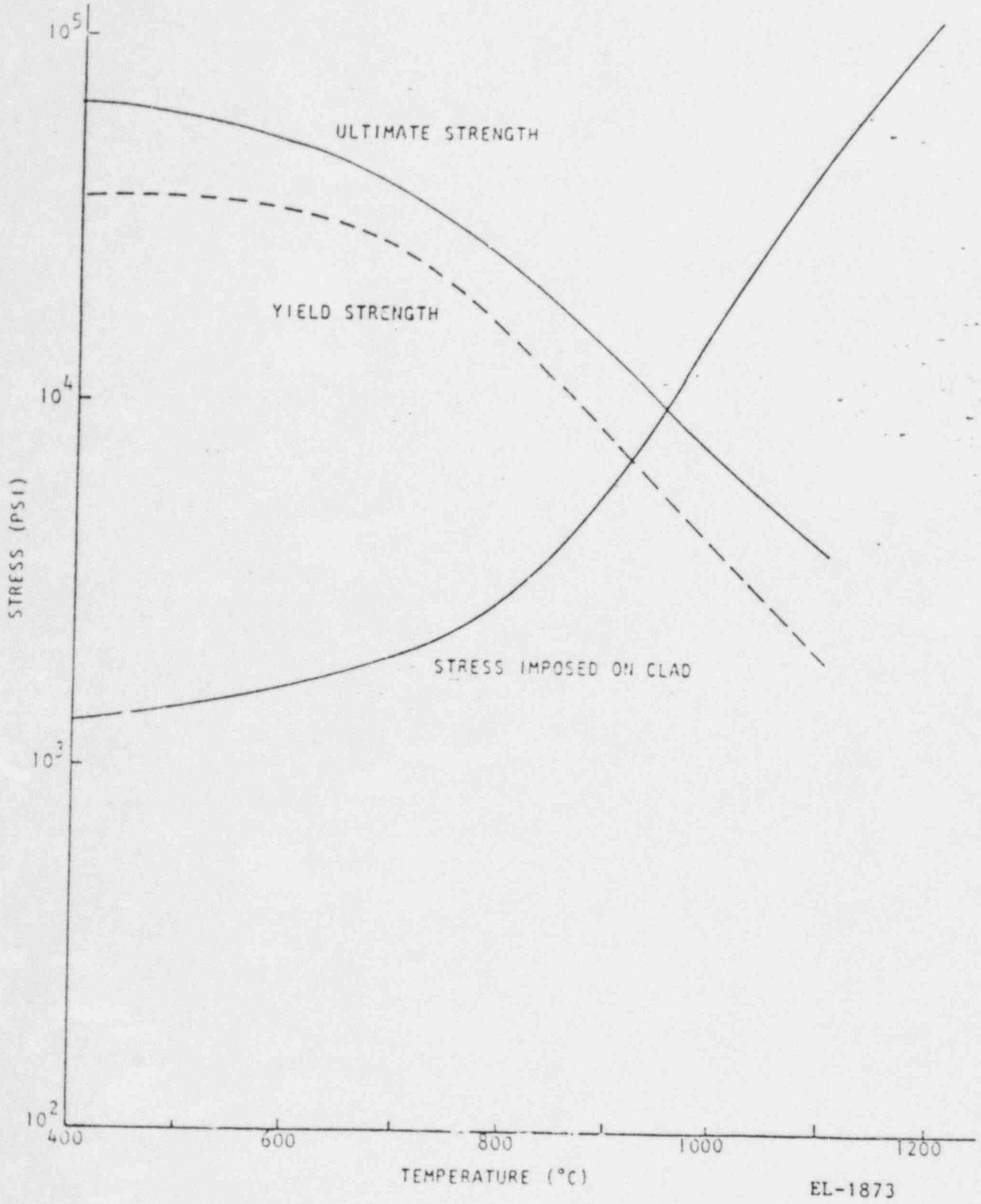


Fig. LCA-2. Strength and applied stress as a function of temperature, U-$ZrH_{1.65}$ fuel, fuel and clad at same temperature.

Calculated Radiation Dose Rates
For Loss of Reactor Pool Water

Time	Direct Radiation r/hr	Scattered Radiation r/hr
10 sec	2,500	0.65
1 day	300	0.075
1 week	130	0.035
1 month	35	0.01

The table indicates that, except for the direct beam from the core radiation exposure in the reactor room would be high but tolerable even immediately after loss of coolant and that emergency operations could be carried out with limited time of action.

Of greater concern is the radiation levels in the uncontrolled area, Room 284, located directly over the reactor. The distance from the core to the occupied area of this room is 30 feet and the radiation levels calculated above (for 18 feet) will be reduced by inverse square $(18/30)^2$ = 0.36x and the shielding of the concrete floor (approximately 6 inches) = 0.2x.

On this basis, the direct radiation in Room 284 is estimated to be

Time	Direct Radiation r/hr
10 sec	180
1 day	22
1 week	9
1 month	2.5

These levels of radiation are sufficiently high to necessitate immediate evacuation of the classroom in case of total loss of pool water.

The integrated exposure to personnel in this room as a function of time delay in evacuation is given below.

Time, Min.	Radiation Dose, R
5	14.97
15	44.77
30	89.07
45	132.9
60	176.3

Evacuation of Room 284 following loss of pool water during or shortly after reactor operation (the case assumed above) could most certainly be done in a time much less than an hour since a reactor operator on duty could assure building evacuation in such a catastrophe. If pool water were to be lost during non-working hours, a longer evacuation time might be experienced as the result of the time delay inherent in emergency response. The radiation levels would be reduced in this case however since the short lived fission products would have decayed away. As an example, assume a 6 hour shutdown period followed by loss of pool water and a 1 hour evacuation delay during which time Room 284 is occupied. The exposure to a person in such a situation would be 132 R. Such an exposure, although high, would not be life threatening.

2. Fuel Element Failure in Air

In this analysis, it is assumed that one of the 12 wt% Uranium fuel elements is ruptured in air after a long (1,000 day) exposure to full power (250 kw_{th}) operation of the reactor. The radioactive material released to the air consists of 100% of the rare gases and halogens which, during reactor generation, have migrated to the gap between the fuel meat and cladding. No credit is assumed for deposition of the isotopes on walls, in pool or in any other manner.

(a) Exposure to reactor room occupants. In this case, the rare gases and halogens are assumed released to the reactor room, and the ventilation in the room is assumed to be zero. A room occupant is assumed to remain in the room for 10 minutes while evacuation takes place.

The fission product gas concentration in the core operated at 250 kw_{th} for 1,000 days is given below (from Lamarsh, p. 535--scaled to MSTR power output). (Note: core loading 70 elements, power density in 12 wt% fuel = 41% greater than core average.)

Radioisotope	Curies, core	Curies, Single Element, Avg.	Curies, Single Element 12 wt%
Kr^{85m}	2800	40	56.4
Kr^{85}	98	1.4	1.97
Kr^{87}	5,000	71.4	100.7
Xe^{133m}	400	5.71	8.06
Xe^{133}	14,320	204.6	288.4
Xe^{135m}	2,220	31.7	44.7
Xe^{135}	3,900	55.7	78.6
I^{131}	5,850	83.6	117.8
I^{132}	8,270	118.1	166.6
I^{133}	14,300	204.3	288.0
I^{134}	15,200	217.1	306.2
I^{135}	13,550	193.6	272.9

For fuel element ruptures in air, the gaseous fission product inventory in the gap is estimated to be 1.5×10^{-5} fraction of the total gaseous fission products (GA 4314). If all of this fraction is released into the reactor room (volume 2×10^8) with no air change rate, the concentration of radioisotopes in the room air is:

$$\text{Curies} \times 10^6 \times 1.5 \times 10^{-5} / 2 \times 10^8 = \mu\text{Ci/ml}$$

Assuming a person occupies the room for a total of 10 minutes following fuel rupture (while evacuation takes place) and that a respiration rate of 3.47×10^{-4} m^3/sec (Reg. Guide 4) is experienced, it is possible to project the personnel exposure and isotope ingestion. The following equations were used:

1. Whole Body Exposure $= \frac{\text{conc. of radioisotope}}{\text{MPC (Table 1, 10CFR20)}} \times 5000 \frac{\text{mr}}{\text{yr}} \times \frac{10 \text{ min}}{2000 \times 60 \frac{\text{min}}{\text{yr}}}$

   (Assumes that continuous exposure to 1 MPC is equivalent to 5 rems/yr whole body dose)

2. Isotope ingested = conc. of radioisotope $\times 3.47 \times 10^2 \frac{\text{ml}}{\text{sec}} \times 600$ sec

The results of such a calculation for a 12 wt% element are given below.

Radioisotope	Conc. µCi/ml	MPC Table 1	10 Min. Dose, mr	10 Min. Ingestion, µCi
Kr^{85m}	4.23×10^{-6}	6×10^{-6}	0.29	0.88
Kr^{85}	1.48×10^{-7}	1×10^{-5}	0.006	0.03
Kr^{87}	7.56×10^{-6}	1×10^{-6}	3.15	1.57
Xe^{133m}	6.04×10^{-7}	1×10^{-5}	0.02	0.13
Xe^{133}	2.16×10^{-5}	1×10^{-5}	0.90	4.50
Xe^{135m}	3.35×10^{-6}	4×10^{-6}(ass)	0.35	0.70
$X3^{135}$	5.90×10^{-6}	4.10^{-6}	0.61	1.23
I^{131}	8.83×10^{-6}	9×10^{-9}(S)	409.0	1.83
I^{132}	1.25×10^{-5}	2×10^{-7}(S)	26.0	2.60
I^{133}	2.16×10^{-5}	3×10^{-8}(S)	300.2	4.50
I^{134}	2.30×10^{-5}	5×10^{-7}(S)	19.2	4.78
I^{135}	2.05×10^{-5}	1×10^{-7}(S)	85.3	4.27
			845.0	

Thus, the maximum whole body exposure to a person in the reactor room for 10 minutes immediately following a fuel element rupture in air would be 845 mrems--a value well within the requirements of 10CFR Part 20.

The ingestion of iodine isotopes identified above would result in the concentration of the isotopes in the thyroid with a resultant thyroid exposure. The extent of exposure can be calculated by multiplying the iodine ingested by the corresponding internal dose effectivity factor.

Radioisotope	10 Min Ingestion µCi	Effectivity Factor rem/Ci	Thyroid Dose, rems
I^{131}	1.83	1.486×10^6	2.72
I^{132}	2.60	5.288×10^4	0.14
I^{133}	4.50	3.951×10^5	1.78
I^{134}	4.78	2.538×10^4	0.12
I^{135}	4.27	1.231×10^6	5.25
Total thyroid dose			10.01 rems

This resultant thyroid dose is reasonable based on the conservative assumptions made.

(b) Exposure to the general public. In case of a fuel element rupture, some of the released radioisotopes would be swept from the reactor room by the ventilation system and discharged through the hood vent into the uncontrolled area. For the sake of the analysis of exposure to the general public, it is assumed that, at the time of the hypothetical fuel element rupture, the ventilation system would be switched to its "emergency" operation in which the exhaust air is diverted through an absolute filter before being vented. Furthermore, the air intakes to the room would be isolated to maintain the reactor room under negative pressure and inhibit radioactivity release except through the exhaust vent. The air flow through the exhaust under these conditions is 150 cfm which represents an air change rate in the room of about 1 change per hour.

The concentration of radioisotopes released from the fuel would be reduced by the air flow through the room. A common engineering calculation for a well mixed vessel assumes essentially complete

flush of the vessel in 5 volume changes. However, for the purpose of the present calculations, only one room volume is assumed, and, thus, the concentration of isotopes in the room exhaust would be the same as was calculated above. However, the air is discharged at the roof level, approximately 40 feet above grade. Thus, a dilution due to wind will be encountered.

The Dilution Factor due to the building is defined by Lamarsh as:

$$DB = cA\bar{v}$$

where

c = shape factor, experimentally between 0.5 and 0.67

A = cross section area of the building

$\bar{v}$ = average wind speed

Since the prevailing winds near the MSTR are form the west, the north-south area of the Engineering Building is used, thus

$A = 500 \text{ ft} \times 40 \text{ ft} = 20{,}000 \text{ ft}^2$

$\bar{v}$ = 10.1 mph = 14.8 ft/sec (from National Weather Service Bureau)

c = 0.5

Thus, $D_{AB} = (0.5)(20{,}000)(14.8) = 1.48 \times 10^5 \frac{ft^3}{sec}$

With a stack flow rate of 150 $\frac{ft^3}{min}$ (= 2.5 $\frac{ft^3}{sec}$), the concentration reduction due to wind dilution will be $\frac{2.5}{1.48 \times 10^5} = 1.69 \times 10^{-5}$. The concentration of nuclides will, thus, be reduced by this amount outside the building. The dose received by a member of the public over an hour[1] of occupancy may be estimated in a manner similar to that used for occupational exposure given above.

1. Whole Body Exposure = $\frac{\text{conc. of radioisotope}}{\text{MPC(Table 2, 10CFR20)}} \times \frac{500 \text{ mr}}{\text{yr}} \times \frac{1 \text{ hr}}{8760 \text{hrs}}$

   (Assumes that continuous exposure to 1MPC is equivalent to 500 mr/yr whole body dose)

2. Isotope ingested = conc. of radioisotope x $3.47 \times 10^2 \frac{ml}{sec}$ x 3600 sec.

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1 One hour exposure assumed because released activity will be dispersed after this time.

The results of these calculations are given below for the rupture of one 12 wt% fuel element in air with 100% release of halogens and rare gases in the air gap of the fuel.

Radioisotope	µCi/ml	Table 2	1 hr dose, mr	1 hr ingestion µCi
Kr^{85m}	7.15×10^{-11}	1×10^{-7}	4.08×10^{-5}	0.89×10^{-4}
Kr^{85}	2.5×10^{-12}	3×10^{-7}	4.76×10^{-7}	0.03×10^{-4}
Kr^{87}	1.28×10^{-10}	2×10^{-8}	3.6×10^{-4}	1.6×10^{-4}
Xe^{133m}	1.02×10^{-11}	3×10^{-7}	2×10^{-6}	0.13×10^{-4}
Xe^{133}	3.65×10^{-10}	3×10^{-7}	6.9×10^{-5}	4.56×10^{-4}
Xe^{135m}	5.66×10^{-11}	1×10^{-7}(ass.)	3.2×10^{-5}	0.71×10^{-4}
Xe^{135}	9.97×10^{-11}	1×10^{-7}	5.7×10^{-5}	1.25×10^{-4}
I^{131}	1.49×10^{-13}	1×10^{-10}(S)	8.5×10^{-5}	1.86×10^{-7}
I^{132}	2.11×10^{-10}	3×10^{-9}(S)	4.02×10^{-3}	2.64×10^{-4}
I^{133}	3.65×10^{-10}	4×10^{-10}(S)	5.2×10^{-2}	4.56×10^{-4}
I^{134}	3.89×10^{-10}	6×10^{-9}(S)	3.7×10^{-3}	4.86×10^{-4}
I^{135}	3.46×10^{-10}	1×10^{-9}(S)	1.98×10^{-2}	4.32×10^{-4}
Total Whole Body Exposure			0.080 mr	

Similarly, the thyroid exposure from the ingestion of iodines would be:

Radioisotope	1 hr Ingestion µCi	Effectivity Factor Rem/Ci	Thyroid Dose Rems
I^{131}	1.86×10^{-7}	1.486×10^{6}	2.76×10^{-7}
I^{132}	2.64×10^{-4}	5.288×10^{4}	1.40×10^{-5}
I^{133}	4.56×10^{-4}	3.951×10^{5}	2.0×10^{-4}
I^{134}	4.86×10^{-4}	2.538×10^{4}	1.23×10^{-5}
I^{135}	4.32×10^{-4}	1.231×10^{6}	5.0×10^{-4}
Total Thyroid Dose			7.58×10^{-4} Rems

These calculations indicate that the exposure to the general public as the result of a fuel element failure in air after extended reactor operations would be negligible.

Bibliography

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3. REACTIVITY INSERTION

The present MSTR core consists of 70 elements, all of which are stainless steel clad U/ZrH with a nominal H to Zr ratio of 1.7. Eight of the elements are 12 wt % Uranium (<20% enriched) while 62 are 8.5 wt % Uranium (<20% enriched). The 12 wt % elements are located in the B and C rings of the core and two of these (one each in the B & C rings) are instrumented with chromel-alumel thermocouples.

Experiments conducted at MSU involving the rapid insertion of 1.39% $\Delta k/k$ into the core described above by means of a pneumatic control rod results in the production of a power pulse of approximately 258 MW_{th} and an integrated power output of about 15 MWsec. The temperature measured in the instrumented fuel elements located in the B and C rings, 12 wt % fuel, is approximately 275°C. It is expected that this fuel concentration in these locations would experience the highest neutron flux and temperature.

By comparison, experiments conducted at General Atomic (GA6216) with a Stainless Steel Core containing 8.5 wt % (<20% U^{235}) Stainless Steel Fuel and subjected to pulses of up to 3.5% $\Delta k/k$ reactivity insertion compared the temperatures produced. The temperatures in both the B and D rings were measured and a linear relationship between the fuel temperature and the quantity ($\Delta k/\beta$-1) was observed. (β = effective delayed neutron fraction = 0.7% for this fuel). Although experiments were not conducted at Δk = 1.37%, the temperatures produced may be estimated by linear extrapolation of the data obtained between 2.1 and 3.5% down to the 1.37% value corresponding to the MSU tests. This yields an estimated peak fuel temperature of 230°C (in 8.5 wt % fuel). This is consistent with the MSTR data. (Note that the MSTR fuel contains 12 wt % U as compared to 8.5% in the GA tests. The higher fuel content would be expected to result in higher power density and a correspondingly higher temperature. This increase might be expected to be approximately 12-8.5/8.5 = 41% to project a 12 wt % fuel temperature in the GA tests of (230-30)(1.41) + 30 = 322°C.)

The same GA report (6216) gives the results of theoretical calculations of peak and integrated power as well as fuel temperature use due to the reactivity insertion. The predicted temperatures compare closely with the observed values for large reactivity insertions. Similar calculations

demonstrated that the peak temperature in the fuel occurs not at the midplane between the centerline and cladding where the thermocouple is located. The peak temperature is approximately 21% higher than the midplane temperature which would extrapolate the measured MSTR fuel temperature to (280-30)(1.21) + 30 = 332°C.

The maximum excess reactivity of the MSTR is 2.25% Δk/k; and, thus, it is theoretically possible to insert this amount of reactivity into the core. Again, based on GA 6216, such an insertion as a step increase would result in a bulk fuel temperature of 450°C. Again, correcting for the peak to bulk calculation and 12 vs 8.5% fuel as above results in a peak temperature of 716°C. This temperature exceeds to the phase transition temperature of low hydrogen (H/Zr≈1.5) fuel (GA7882) but the MSTR fuel with H/Zr≈1.7 shows no such phase transition; and, thus, temperatures well above 1000°C are permissible. Thus, the rapid insertion of the full 2.25% Δk/k reactivity into the MSTR is not expected to result in a thermal degradation of the fuel.

High fuel temperatures might be expected to result in increased gas pressures within the fuel due to expansion of the gas between the fuel meat and the cladding as well as the release of fission product gases. Similarly, the $UZr/H_{1.7}$ will exert a partial pressure of hydrogen which is a function of fuel temperature.

Tests reported in GA6216 indicated that the maximum pressure generated in the fuel element was only 7 psig with a reactivity insertion of $4.20 (2.95% Δk/k). It is reasonable to assume, then, that the peak pressure in the MSTR reactor with 2.25% insertion will be less than this (note that at $4.20 insertion, the peak fuel temperature according to this same report would be 610°C (bulk)-30 x 1.21 (peak/bulk) + 30 = 732°C which is consistent with the anticipated MSTR peak of 716°C). A peak pressure of 7 psig would result in a stress of about 1500 psi in the fuel cladding. Report GA6216 gives the tensile strength of 304SS at 650°C to be 44,500 psi. Thus, the pressure generated by a 2.25% Δk/k pulse will not even approach the bursting pressure of the cladding.

On the basis of this analysis, it is concluded that the rapid insertion of the full excess reactivity into the MSTR would not result in damage to the fuel.

4. Mechanical Rearrangement of Fuel

When it is necessary to remove irradiated fuel from the MSTR, the following procedure is typically followed. A 400 lb lead transfer cask (such as is used with the BMI-1 shipping cask) is lowered into the reactor pool by means of a chain falls and A-frame superstructure. The cask is capable of holding three standard Triga fuel elements which are remotely loaded into the cask by a fuel handling tool. The cask is then removed from the pool and the lead shielding protects personnel from the radiation emitted by the fuel.

During the cask handling process it is possible that the transfer cask could be dropped into the pool. Such an accident might impact upon the reactor and the reflector. It is proposed to analyze the consequences of such an incident.

Several accident scenarios are possible:

1. Deflection of the control rod extensions with the resultant control rod withdrawal. Since the cask will impact in a downward direction, the principle force exerted will tend to drive the control rods into the core (a "safe" configuration). Even if a horizontal force is exerted on the extension rods, the removal of sufficient control rod worth to enable the reactor to go critical is unlikely in light of the shutdown margin inherent in the MSTR.
2. Crushing of fuel. In case of impact of the cask onto the fuel, deflection or crushing of the fuel is the likely result. The fuel cladding of several elements would probably be damaged and the rare gas/halogen fission products in the gas gap between the fuel an the cladding would escape. Since the only situation involving the fuel transfer cask would involve a flooded pool, the fission product release described above (for fuel failure in air) would be reduced by the dissolution of halogens in the pool water. As indicated in the air rupture analysis, the largest radiation is due to the Iodine release. For the present analysis, more than one element might be damaged resulting in the releases of greater amounts of rare gases and Iodine. However, the presence of the pool water would reduce the amount of Iodine released to the room and, thus, compensate for the increased number of elements involved. It is,

thus, estimated that the radiation exposure for this accident postulation would approximate that of the one analyzed previously (Fuel Element Failure in Air).

3. Impact on Reflector Ion Chambers. The reflector of the MSTR will serve as an impact shield for the reactor core. It will, therefore, reduce the consequences of a falling cask over that described in #2 above. Since the reflector contains little radioactivity and no fuel, damage to it will not result in a significant radioactivity release.

It is, therefore, concluded that the worst case resulting from a cask dropping into the reactor pool would result in no greater consequences than the fuel element failure in air previously analyzed.