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HTRE HAZARDS REPORT

This report has been compiled from contributions by members of the Engineering and Idaho Plant groups. The aid of these people and the many others who have also contributed through discussions and comments is greatly appreciated.

Carl C. Gamertsfelder, Editor

December 15, 1954

AIRCRAFT NUCLEAR PROPULSION DEPARTMENT
Cincinnati 15, Ohio

ATOMIC PRODUCTS DIVISION
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CONTENTS

	Page
1. Description of the Site, Facilities, and Reactor	9
1.1 Introduction	9
1.2 Site	9
1.3 Associated Facilities	9
1.4 HTRE Power Plant	21
1.41 Reactor Assembly	24
General Description	24
Reactor Components	24
Development Program	28
1.42 Fuel Cartridge Assembly	33
1.43 Nuclear and Thermodynamic Characteristics	33
Uranium Inventory	33
Temperature Effects	42
Power Distributions and Thermodynamic Characteristics	45
1.44 Control System	46
General Description	46
Engine Control Characteristics	47
Important Features of the Reactor Control System	48
1.45 Summary of Physical Design and Design Characteristics of the Reactor	54
1.5 Operation of the Reactor	59
1.51 IET Organization	59
Power Plant Test Personnel	59
1.52 Check List - Prior to Startup	60
1.53 Dummy Test	62
1.54 Meteorological Control During Operation	62
1.55 Initial Startup Procedure	63
1.56 Program of Experiments	65
1.57 Emergencies	65
Emergencies Due to Failure of Equipment	65
Unusual Emergencies	68
1.58 Security Measures	69
1.59 Handling of HTRE in Hot Shop	70
Removal of Reactor Assembly from CTF Tank	70
1.6 Waste Disposal	71
2. Hazards	73
2.1 Analysis of Runaways	73
2.11 Summary of Results	73

SECRET
DECLASSIFIED

DECLASSIFIED

SECRET

Page

2.12 Methods of Calculation 73
The First Stage - Before Fuel Elements Vaporize 73
The Second Stage - Vaporization of Fuel Elements 74
The Third Stage - The Delayed-Neutron-Sustained After-Reaction 74
2.13 Comparison of Runaways Resulting from Various Reactivity Increases 75
2.14 Correlation of Physical Events Causing Runaway with Reactivity Increases 75
Increases Due to Accidents 75
Increases Due to Sabotage 84
2.2 Other Hazardous Features 84
3. Hazards to the Surrounding Area 87
3.1 Hazards Calculations for Major Releases of Activity 87
3.2 Radiation Hazards Due to Airborne Contaminants During Normal Operation 94
4. Appendix 101
4.1 Core Test Facility 101
4.11 Components and Systems 101
Shell 101
Shielding 101
Cocoon 106
CTF Cocoon Drain System 106
Ducting 107
Moderator System 112
Auxiliary Blower System 112
Auxiliary Power System 114
Turbojet Fuel and Lube Oil Systems 114
Coupling to the Exhaust Gas Handling System 115
4.12 X39 Engines 116
Engine Performance Data 116
Components 116
Control System 122
Operating Limits 124
Engine Operation Experience 124
4.13 CTF Performance and Design Specifications 125
4.2 Reactor Control System 128
4.21 Control Rod Operation 128
4.22 Startup Instrumentation 130
Source Range and Counter Range Instruments 130
Period Range Instruments 130
4.23 Power Range Servo System 133
4.24 Operating Procedure for Reactor Controls 135
Reactor Startup 135
Reactor Control in the Power Range 135
4.25 Reactor Scram and Setback 136
4.3 Hydrology and Geology of the NRTS Area 138
4.4 Population Distribution of the NRTS Area 139
4.5 Meteorological Aspects of IET Operation 140
4.51 Effective Stack Height 140

SECRET

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SECRET

Page

4.52 Diffusion Types 142
4.53 Wind Frequencies 146
4.54 Atmospheric Dust 149
Concentrations 149
Particle Size Distributions 149
Chemical Composition 151
Abrasiveness 152
Seasonal and Diurnal Variations 152
4.6 The Application of Sutton's Diffusion Equations to Radiation Hazards from Radioactive Clouds 153
4.61 Formulae for Determining Concentration of Radioactive Material in Air 153
Instantaneous Emission from an Elevated Point Source 153
Continuous Emission from an Elevated Point Source 153
4.62 Radiation Hazards due to Radioactive Clouds 154
Inhalation 154
External Dose From Cloud 155
Dose Due to Rainout Material 160
Dose Due to Fallout Material 161
4.63 Values of Parameters for the Dose Equations 169

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1. DESCRIPTION OF THE SITE, FACILITIES, AND REACTOR

1.1 INTRODUCTION

The HTRE (Heat Transfer Reactor Experiment) of the General Electric Aircraft Nuclear Propulsion Department is designed to test operationally some of the problems in the design, fabrication, and operation of a direct air cycle nuclear propulsion system for aircraft. It is to be tested in the IET (Initial Engine Test) facility being built in the NRTS in Idaho. The IET is unique in that it is designed to inclose the operating crew within shielding rather than build all of the shielding around the reactors being tested. It is intended that several different reactors will be tested in this facility. The reactor proper is to be mounted on a special movable dolly and will be assembled and maintained in a hot shop located in the A & M area located about a mile from the IET.

This design of supporting facility allows a considerable amount of flexibility in the reactor and power package configuration and allows for setting up of special experiments to obtain information on associated problems such as shielding and air scattering.

1.2 SITE

The ANPD facility is located in the northeastern part of the NRTS on the Snake River Plain in southeastern Idaho, Figure 1, a location which is remote from heavily inhabited sections. There is no agriculture within the NRTS and very little surrounding the immediate boundaries. The surface of the area is nearly flat with an elevation of 4800 feet at the IET. Surface drainage is good. Several streams flow into the NRTS and disappear into the ground.

Details of the meteorology and geology of the area and the population distribution are given in the appendix.

1.3 ASSOCIATED FACILITIES

The layout of the IET buildings is given in Figure 2. The test building, which is made of aluminum, is only a weather protection for the reactor and can be rolled on tracks from its normal location to a position 250 feet away. Then, since the reactor control building is largely underground, a relatively large unobstructed space surrounds the reactor so that shielding and air scattering tests may be conducted.

The control and equipment building is of poured concrete construction; the ceiling is three feet thick; and the walls are two feet thick. The floor of the building is 15 feet below grade, and the ceiling height is 13 feet. To provide sufficient shielding, tamped earth is mounded 14 feet deep over the building and tunnels. This shielding is far more than sufficient for the HTRE, but it is designed to be enough for higher-power reactors supplied

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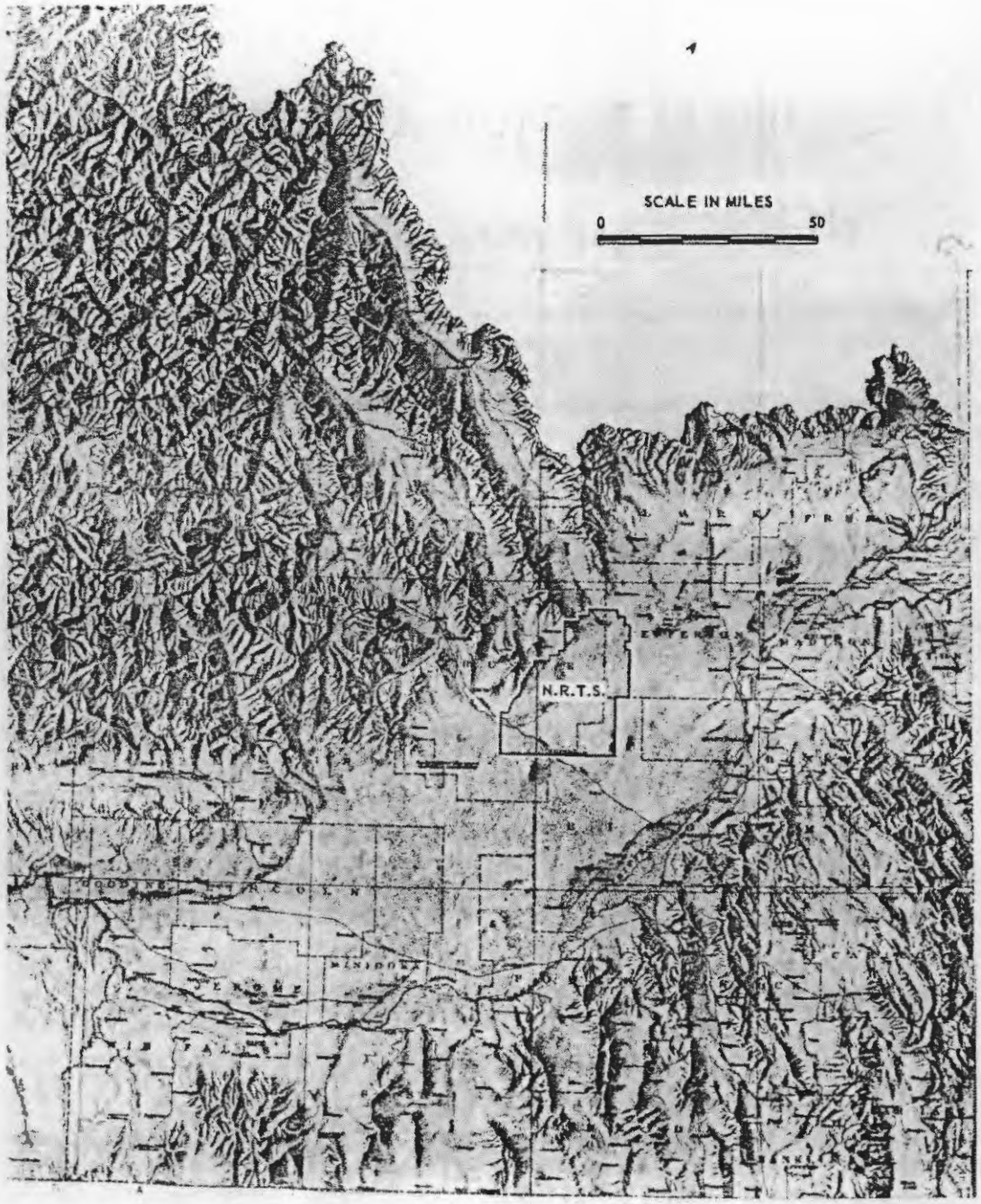

Fig. 1 - The National Reactor Testing Station in relation to surrounding terrain

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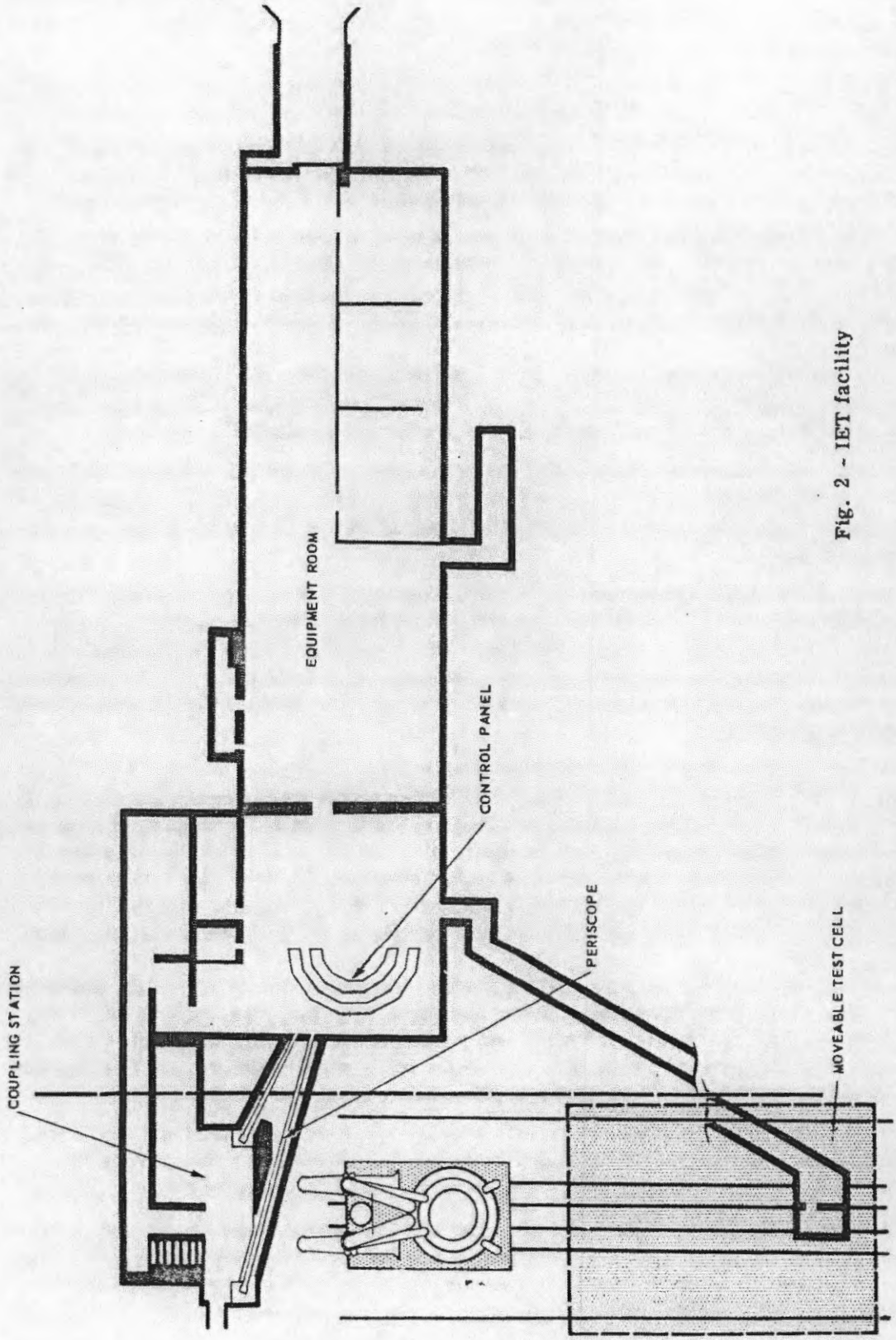

Fig. 2 - IET facility

with less shielding. The end of the equipment room facing away from the test building has an 8-foot-wide door which provides access to grade level by means of a ramp. This is the normal entrance when no reactor is in the area.

The reactor may be viewed directly from the control room through two periscopes. The two viewing heads are situated one on each side of the tracks at the coupling station.

The electrical leads from the coupling station terminate at a distribution panel which forms the north wall of the control room. From the panel the wires are routed either into the control room or instrument room, depending upon their function as outlined below.

A semicircular console having a 12.5-foot radius is located in the center of the control room. On this console are located all controls which affect the power plant operation. Recording devices which are connected to the control circuits and can actuate a power plant shutdown are located either on the console, or on a secondary panel behind the console.

To provide for different power plant control arrangements, the console is made of 15 dimensionally identical units, each wired as an integral unit. By disconnecting the leads on a terminal strip at the rear, any unit may be removed and replaced by another.

It is the goal in a nuclear power plant control system to approach a single throttle operation. Space and wiring ducting have been provided at the origin of the console semicircle for a one-man console, where a simplified control panel may be located when this goal is realized.

Instrumentation which indicates and records power plant performance information but is not connected to control circuits is located in the instrument room adjacent to the control room. Space is available for approximately 100 recorders. Facility instrumentation is grouped at one end of the room where such information as engine fuel and lubricant tank level, exhaust gas filter operation, stack air activity, and radiation levels are recorded or may be monitored.

Adjacent to the control and instrument rooms are a conference room and a counting room. The former has a seating capacity of twelve people and is useful for briefing of test personnel away from high noise level areas, for holding group discussions without interfering with test operations, and for performing "on the spot" computation of test results. The counting room is designed for a background level no higher than 1/10 laboratory tolerance when the reactor is operating at full power. This permits the measuring of air sample filter paper activity as well as foil activities as obtained from certain nuclear tests.

Auxiliary equipment of the main cooling system consists of two 12,000-gallon stainless steel tanks to store primary fluids; these tanks have provisions for draining and filling. In addition, space is reserved for tanks and pumps for use with liquids of higher specific gravity. The storage tanks are located in a heated building above ground, and future tanks can be located underground with piping to allow filling from tank trucks.

Softening equipment is provided for both primary and secondary water, and two 18-gpm demineralizers are located in the equipment building. The necessary instrumentation for determining purities, temperatures, flows, pressure, etc., is provided for both systems.

All pumps are electric-motor driven. The electric power system is backed up by a diesel generating system with a fuel capacity for operating the cooling system from 15 to 20 days in case of emergency. Water is supplied from the administration area where two 1000-gpm wells are located. Storage capacity in this area is one-half million gallons, with a pumping capacity of approximately 2000 gpm. Pressure maintained at the IET is 90 psig at a potential flow of 1000 gpm.

Provisions have been made for draining contaminated fluids back to a concentrator at the assembly and maintenance area where holding tanks are available for use before disposal of the fluids. Normal drainage is provided for all other fluids.

An exhaust gas system has been provided for disposal of about 250 pounds of air per second with provision for expansion to 1000 pounds per second. The facility part of the system is comprised of stainless steel duct work leading from the coupling station to a 150-foot stack. Design of the system is based on a 1400°F operating temperature at engine exhaust with a total pressure loss of less than 8 inches of water.

Exhaust gases from several jet engines can be collected and brought through transition sections into the main ducting system. Duct design is such that one engine may run without backflow of gases through the idle engines. The connections from the facility to the jet engines are removable and adaptable to various engine configurations. The main transition section of the duct work is part of the facility.

Disposal of gases through the stack is such that in all but adverse weather conditions, when no operations will be permitted, the concentration of fission products in the event of a nuclear accident will be within safe limits. Location of the stack and effective stack height discharge under normal atmospheric conditions are such that parctically no radioactive gases can be carried back to the ventilation entrance for the underground facility. Instrumentation is provided to measure activity of the gases at various locations in the disposal system and to transmit this information to the control room.

The IET facility includes a complete system for the operation of turbojet engines. Turbojet operation may be carried out on 100 per cent chemical power, 100 per cent nuclear power, or any combination of the two. Under presently proposed methods, all turbojets are started on chemical fuel and brought up to a transition speed. The reactor is then started up, and as tt supplies heat, the control system decreases the chemical fuel flow until full nuclear operation is attained. As the nuclear power is reduced, a shift to chemical power takes place. These transitions can be accomplished either manually or automatically. After nuclear operation, the turbojets operating on chemical fuel can remove reactor afterheat until it is safe to remove the dolly and power package to the hot shop.

A fuel transfer pumping building is situated just outside the control and equipment building. One 50,000-gallon tank of jet fuel is buried 4 feet below grade and supplies fuel at 35 psi to the engine-mounted fuel pumps by means of one 60-gpm transfer pump. These tanks may be filled directly by truck or by a pipe connection from a 190,000 gallon storage tank in the administration area. In case of pump failure, fuel can be delivered directly to the engines from the administration area. Tank levels are remotely indicated and recorded in the instrument room. Alarm lights flash in the event that some pre-set low or high level is reached.

The movement of the reactor within the testing station area is provided by mounting the power package (reactor and engines) on a special flat car or dolly having four sets of trucks which ride a four-rail track system. The mobility of this arrangement permits the separation of the assembly and maintenance shops from the IET area. During later phases of development, the dolly system can transport the power plant to other test stations as required.

A narrow, horizontal plug is suspended across one end of the dolly. There all control and instrument wires, and piping for fuel, lubricant, inert gas, compressed air, coolant, etc., from the power package terminate in quick disconnects. This plug mates with a recess in the coupling station at the test building. A wide variety of nuclear power plants may be mounted on the dolly and connected to the test facility through the plug.

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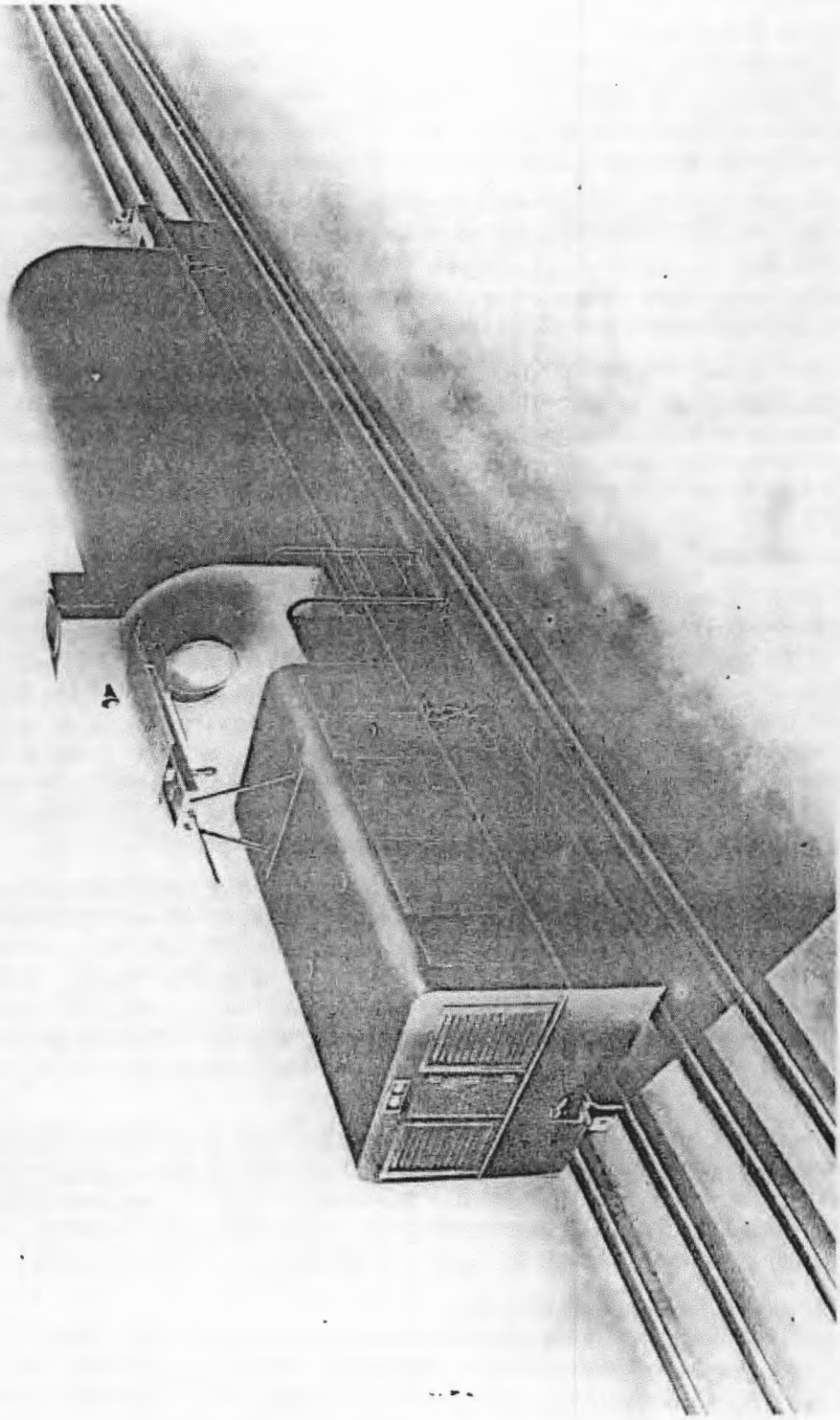

Fig. 3 - Shielded locomotive

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A shielded locomotive (Figure 3), weighing some 210 tons, provides power for moving the dolly along the rail system. The tractive force, supplied by two 200-horsepower diesel-electric motors, enables the locomotive to travel 15 miles per hour without load and 5 miles per hour while pushing the power plant up the 1 per cent grade to the IET.

The locomotive also serves as a personnel carrier, seating 12 people within the shielded cab. When the reactor is operating under full power, the locomotive can approach a point 100 feet away and discharge passengers through a retractable shielded hatchway in the floor of the cab into a mating hatch located between the two center rails of the railroad track. A personnel tunnel below the tracks allows access to the test operations area. Such usage is required, for example, during a shift change. The operator of the locomotive has direct forward and rear vision through non-browning laminated glass and oil windows. Radio communication is maintained at all times from the locomotive to the hot shop and the IET.

Below grade, at the end of the test building, is the coupling station, a small room where the power plant dolly plug mates with a recess in the facility. Pipe connections from the facility services are made manually by means of quick disconnects. The piping then crosses the room overhead, passes through the walls and into the earth beyond, where it is routed below grade to the source of the service. The facility also provides for connecting a maximum of 6000 electric wires to the dolly plug. They will be grouped by function in multiple contact electric plugs. These wires pass through the floor into an electrical service room where they fan out, are grouped into 12 cable trays, and are led in this manner along a tunnel to the control room. This same tunnel affords personnel travel between the control room and coupling station. A ventilating system, a 100-gpm sump pump to handle piping leaks, combustible gas detectors, heat detectors, and alarm horns are located in this area. The piping and wiring system in the coupling station allows wide latitude in the power plant design and in the choice of dolly plug arrangements which may be connected to the test facility.

The IET requires certain auxiliary systems and equipment. The bulk of this equipment is housed in the equipment room of the IET. Besides the space provided for initial equipment, space has been provided for additional items which may be required for future power plants.

The compressed air system is one of the largest auxiliary systems in the facility. One 1-pound-per-second compressor delivers air at 200 psig to various parts of the facility and the dolly plug. Of this output, 0.1 pound per second is dried and filtered for instrument use. This compressor is powered by the emergency electrical system and is available at all times. Space has been provided for an 1800 psig compressor if required. Shop air at 90 psig is provided at various points in the facility and on the test pad.

Electricity is brought to the facility at 13,800 volts to a 1000-kva substation outside the IET where it is transformed to 3-phase, 440-volt power. Lighting is on a 3-phase, 4-wire distribution system except the outside area lighting, which is on a 20-ampere series circuit. Load and motor control centers are located in the equipment room from which power is distributed to all parts of the facility. Circuit breakers in the substation are remotely controlled from within the facility.

A 700-kva diesel generator is used to furnish emergency power in case of failure of the normal power supply. Due to the undesirability of running the diesel idle and the necessity for an uninterrupted power supply, it is planned to operate the diesel under partial load continuously during test operation with the emergency load to be transferred to the diesel in the event of power failure.

Certain nonstandard voltages and frequencies are provided for control and instrumentation work. There are 30 kva of 400-cycle, single-phase power, 30 kw of 28-volt d-c power, 20 kva of 3-phase, 400-cycle power, and 30 kw of regulated 120-volt, 60-cycle power. All 400-cycle power is at 120 volts. Single-phase convenience outlets are provided in all parts of the facility, and 3-phase welding outlets are provided on the test pad.

Two boilers heat the facility in winter and heat the primary power package cooling fluids to operating temperature when necessary. The boilers can be set to operate at any pressure up to 100 psig.

The administration area consists of a guard house, office building, service building, warehouse, fuel oil storage, water supply, cafeteria and first aid services. The assembly and maintenance area is located adjacent to the administration area as indicated in Figure 4. The assembly and maintenance (A & M) building will provide within one structure the supporting facilities, services, and equipment requisite to the testing of a mobile-reactor-type power plant.

The shielding of personnel from radioactive power plants and components is designed to accommodate a wide variation in power plant size and configuration. A layout of this building is shown in Figure 5.

The principal facility in the assembly and maintenance building is the hot shop, which occupies an area approximately 52 ft by 160 ft and contains remotely controlled equipment capable of dismantling, inspecting, and reassembling radioactive power plants. This room shields equipment operators by normal concrete walls 6 ft 10 in. thick at the base and tapering to 2 ft at the roof. The roof is approximately 60 ft high and has a thickness of two feet. Two opposing walls contain a total of nine shield windows to allow operators working outside to observe and control all equipment and operations within the hot shop.

The west end of the hot shop contains bi-parting, concrete doors which provide a clear opening 28 ft wide by 33 ft high. A four-rail track, entering at the door, will accommodate a two-rail standard-gage carrier or a carrier equipped with two standard trucks side by side on the outside tracks.

Once inside the hot shop, power plants or other components can be maneuvered and oriented by means of a 100-ton bridge crane, with a 49-ft clearance under the hook, or the components can be handled by a bridge-mounted overhead manipulator, which, in its weakest position, is capable of exerting a force of 400 lb in any direction or a torque of 400 lb-ft. This manipulator has a 35-ft clearance under the hand and possesses a total of 10 motions which can be precisely controlled by the operators.

The floor of the hot shop contains two remotely controllable turntables, 16 ft in diameter and designed to carry 50 tons each. With the addition of a simple adaptor mounted on an upending jig, these turntables will permit a component to be seen from any position. The floor also contains a 24-ft by 25-ft water-filled vestibule which extends down and under the north wall to provide an entrance to an underwater storage pool.

This bulk shielding storage pool is 70 ft by 48 ft and is filled to a depth of 24 ft with water. It can receive any part or component which can be accommodated by the 100-ton crane and can be fitted through the vestibule. Parts are lowered into the vestibule and onto a transfer dolly which moves on rails laid in the pool floor. The loaded dolly is then pulled under the wall by means of a telescoping boom of a 15-ton crane bridge-mounted above the pool. The pool walls are provided with shelves and underwater lighting -- a versatile arrangement to accommodate a wide range in size and weight of radioactive parts to be stored.

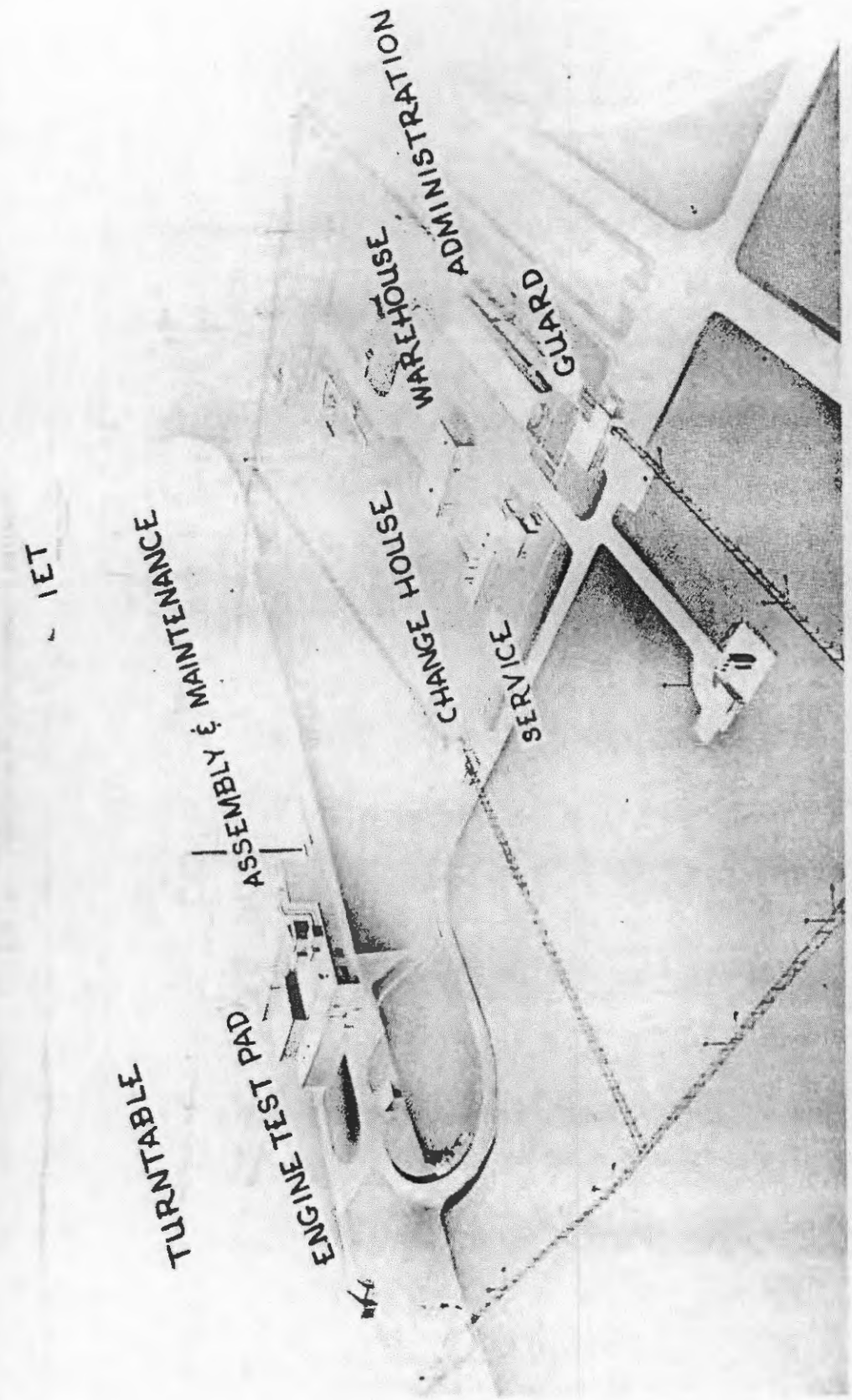

Fig. 4 - Administration and shop areas

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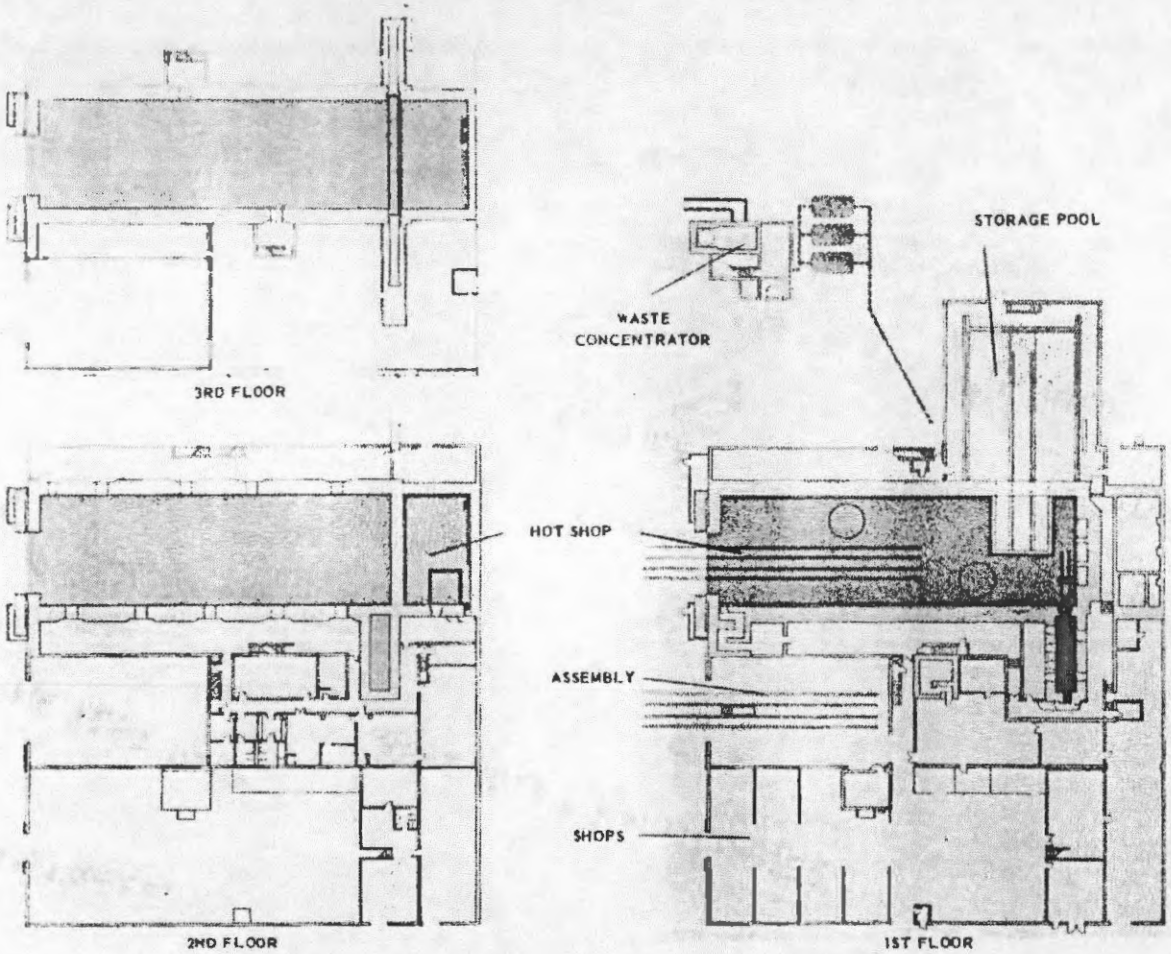

Fig. 5 - Assembly and maintenance building

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Each 160-ft wall of the hot shop is equipped with two boom-mounted General Mills manipulators which can travel the entire length of the wall. The horizontal booms extend from a wall-mounted carriage which is capable of vertical travel from floor level to the 30-ft elevation. The manipulator hand can be moved horizontally along the length of the 24-ft boom. In addition, the boom is pivoted at the wall so that the hand can be positioned at any point on a 180-degree arc. The combined motions, nine in number, will permit operators to position any or all of the four manipulators so that singly or in groups they can assist each other and the overhead crane and manipulator in performing precise and complex operations on a component.

The highly maneuverable manipulators together with the adapted power tools - such as pneumatic wrenches, drivers, and hammers - make the hot shop a versatile facility capable of performing a wide range of remotely controlled disassembly, maintenance, or reassembly operations.

The shielded space in the hot shop contains pedestal mounted outlets for all required services - such as electric power, air, water, and gas. The lines can be coupled or uncoupled, flow controlled, and metered remotely by the operators. Additional service and supply lines are routed to wall plugs to provide services and leads (1/2 in. to 8 in. diameter) to permanent or semi-permanent fixtures. Both the service pedestals and the wall plugs contain spare lines and conduits for future installations.

The hot shop is provided with a special equipment service (SES) room, 52 ft by 30 ft, which adjoins the east end. The SES room is separated from the hot shop proper by a shield wall containing an opening through which the crane and bridge mounted manipulator can be moved. This opening may be closed by biparting concrete shield doors for special maintenance, inspection, and servicing of the overhead manipulator or crane while an exposed radiation source is in the hot shop. This assures that the equipment will at all times be available for inspection and maintenance.

A second shielded room adjoins the hot shop at the east end of the south wall. This room, known as the inspection cubicle, is approximately 10 ft by 30 ft with a ceiling height of 17 ft, and it has 4-ft-thick high-density concrete walls. Radioactive parts which require a close degree of inspection and examination can be moved from the hot shop into the cubicle through a plug-type door 4 ft wide by 13 ft high.

The cubicle contains two bridge-mounted overhead manipulators, a pair of Argonne Master Slave manipulators, sectioning devices, a laboratory remote operating scale, and a periscope with a 30-inch field of focus and selective magnification. The periscope is equipped with a camera.

The cubicle is serviced by lines carrying power, industrial water, deionized water, air, vacuum, and full provisions for decontamination.

Over-all flexibility is enhanced by the ability to isolate radioactive parts in the cubicle from the radiation zone within the hot shop, and at the same time be able to perform required operations in both areas. This will also permit either area to be serviced or decontaminated without disrupting activity in the other.

The control and observation galleries for the hot shop, special equipment service room, and inspection cubicle are designed to accommodate any equipment which may be required for any foreseeable control need.

Each shielded observation window station is provided with plug-in receptacles which receive conductors from consoles designed to control all motions of the manipulators. Two

wall-manipulators, the overhead manipulator, and the overhead crane may be operated from any one of the stations. Observer stations are equipped with an audio transmitter connected to a selective sound pickup microphone system within the hot areas. Each station is also provided with a switch which will control the degree of illumination on the observer's side so that optimum viewing can be quickly and easily obtained.

A well equipped instrumentation laboratory will be located in the A & M building. This laboratory will provide specialized equipment required to carry out the test program; will maintain facilities for repair, modification, installation, and calibration of equipment; and will develop special instrumentation or techniques required to support the test operation.

In order to carry out these functions, the instrumentation laboratory will be equipped with electronic instruments and accessories, special tools and fixtures, and calibration equipment and standards. A shielded room for counting low activity specimens, for radiation instrumentation calibration, etc., is provided. The normal water, air, gas, power, telephone, and other services are also provided.

Other laboratories are provided in the Idaho plant to function as a service group. These will be staffed and equipped to perform all routine chemical, metallurgical, and materials control work, in addition to providing counting equipment, photographic services, and facilities for examination of radioactive fuel assemblies and components.

Shop areas are provided for the assembly and maintenance of components and for the making of special parts.

The assembly shop embraces approximately 4000 sq ft (80 ft x 50 ft) of unobstructed floor space, with a ceiling height of 49 ft. Railroad or truck entrance to the shop is obtained through a 28-ft-wide x 33-ft-high door in the west wall. Compressed air, water, and electric outlets are located throughout the shop area. Because of the high ceiling (49 ft), unobstructed floor space (80 ft x 50 ft), and heavy crane capacity (30 tons), this shop is adaptable to the fabrication or assembling of heavy, bulky equipment.

The engine maintenance shop embraces a space of 80 ft x 72 ft, with a ceiling height of 21 ft. A 12-ft-wide aisle through the center permits free movement of equipment and materials in and out of the adjacent machine shop. This aisle terminates in a 12-ft-wide by 16-ft-high doorway in the west wall giving access to the roadway along the west side of the A & M building.

The floor space south of this aisle is divided by temporary fencing into four assembly areas (each 20 ft x 25 ft). Each stall contains fixed workbenches, parts bins, tool cabinets, and miscellaneous hand tools, as well as electrical and compressed air outlets along the wall.

The area north of this 12-ft center aisle is divided into three stalls (each 20 ft x 25 ft) containing different equipment: one stall encloses zyglo and magnaflux inspection equipment; another contains a U.J.P. model and a 3-S model Gisholt balancing machine; and the third stall contains several shelving units, parts bin, and pipe rack storage for tools and fixtures. Adjacent to the balancing machines is a spray booth for degreasing and washing parts and equipment.

Machine shop and welding work requirements for the Idaho plant of the ANP Department are expected to be extremely varied in nature. Equipment has been selected to provide the shop areas with a limited number of machines which will perform practically all types of work, including rework and modification of engine parts; building assembly tools, jigs, fixtures and gauges; performing routine and emergency maintenance work on all types of

equipment; building special accessories for remote handling equipment; and making special engine parts, and parts and fittings for engine and facilities instrumentation. The variety of work is expected to range from making extremely small parts made to very close tolerances, to the remachining of large parts of the shielded locomotive.

A single engine test cell has been constructed adjacent to the assembly and maintenance building. This resembles a typical jet engine test stand, but it is arranged to accept an engine with a throttling valve between the compressor and unit combustor to simulate reactor or heat exchanger pressure drop. Engine instrumentation is more complete than at the IET but incorporates an identical console panel unit. After an engine has been overhauled and reassembled, it gets a performance check before it is installed on the dolly for IET operation. All facilities for intermittent or continuous testing with the exception of thrust measurement are provided. Due to the isolated location of the area, no provision has been made for noise abatement.

A meteorology tower is being included to provide information as to the suitability of the weather for the disposal of radioactive materials to the atmosphere. It will also serve to collect a background of information to help in making precise forecasts of operating time.

The tower is to be 200 feet high with wind direction and temperature measuring equipment located at 50 foot intervals. The tower is located in the IET area in such a manner that in case of accident neither the tower nor its supporting cables could fall on any vital part of the facility.

1.4 HTRE POWER PLANT

The HTRE power plant consists of an air-cooled, metallic-fuel-element, water-moderated reactor operating a single modified J47 turbojet engine. The power plant is illustrated in Figure 6. The turbojet engine and shield are part of a mobile facility called the Core Test Facility. The facility includes two engines, although only one is needed to provide cooling air for the first HTRE core.

The shield consists of borated water, lead, and steel. The shield was designed to provide sufficient neutron and gamma shielding to reduce the combined effect of the induced activity of external components and the leakage of core decay gammas to 100 mr per hour three hours after twenty-five hours of operation.

A reactor core and stepped shield plug is shown inserted in the shield. The core, shield plug, control actuators, source rod, startup fission chambers, and operating ion chambers are combined into an integral unit before insertion into the shield.

A simplified schematic of the power plant and control system is shown in Figure 7. The air enters the turbojet engine, and is compressed to approximately five times the intake pressure. From there it is collected in a scroll and ducted to a manifold on top of the shield tank. The air passes through the shield in a number of parallel ducts and enters the air plenum chamber above the reactor. The inlet plenum chamber is shown cross-hatched in the schematic. The air passes through the reactor, is heated to a temperature of 1450°F, and enters a plenum chamber at the reactor exit. The exit plenum chamber is shown shaded. From there the air returns to the engine, turns the turbine which drives the engine compressor, and is exhausted to the exhaust handling system.

The engine may be operated on nuclear or chemical fuel, or a combination of both. The chemical fuel is burned in an external burner can since the space normally occupied by

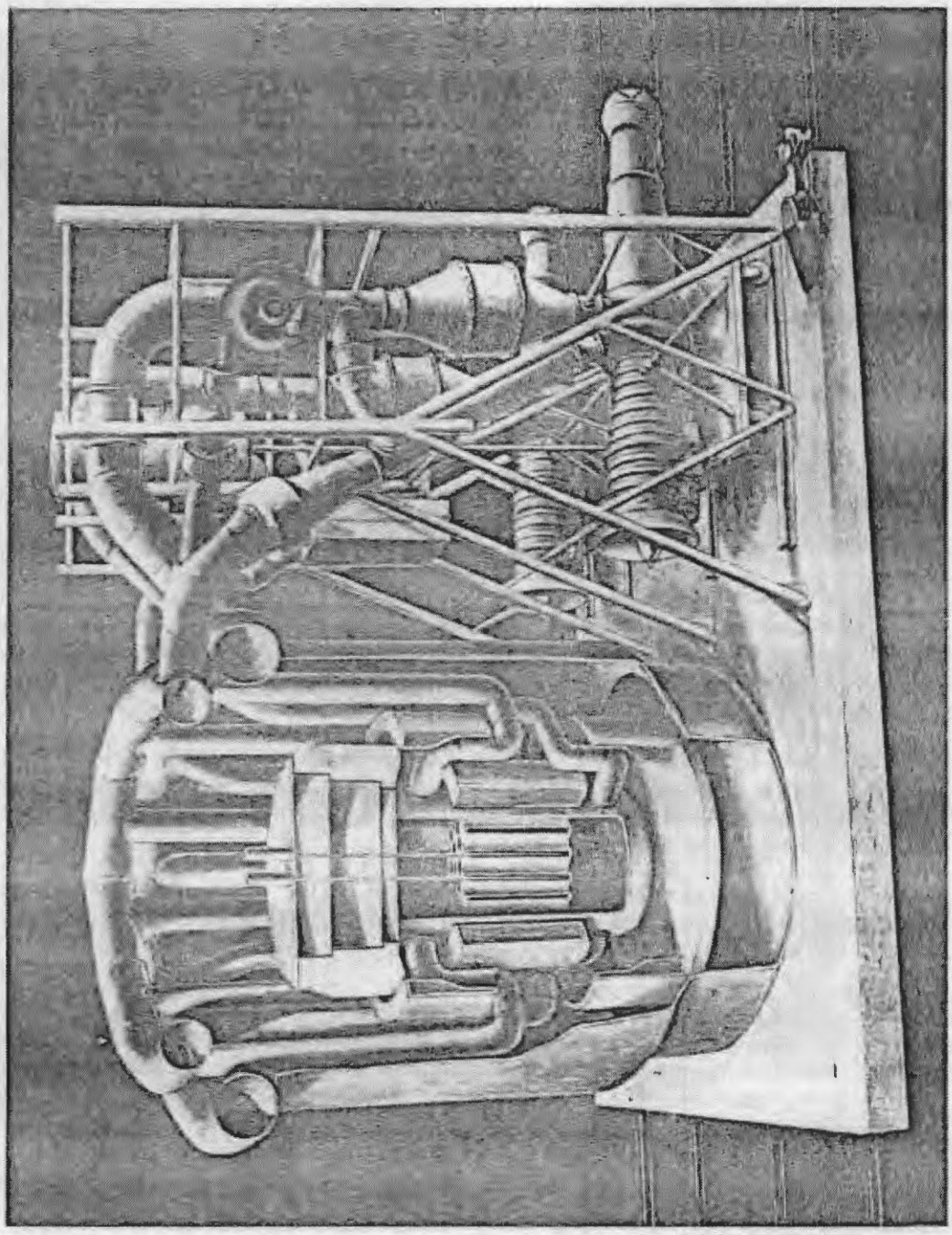

Fig. 6 - Artist's conception of HTRE power plant

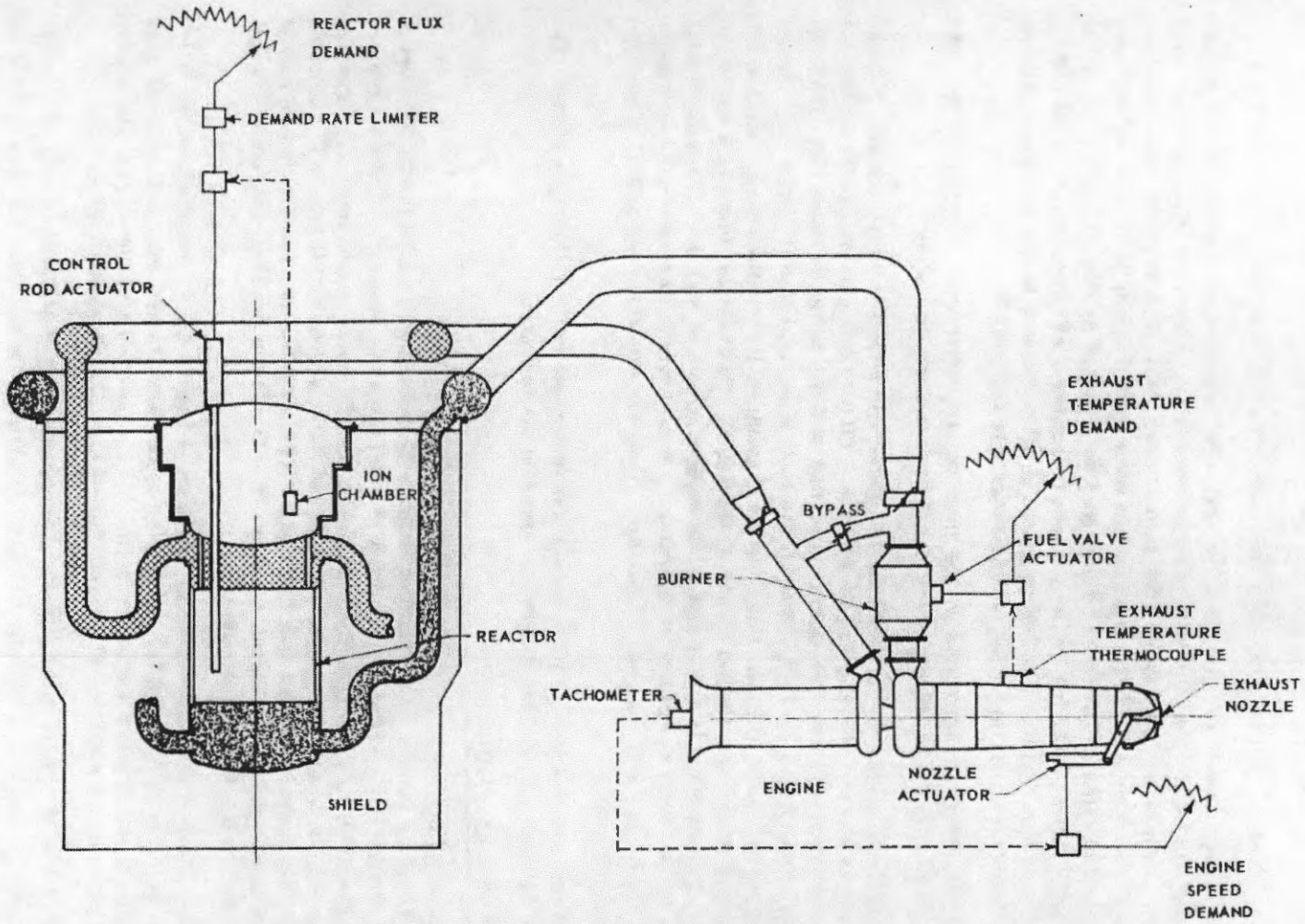

Fig. 7 - Schematic of power plant and control system

burner cans in the engine has been taken up by the air scrolls used in ducting the air to the reactor. When operating on chemical fuel, the compressor air may pass through either the reactor or a bypass duct.

The basic method of controlling the power plant is shown schematically in Figure 7.

When operating on chemical fuel only, the engine is controlled by controlling the turbine exhaust temperature. A demand for increased temperature causes the chemical fuel valve to open, thus supplying more fuel to the burner can. When the desired temperature is reached, a thermocouple in the turbine exhaust feeds back a signal to balance out the temperature demand signal. The engine speed may be changed by changing the area of the engine exhaust nozzle. Reducing the nozzle area increases the back pressure on the system and slows down the engine. The engine speed is held constant by an automatic control system independent of variations in turbine exhaust temperature.

The reactor power is controlled by the insertion or withdrawal of poison rods. The neutron flux level in the top plug is used as a measure of reactor power.

The power plant is started on chemical fuel alone with compressor air passing through the cold reactor. Then with the engine speed and turbine exhaust temperature controls set at a predetermined level, the reactor is started and the power is increased. When the nuclear heat added to the air is detected by the turbine exhaust thermocouple, the chemical fuel valve will start to close in an attempt to maintain the exhaust temperature at the predetermined level. As reactor power is increased, the chemical fuel valve will close completely. Engine speed is held constant throughout. Further increase in reactor power will cause an increase in exhaust temperature. Temperature limiters cause automatic power setback or scram if the reactor operator allows an excessive temperature increase while on nuclear power.

The reactor, fuel elements, and controls are described in the following sections. The Core Test Facility is described in greater detail in the appendix.

1.41 REACTOR ASSEMBLY

General Description

The first reactor for the Heat Transfer Reactor Experiment is called the HTRE Core A Reactor Assembly. An artist's conception of the reactor is shown in Figure 8. The reactor is aircooled, has metallic fuel elements, and is water moderated. The reactor structure is aluminum and consists of a cylindrical water vessel penetrated by 37 air tubes. Each of the air tubes contains a fuel cartridge. The air tubes are lined with a thin layer of stainless-steel-jacketed mineral wool felt type insulation to reduce escape of the fuel element heat into the water moderator.

The reactor and shield plug assembly is shown in Figure 8A. The dished header which constitutes the lower portion of the shield plug is known as the transition section. It is an integral part of the reactor assembly in that it is connected by control rod guide tubes and water tubes to the reactor. The transition section is also made of aluminum.

The shield plug structure and the heavy gamma shielding is stainless steel. Moderator water is used for neutron shielding in the shield plug. Figure 9 is a schematic showing the manner in which the shield plug matches the rest of the Core Test Facility shield.

Reactor Components

Reactor Core - The core is a 37-tube tube bank of hexagonal pattern with radially varying tube spacings. The active portion of the lattice is a regular hexagonal prism 29.4 inches across flats, 34.4 inches across corners, and 29.125 inches long. The tubes extend 12.94

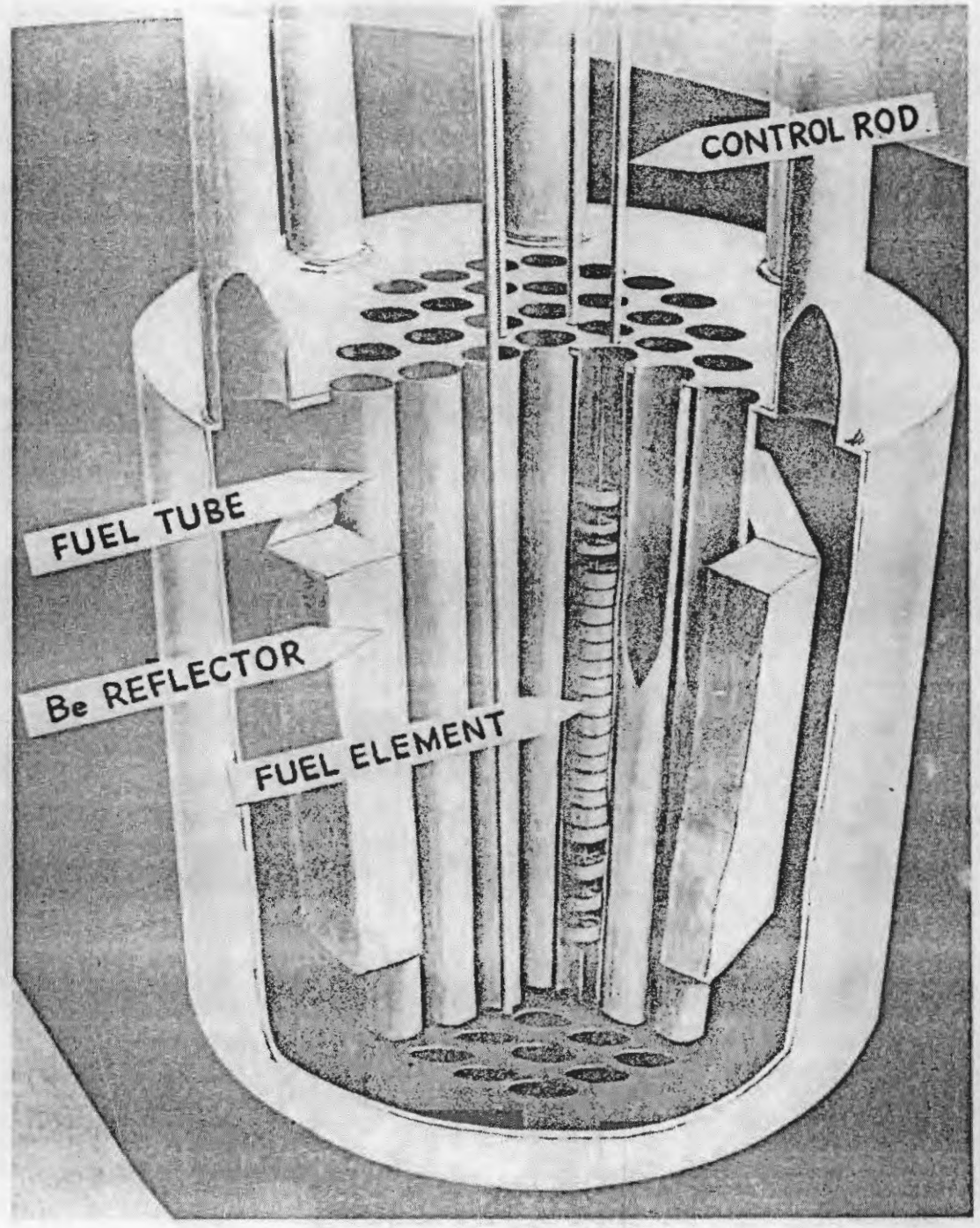

Fig. 8 - Artist's conception of reactor core assembly

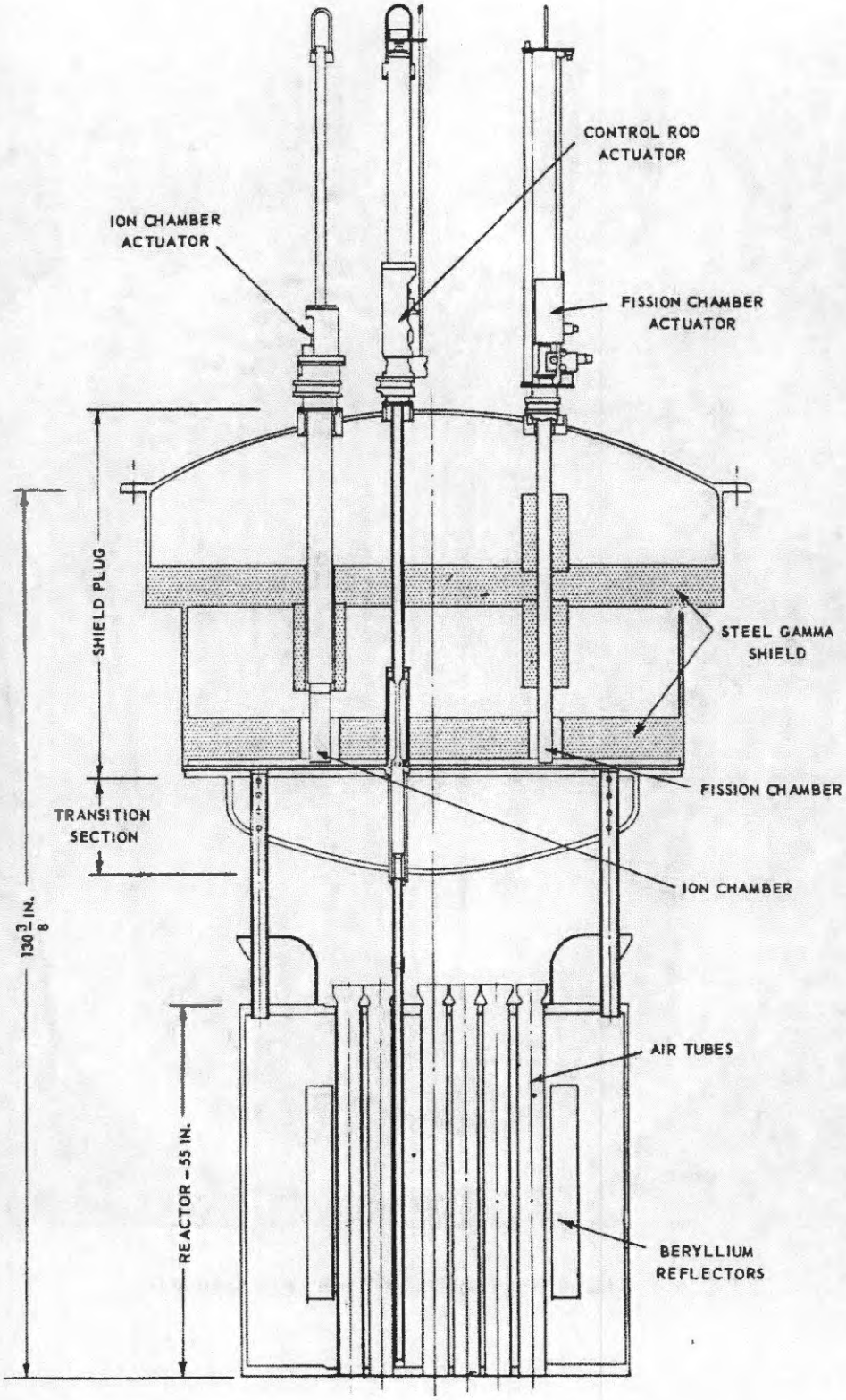

Fig. 8A - Core A2 reactor assembly

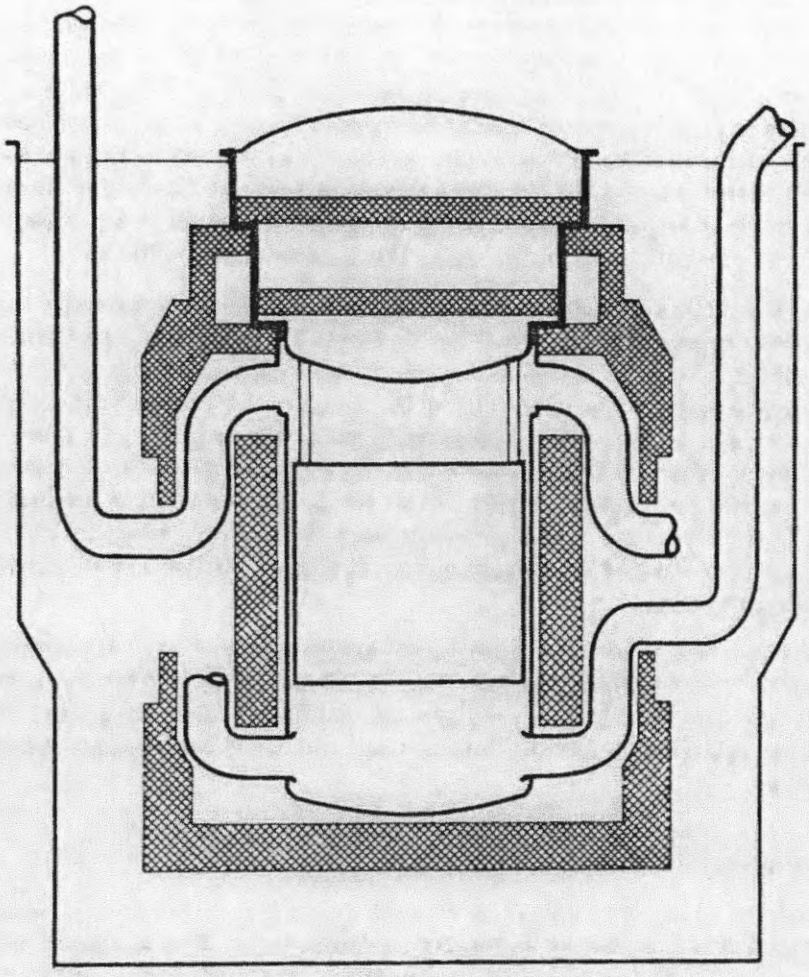

Fig. 9 - Schematic of HTRE shield

inches beyond each end of the active section. The tube bank is contained by tube sheets at either end and a cylindrical shell forming a tank 59 inches in diameter and 55 inches long. The core tank also contains the beryllium reflector which is a 4-inch-thick hexagonal shell spaced 5/8 inch from the outside tubes and supported from brackets which are welded to the core tube sheets. The control rod guide tubes are welded into the top tube sheet and are located by small spacer plugs which are welded to the top face of the bottom tube sheet. These guide tubes not only guide the displacement type control rods, which penetrate the core to the depth of the bottom of the active lattice, but also serve as moderator water inlet tubes. The water flow in the core is a two-pass system. The water flows down the control rod guide tubes and splits, part going up along the fuel tubes and along the inside of the reflector, the remainder going up along the outside of the reflector.

Shield Plug - The primary purpose of the plug is to shield the area above the core insertion hole in the top of the Core Test Facility shield from nuclear radiation. It is constructed of stainless steel with two thick layers of steel gamma shielding. The transition section adds significantly to the shielding of the reactor. The plug also serves to hold the reactor core by way of the control rod guide tubes and core water exit tubes which run through the air plenum formed between the top of the core and the bottom of the transition section. Since the plug must contain water for shielding and for cooling the plug structure and steel shield, it is used as a reservoir for core inlet water, being in series with the moderator loop. The cooling of the remainder of the Core Test Facility shield is separate from the moderator system.

The plug has two steps to avoid straight-line passage for radiation streaming. The top plate of the plug is bolted to the Core Test Facility shield. The control rod actuators are mounted on the top plate of the plug, as are the nuclear sensor supports, the neutron source actuators, the water inlet and outlet pipes, and the instrumentation leads for the reactor assembly.

Development Program

In the development of the HTRE Core A reactor assembly, a full scale reactor mockup (designated HTRE Core A1a reactor assembly) is being built. This assembly will be used to solve fabrication, development, fitting, handling, and - to some extent - operating problems for the active reactor assembly. After construction at Evendale, the HTRE Core A1a reactor assembly will be shipped to the National Reactor Testing Station to be used for training the remote handling crew and for checking the adequacy of the facilities for handling the active reactor.

The active reactor (designated HTRE Core A2 reactor assembly) and a spare are presently in manufacture and have the same configuration and major design features as the HTRE A1a assembly. The design revisions being made are to facilitate manufacture or to improve the design toward meeting operation conditions.

The illustrations shown in Figures 10 - 13 are of the HTRE Core A1a reactor assembly. The major changes effected in the A2 design are redesign to contain a higher moderator pressure (the full shutoff head of the moderator system pumps) and revision of the water purge system. In the revisions the most apparent physical change is the use of dished heads for the transition section and the plug. The outside diameters are the same for all reactor models.

Figure 13 clearly shows how the transition section is integral with the reactor assembly. The shield plug fits down over the array of control rod guide tubes and is bolted on to the transition section.

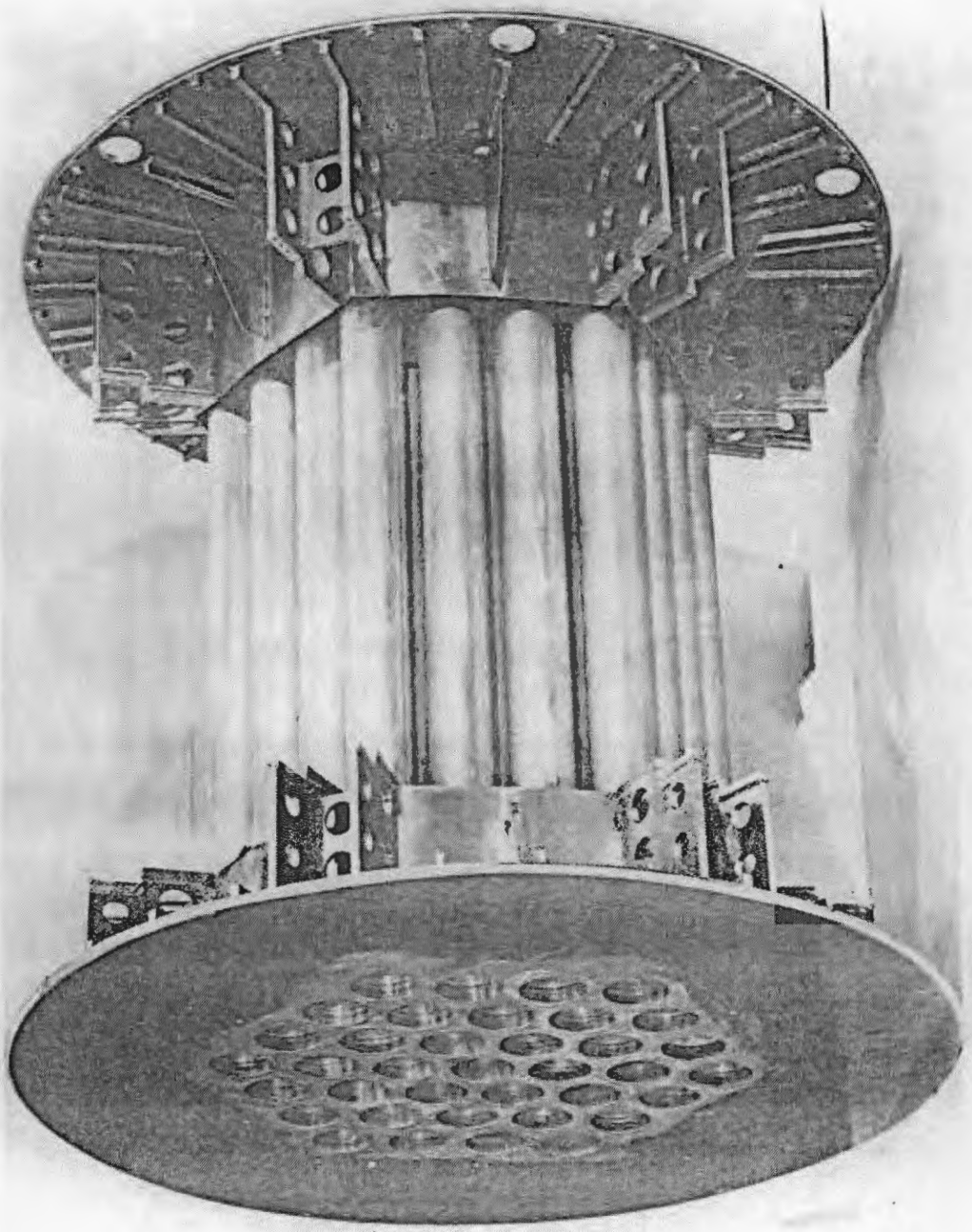

Fig. 10 - Completed A1a core assembly with reflector and outer shell omitted

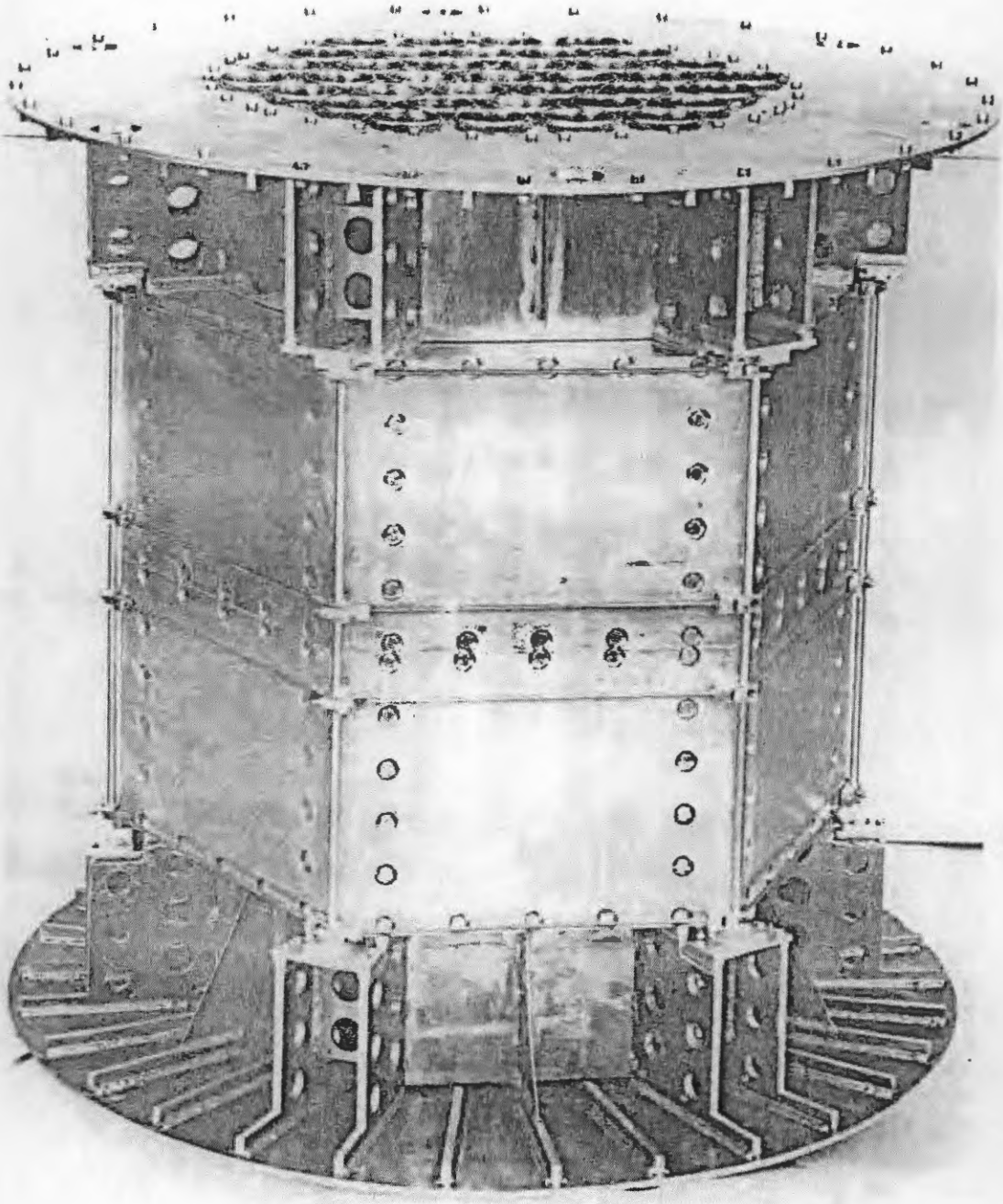

Fig. 11 - A1a core assembly with simulated reflector in place

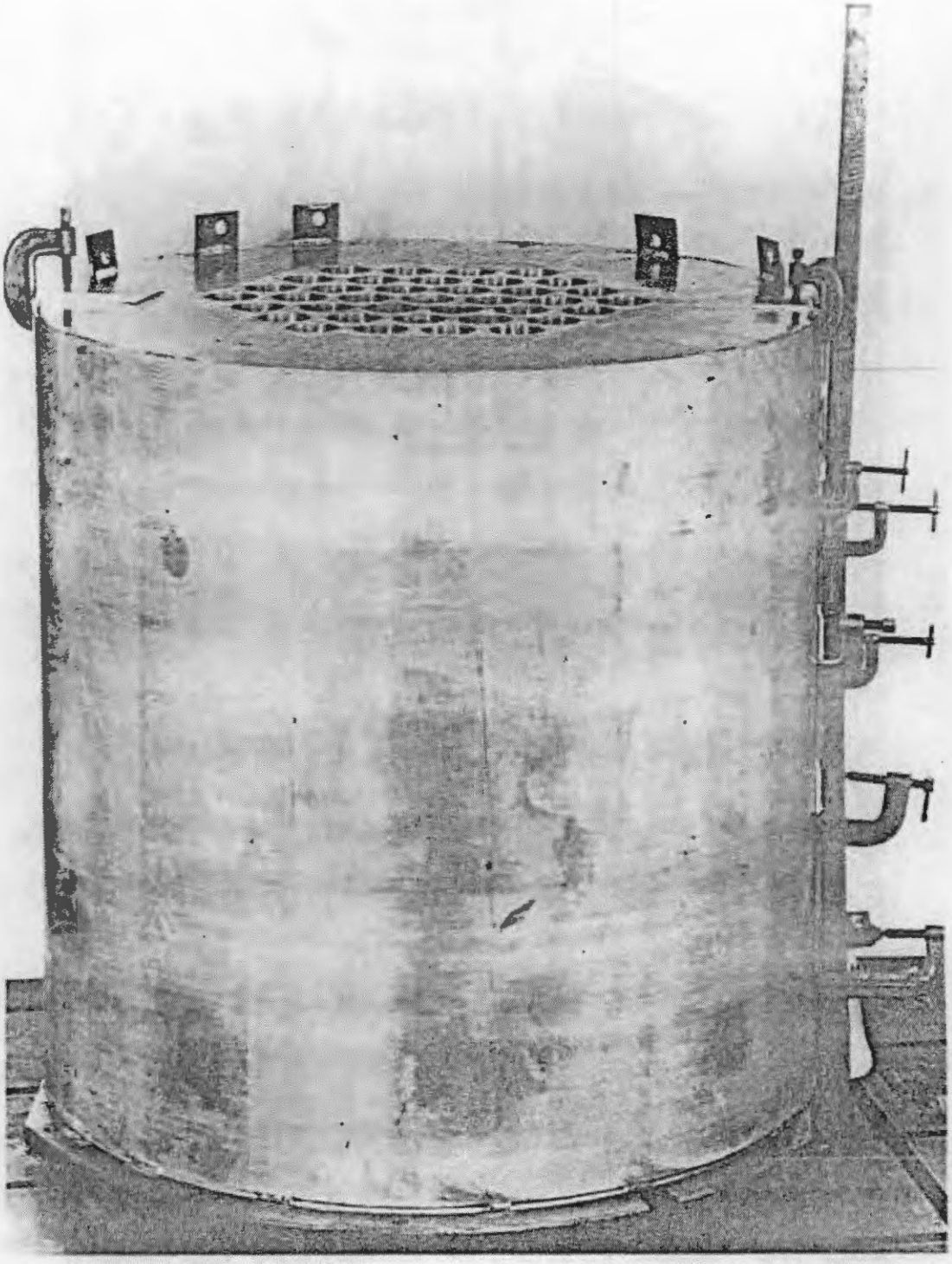

Fig. 12 - Complete A1a core assembly

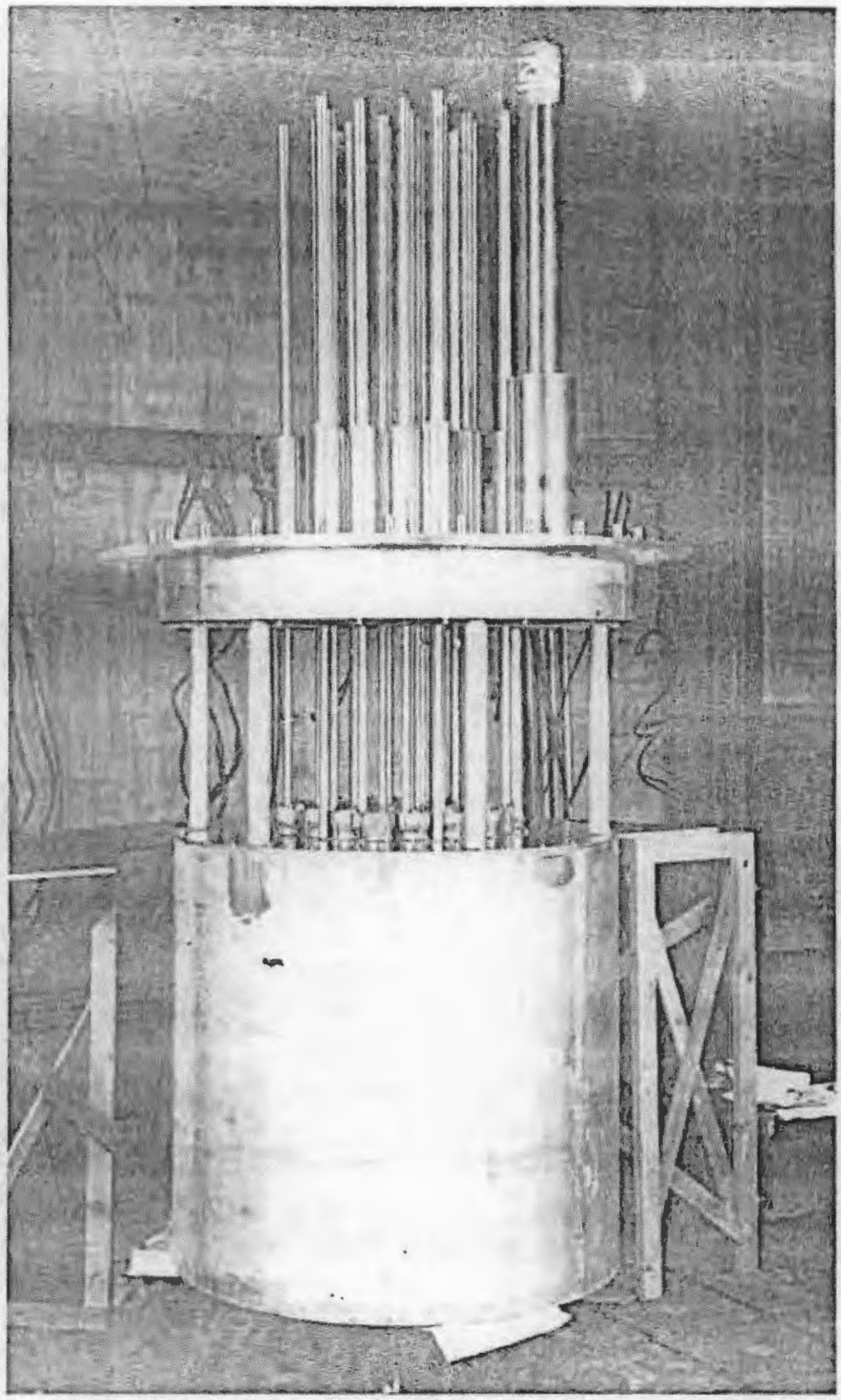

Fig. 13 - A1a core and transition assembly with small inlet bellmouths in place

1.42 FUEL CARTRIDGE ASSEMBLY

The A-1 fuel cartridge (part number 7003R11), when inserted in the core, fills the entire length of the fuel tube. The cartridge is 59.146 inches in length overall and it is composed of three subassemblies, the fuel element assembly, the forward ring assembly complete, and the aft ring assembly (see Figure 14).

The fuel element assembly consists of 18 fuel elements and four support strips. Each element is made up of a number of fueled, concentric cylinders brazed together through nonfueled channels at the inlet end and separated by nonfueled spacers at the outlet end. See Figures 15 and 16.

Each cylinder is made from a fueled ribbon with a trimmed nonfueled edge on the inlet and exit sides and a brazed wire sealed edge at each end. The ribbon is rolled into a cylindrical form, and the ends are joined by a nonfueled joint strip. The ribbon thickness increases in the smaller diameter cylinders, providing more fuel per unit area in regions of depressed neutron flux, thus equalizing the heat flux from each cylinder.

The outside cylinder of each element has eight feet brazed to it. The forward four feet have tabs which are spot-welded to four strips to make up the fuel element assembly.

The forward ring assembly complete is composed of the forward ring assembly, the support assembly, several ring assemblies, and four rails (see Figure 17). The forward ring assembly contains the thermocouple disconnect ring and the insulation support ring. The support assembly provides the means for holding the cartridge in position and remotely releasing it.

The aft ring assembly (Figure 18) contains several plain rings and the pull ring. The pull ring is used for insertion and withdrawal.

When in position, the fuel cartridge is supported by the support rod which is attached to the core face through the small bellmouth. The load runs through the coupling of the support assembly, outward to the ring of the support assembly, and then down through the rails.

Thermocouple leads are brought forward along the outside of the cartridge of the thermocouple disconnect ring. Two of the thirty-seven cartridges have eighteen thermocouples each while the other cartridges have two each. All thermocouples are located on the trailing edges of the fueled cylinders.

Mockups of the HTRE fuel elements have been tested in the MTR or in other tests under conditions equal to or more severe than those anticipated in the HTRE. A comparison of the multistage elements tested to date in the MTR and the calculated HTRE stage temperature and dynamic head operating conditions is shown in Figure 19.

Figure 20 is a microphotograph of a ribbon from a typical element after stress-rupture testing showing the Nichrome V - uranium mixture in the ribbon clad on either side with four mils of Nichrome V.

1.43 NUCLEAR AND THERMODYNAMIC CHARACTERISTICS

Uranium Inventory

The nuclear design of the HTRE Core A reactor has been based on two critical experiments as well as on several calculations. The first critical experiment was run at the Building 9213 facility of the Oak Ridge National Laboratory. This experiment, designated the TRA-1 (for Tube Reactor Assembly-I), utilized the same basic core geometry that is now under design for the HTRE Core A reactor. There were two principle differences be-

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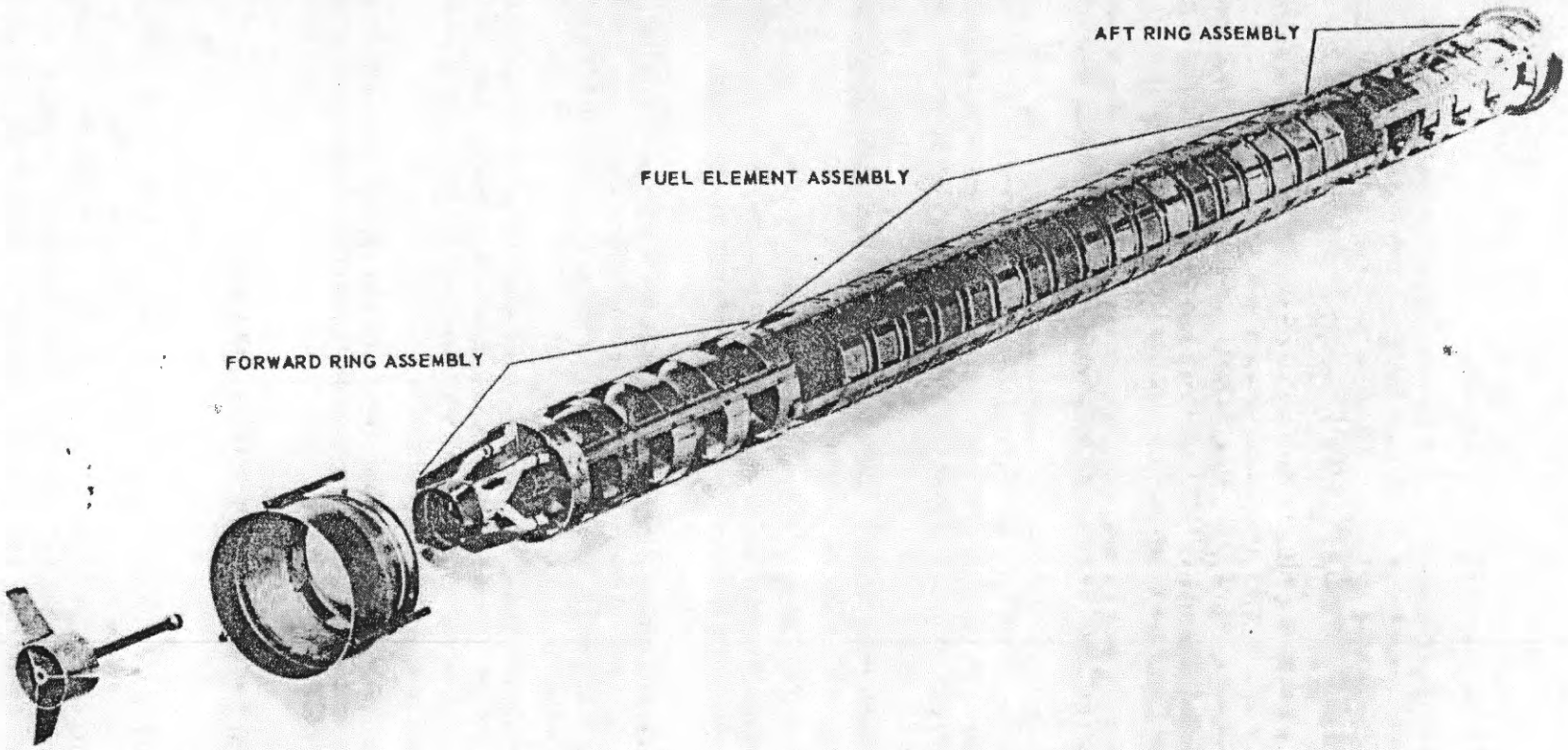

Fig. 14 - Fuel element cartridge with bellmouth and thermocouple disconnect

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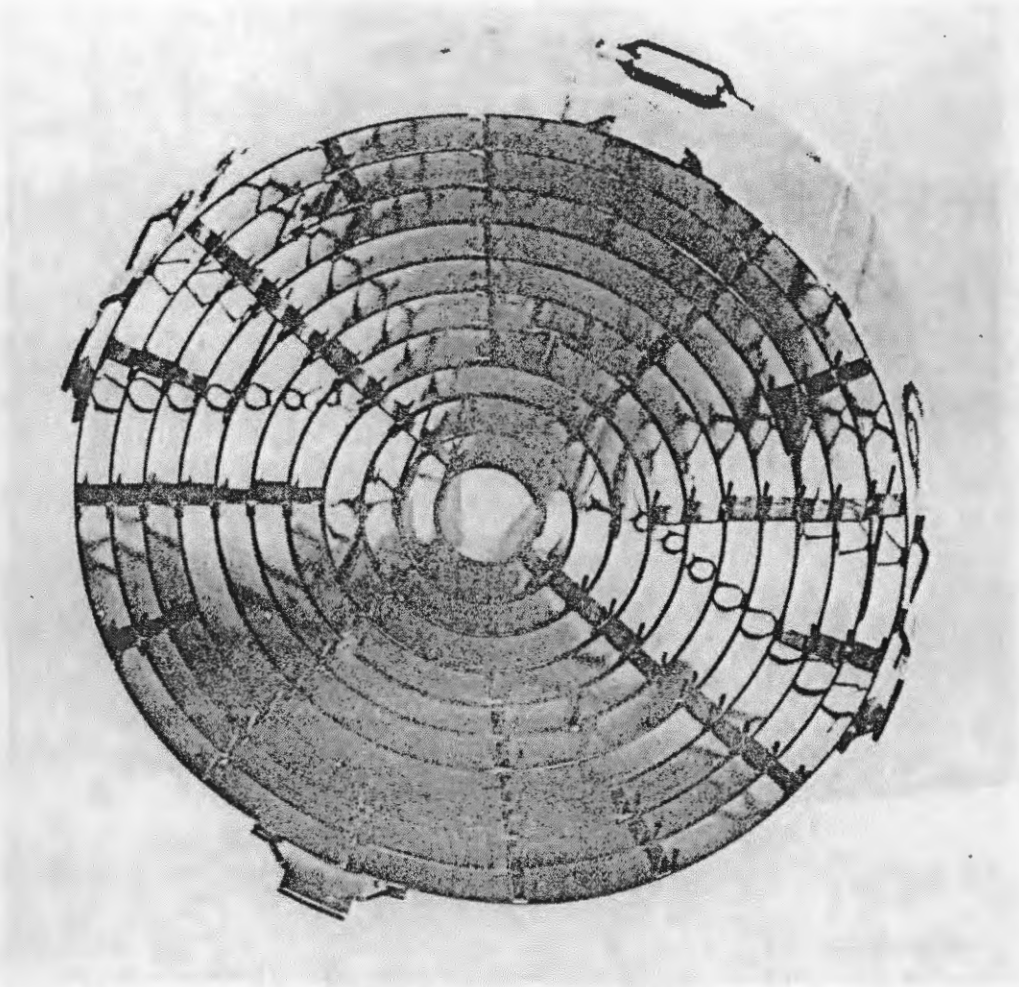

Fig. 15 - Front view of element

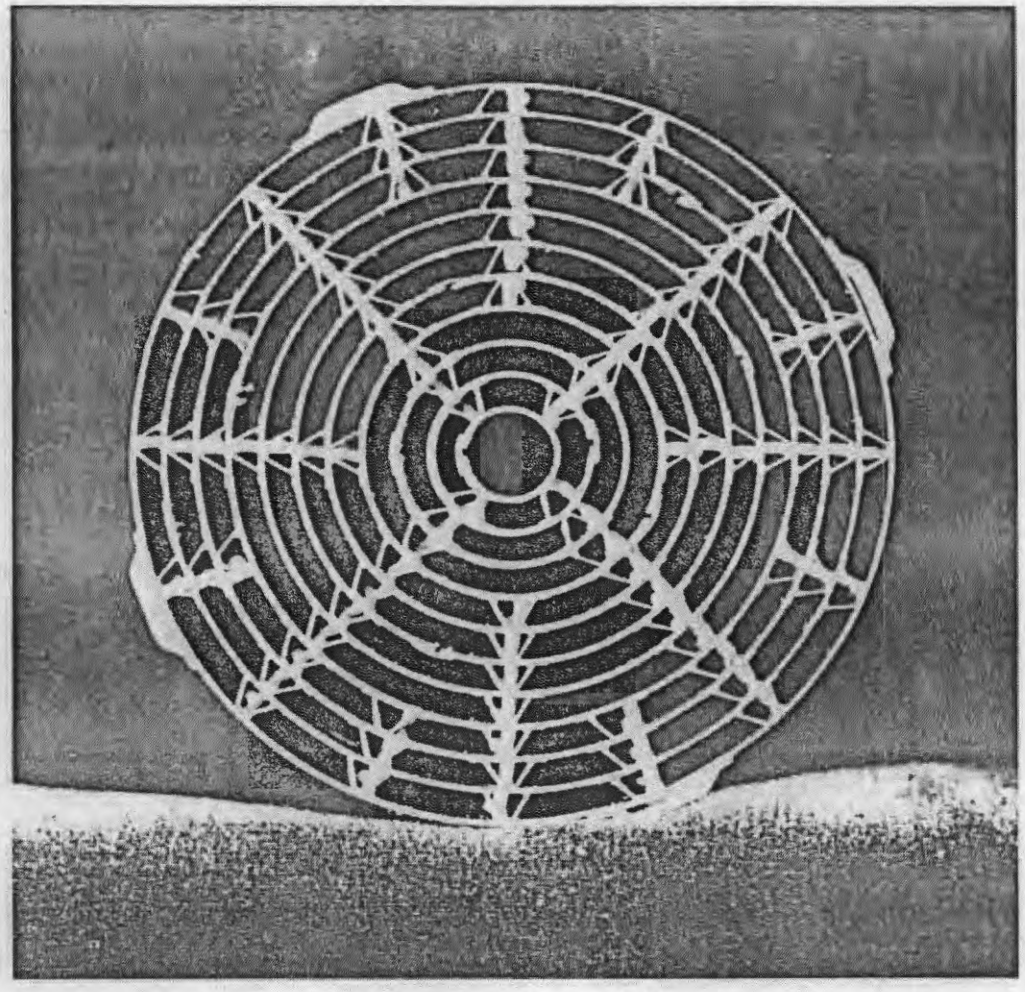

Fig. 16 - Rear view of element

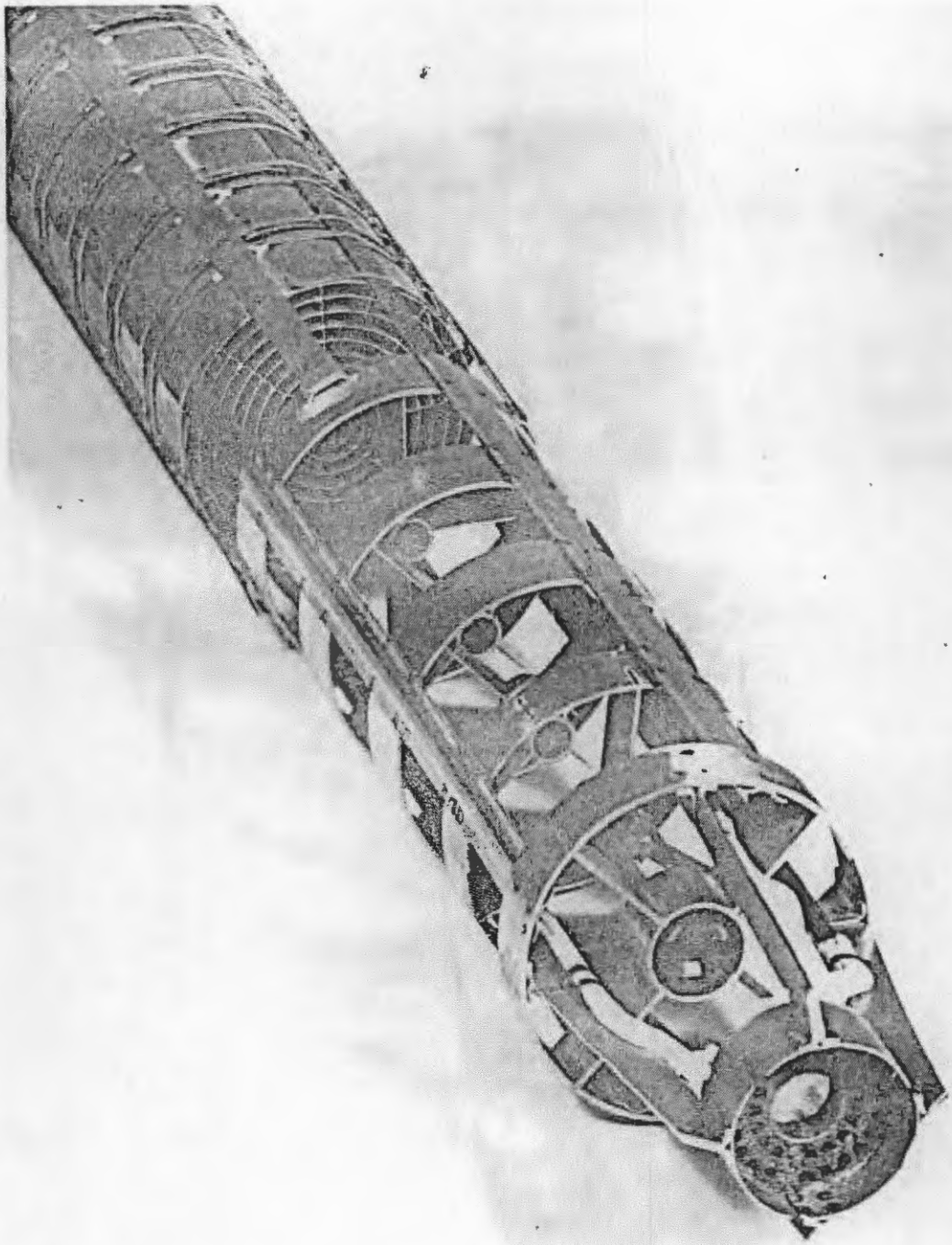

Fig. 17 - Forward ring assembly complete

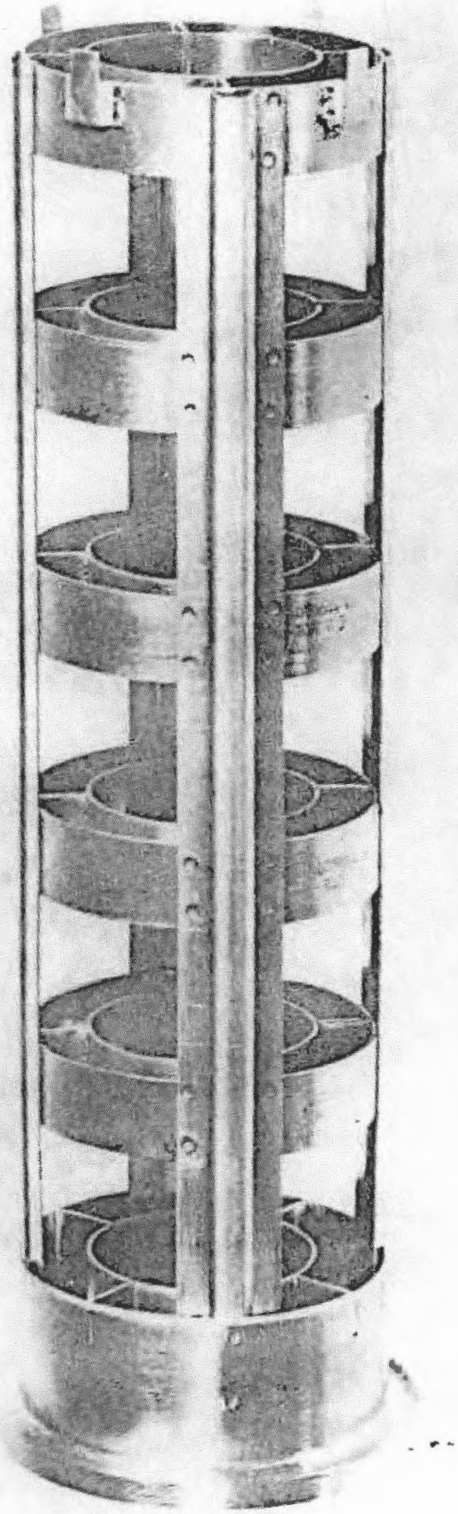

Fig. 18 - Aft ring assembly

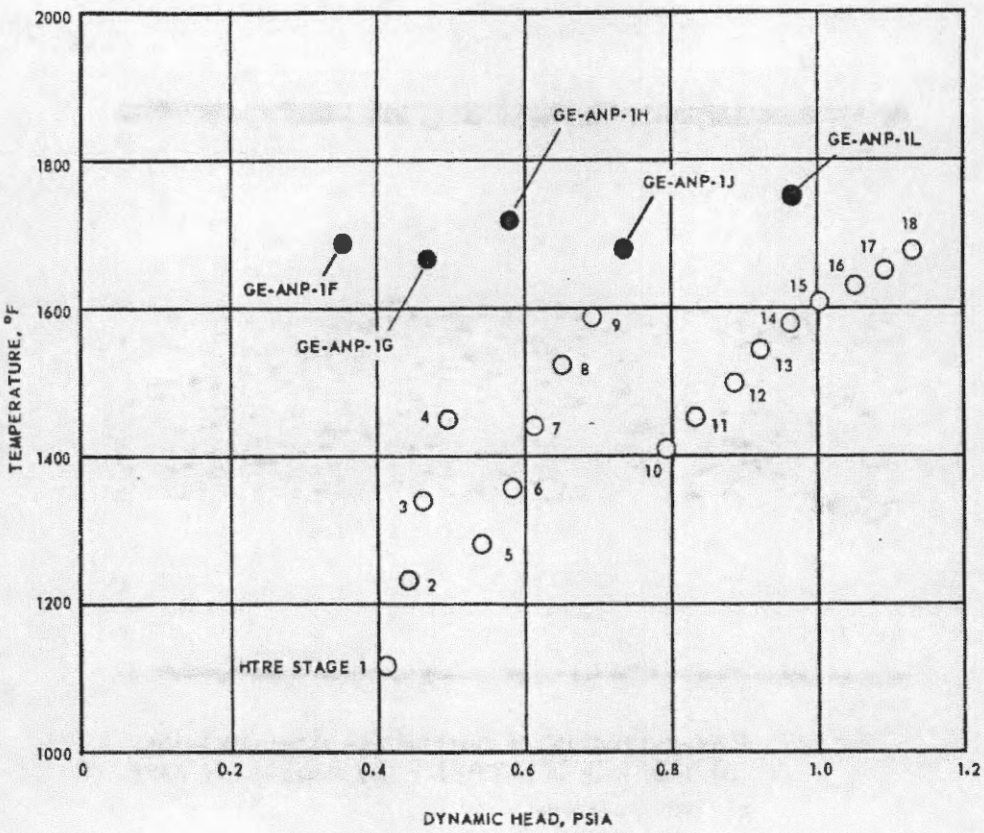

Fig. 19 - Comparison of MTR multistage test conditions with HTRE conditions

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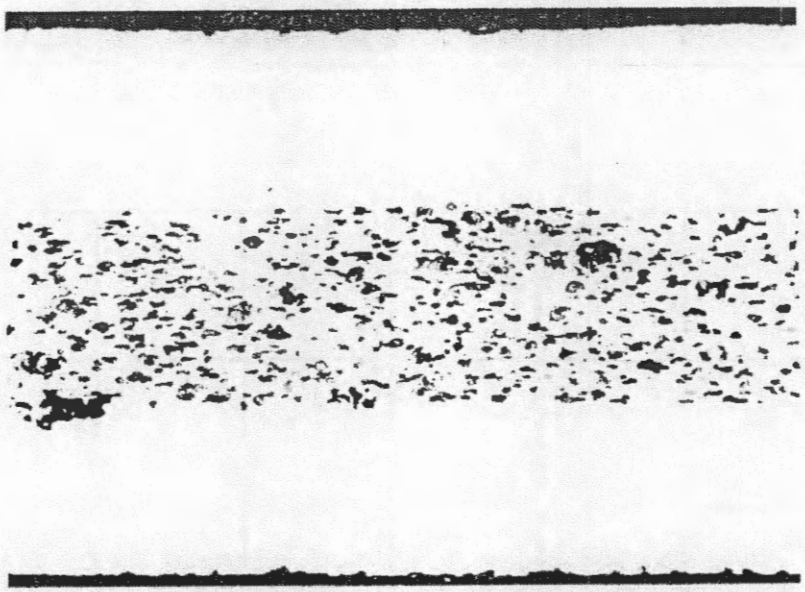

Fig. 20 - Photomicrograph of unirradiated stress oxidation specimen held at 1500°F for 100 hours under 1800 psi tensile stress

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tween the TRA-1 experiment mockup and the HTRE Core A configuration. The TRA-I mockup had an infinite water reflector (radial) rather than beryllium, and the fuel elements were mocked up using the metallic uranium fuel discs available at the facility. It has been experimentally and analytically estimated that the discrepancy in fuel element mockup was worth about 2 per cent - 4 per cent in reactivity (negative).

The second critical experiment, designated the TRA-II, is now in operation in Evendale. The TRA-II assembly has the same configuration as HTRE Core A, has a beryllium reflector, and through the use of fuel-bearing Teflon sheets has fuel elements which are faithful mockups of the design fuel elements. The data obtained from the mockup are, therefore, felt to be directly applicable to HTRE Core A.

Criticality calculations for the two critical assemblies and for the test reactor have utilized an 18 group, discontinuous, slowing down model based on an equivalent bare core (actual core dimensions modified by reflector savings). The equivalent bare core calculation model was tested by calculating a series of small, bare, homogeneous critical assemblies for a wide range of concentrations and sizes.* The predicted value of the reactivity (k_{eff}) was found to agree in all cases with the experimental value within approximately 3 per cent. It is therefore believed that the slowing down model used is essentially correct and that this method can be used for the prediction of the heterogeneous reflected reactors under consideration provided the following effects are properly accounted for:

1. The effect of the reflector
2. The effect of heterogeneity on the thermal utilization
3. The effect of heterogeneity on leakage

The first two effects are taken into account by more or less standard calculation methods. There was a discrepancy between the calculated and the observed values of reactivity (k_{eff}) for the TRA-I (Oak Ridge) assembly which was taken to be due to heterogeneity effects on leakage. The magnitude of this discrepancy corresponds closely to that estimated by relations developed by Behrens, although the theory for reactors of this type is not developed sufficiently for direct application.†

The reactivity of the TRA-II assembly was then estimated by using the identical techniques which were used in calculating the TRA-I with the following corrections:

1. The value of the addition of the beryllium reflector was estimated by extrapolating from the experimental value of stacking beryllium along two sides of the hexagonal core of the TRA-I.
2. The heterogeneity effect on leakage was estimated by correcting the calculated value of reactivity for the TRA-II by the ratio of observed to calculated values for the TRA-I.

When the TRA-II was made critical, the observed reactivity was within about 3 per cent of that calculated in the above manner.

It is felt that the uranium requirement of HTRE Core A can be extrapolated from the TRA-II with a very small error for the following reasons:

1. One of the major uncertainties in extrapolating from the TRA-I to the TRA-II was the effect of the beryllium. The TRA-II incorporates the exact beryllium geometry that is designed for HTRE Core A.

*K-343, Beck et al, Critical Mass Studies, Part III

†AERE-T/R 103 – "The Effect of Holes in a Reacting Material on the Passage of Neutrons, with Special Reference to the Critical Dimensions of a Reactor," D. J. Behrens, Feb. 1949.

2. The single discrepancy remaining between the two is the fact that the TRA-II has an appreciable amount of Teflon present in its fuel elements and there are small departures in fuel element geometry. The calculated effects of the Teflon and of the fuel element geometry are very small. Experiments are planned which will measure these effects.

3. The reactivity of the TRA-II assembly (loaded with 60 pounds of enriched uranium) is 1.026. The reactivity required for the HTRE Core A is 1.05. Consequently only a small extrapolation will be needed in going from the TRA-II to the HTRE Core A.

Errors of the order of 0.02 in reactivity in estimating the uranium requirement can be tolerated without seriously interfering with the operation of the reactor. This can be seen in Fig. 21.

The fuel elements will be manufactured so as to contain sufficient uranium to provide a calculated excess reactivity of 0.05 in a clean reactor with a hot moderator.* The control rods have sufficient capacity to control 0.09 in reactivity. Thus, if the criticality calculations are exactly correct, the reactor will go critical with control rods worth 0.04 in reactivity withdrawn from the reactor and rods worth 0.05 remaining in the reactor. However, if the uranium requirement has been underestimated to the extent of 0.02 in reactivity, the reactor will go critical with control rods worth 0.06 withdrawn from the reactor and rods worth 0.03 remaining in the reactor. Since 0.03 in reactivity is needed to compensate for fission product poisoning and depletion, this disposition of control rods will allow full life operation of the reactor. On the other hand, if the uranium requirement has been overestimated to the extent of 0.02 in reactivity, the reactor will go critical with control rods worth 0.02 withdrawn from the reactor and rods worth 0.07 remaining in the reactor. Since a scram potential of 0.02 is considered to be an adequate safety margin, this disposition of the control rods is also acceptable. Should no error be realized, the leeway becomes available for additional safety margin and for unanticipated operating effects (eg, a large fuel element temperature reactivity change).

Nuclear measurements in the TRA-II mockup are not complete, so that it may be expected that the numerical values quoted above will be modified somewhat, although the principles involved should be left unchanged.

Temperature Effects

There are two temperatures which affect the reactivity of the HTRE Core A reactor; the moderator temperature and the fuel element temperature. The moderator and fuel elements are loosely coupled thermally in that the moderator receives heat principally through the absorption of gamma and neutron energy whereas the fuel elements are heated directly by the fission fragments. Furthermore, the fuel elements and moderator are separately cooled so that the two temperatures are to a large extent independent. Consequently it is convenient to separately consider a moderator temperature coefficient and a fuel element temperature coefficient.

Few data are available upon which to base estimates of the fuel element temperature coefficient. Based on work which has been done at KAPL, it is presently thought that the fuel element temperature coefficient of the HTRE Core A reactor will be small and negative. No experimental information is available on which numbers can be based. Measurements are planned which will determine directly the value of this coefficient after HTRE Core A is in operation in Idaho.

There are two principal physical effects on the reactivity when the temperature of the water moderator is raised. The first is the increase in fast neutron leakage with the de-

*See section on temperature effects.

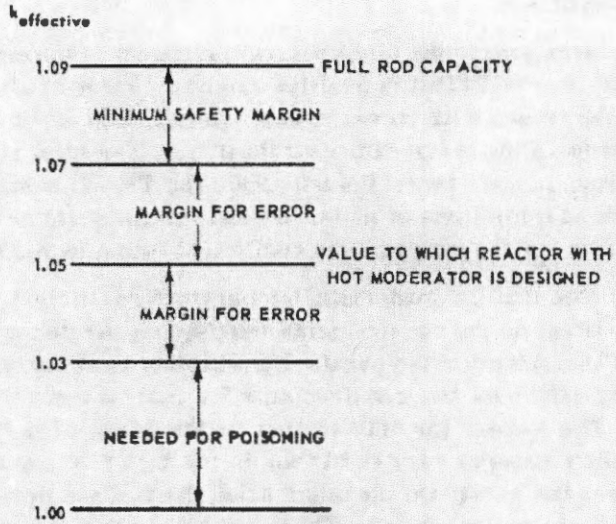

Fig. 21 - Graphic representation of reactivity range

crease in water density accompanying the increase in temperature; this is the negative component. The second is a decrease in the thermal disadvantage factor which is due primarily to the increase in the thermal base; this is the positive component since it increases the thermal utilization. As the temperature is raised from 70°F, the decrease in reactivity due to increased leakage starts off quite slowly but then begins to increase in magnitude in about the same way as the magnitude of the water density changes. On the other hand, the increase in reactivity due to the increase in thermal utilization falls off somewhat with increasing temperature. Near room temperature, the increase due to the rise in thermal utilization predominates with the result that the reactivity first rises with increasing temperature. However, the leakage effect, changing more rapidly, catches up; and beyond a certain temperature the reactivity will start falling, resulting in a negative temperature coefficient.

Preliminary measurements of the temperature coefficient of the moderator in the TRA-II mockup indicate that the coefficient is positive and has a value of about 1.8×10^{-4} per °F at 70°F and that it decreases with increase in temperature to about 1.3×10^{-4} per °F at 150°F, the expected operating temperature for the HTRE. The total reactivity change from 70°F to 150°F is about 1.2 per cent. Unfortunately the TRA-II mockup cannot be heated beyond 150° because of limitations of materials and instrumentation so that it could not be determined whether or not the temperature coefficient becomes negative.

It is important to note that the moderator temperature coefficient, whether positive or negative, has little effect on the requirements imposed on the design of the dynamic control rod system. The moderator temperature coefficient is of design importance principally because of its effect on the requirements for control capacity in the form of slow moving shim rods. The reason for this is that in the event of a reactivity change, the moderator temperature changes very slowly due to the high heat capacity of the water and the low heat input into the water. On the other hand, the fuel elements have low heat capacity but contain most of the fission heat. The net result is that even if the moderator temperature coefficient is negative, a fast change in reactivity, if sufficiently large, may result in undesirably high temperatures in the fuel elements. Simulator studies have confirmed this with assumed temperature coefficients of plus and minus 2×10^{-4} $\Delta k/k$ per °F. The negative temperature coefficient of the moderator was not of appreciable help in limiting the fuel element temperature immediately after the change in reactivity. Conversely, a positive moderator coefficient did not appreciably increase the immediate fuel element temperature excursion. Consequently the dynamic control rod system must be designed to prevent undesirable fuel element temperature excursions whether the moderator temperature coefficient is positive or negative. In practice, this requirement has not presented a difficult controls design problem.

Specific numbers which more clearly demonstrate the effect of heat capacity are given below. Calculations which were used in the design of the reactor have shown that approximately 9.2 per cent of the total power is delivered to the moderator. The total mass of water in the reactor core structure is 3600 pounds, with a heat capacity of 3600 Btu-°F^{-1}. The total mass of fuel and associated nichrome in the reactor is approximately 440 pounds, with a heat capacity of 62 Btu-°F^{-1}. It is thus seen, with the above division of heat capacity and power, that if one were to assume all power went into raising the temperature of both moderator and fuel (no cooling of fuel or moderator), the fuel temperature would rise 570°F for every 1°F temperature rise in the water. (Such a temperature rise would not be expected in operation since the fuel elements are being continuously cooled.) Based on a total power of about 18000 Btu-sec^{-1}, it is seen that with no cooling, the maximum rate of rise of the moderator temperature would be roughly 0.5 °F-sec^{-1} at full power. Even if the fuel element temperature coefficient were between 10 and 100 times smaller than the

moderator coefficient, the more rapid rate of temperature rise in the fuel could easily make the fuel element temperature the governing factor.

Power Distributions and Thermodynamic Characteristics

While a nuclear reactor can in principle deliver an unlimited amount of power, the practical limit on the power which can be extracted from a reactor of given size is imposed by the ability to remove heat. Heat removal is limited by the maximum temperature at which fuel elements can be operated, or, more specifically, by the maximum temperature difference which can be maintained between the fuel elements and the coolant, namely air. Since in the air cycle, pressure losses also impose a limitation on performance, it is desirable to keep the fuel element area to a minimum. The resulting optimum configuration is thus one in which the fuel elements are all operated at a uniform temperature, namely the maximum possible temperature.

In order to achieve such a design there are three nuclear power distributions which must be compensated for:

1. The longitudinal power distribution
2. The gross radial power distribution, namely the variation of average power from tube to tube in the transverse plane
3. The fine radial power distribution, the variation of power per unit mass of fuel due to self shielding within a single fuel tube

In the design of the HTRE Core A reactor, these three effects are compensated for in the following manner:

1. The fuel elements are divided into 18 stages for purposes of structural integrity; these 18 stages are, in turn, divided into three sections of six stages each. Each section has a different total heat transfer area per stage, the section in the entrance region having the smallest area since, assuming the fuel elements are operated at or near their maximum temperature, the available temperature difference between fuel element and air is high near the core inlet, allowing high heat transfer per unit area.

2. The gross radial power is equalized from tube to tube by varying the spacing of the tubes. Near the outside of the reactor, where the power would normally be low, the tube spacing is increased, thus associating more moderator with each tube and equalizing the thermal flux within the tube. The beryllium reflector is also important in maintaining a sufficiently high flux in the outer tubes.

3. The fine radial power distribution within each tube is compensated for by making the fuel sheets thicker near the center of the tube. Thus, the fuel mass per unit heat transfer area is increased in proportion to the decrease in power per unit mass of fuel which is imposed by self shielding.

An important feature of the above methods of power compensation is that all fuel cartridges may be designed to be identical. This greatly simplifies fabrication. Such simplification would not be possible if, for instance, the gross radial power distribution were compensated for by increasing the fuel loading in the outer tubes.

The fuel element heat transfer area is designed for a nominal maximum element temperature of 1700°F assuming that the temperature of the discharge air is 1450°F. The term nominal means that if all the elements were at the same temperature this combination of fuel element temperature and air temperature would be achieved. There are, in practice, some departures from this condition due to power maldistributions.

Experimental work on the power distributions in the TRA-II critical mockup has indicated that the desired gross radial power distribution has been effectively achieved. The ratio of peak to average power from tube to tube has been estimated at 1.075; this experimental work is not yet completed. The degree of power flattening achieved within the fuel tubes is limited by manufacturing tolerances to maldistributions of not over about 10 per cent. In practice, therefore, local temperatures may be in the neighborhood of 1900°F. Single plate irradiation tests indicate that Nichrome V has satisfactory oxidation resistance at this temperature. Since the temperature limitation is imposed by oxidation resistance over a long period of time, transient temperatures considerably higher can be tolerated. It is presently contemplated that sufficient temperature instrumentation will be available so that the expected hottest portions of the fuel elements may be well instrumented.

1.44 CONTROL SYSTEM

General Description

The purpose of the HTRE is to demonstrate the feasibility of using a direct air cycle reactor in place of a chemical combustion chamber, not to determine the maximum performance of the cycle. For this reason, a simplified, flexible control system has been selected rather than a more complex high-performance system of a type that may be installed in future aircraft.

In the simplified HTRE control system, the engine controls are separate from the reactor controls. Engines are controlled separately from the reactor and the engine and reactor control panels are attended by different operators. The only links between reactor and engine control systems are a few safety interlocks operated from engine overspeed and loss of airflow when an engine is being shut down. Both of these conditions can scram the reactor.

Both of the X39 engines may be controlled either manually or automatically and separately from each other. Manual operation is selected by placing the temperature and speed transfer switches in the manual positions. The attending operator then controls the speed of the engine and temperature at the tailcone by observing appropriate indicators and manually controlling nozzle area and fuel flow, respectively. When the speed and temperature transfer switches are placed in the automatic position, the attending operator merely selects the desired temperature and speed within the operating region, and the speed and temperature regulators held the selected values.

The general control procedure in testing the reactor is as follows. One of the engines is put into operation so that its air flows through the reactor. The second engine can stand by in an idling condition, if desired. The engine is placed on automatic temperature and speed control, and a suitable operating point is selected in the operating region. For convenience, let us say this operating point is an engine speed of 6500 rpm and a tailpipe temperature of 1000°F. The reactor is then checked out and started up. After the reactor power level is brought up to the power range (1% of full power), appreciable heat is transferred to the air. As the reactor power level is increased, the engine temperature control meters down the fuel flow to its unit combustor to maintain the 1000°F tailpipe temperature. Eventually, as the power level of the reactor is increased, a point is reached at which the fuel flow is metered down to the minimum sufficient to maintain flame propagation. At this transition point a solenoid valve closes, and the fuel lines are air purged so that the unit combustor is completely cut off. At the same instant the temperature reference is reduced 100°F to prevent instability in this region. The engine is now operating on nuclear power without direct temperature control but with speed control. The pro-

cedure outlined above is carried out in reverse when returning to chemical power. A block diagram of the entire control system is given in Figure 22. Figure 23 is a layout of the reactor control panel.

Summaries of the important features of the engine and reactor control systems are given in the following sections. A more complete description of the reactor controls is given in the appendix.

Engine Control Characteristics

The control characteristics of the X39 turbojet engines are described below with respect to single-engine operation and two-engine operation.

1. Single Engine Operation

Stable control of the engines has been demonstrated in all areas of operation to be utilized in the test of HTRE Core A.

Tailcone temperature of the engine is independently and automatically controlled at any point in the operating range with an accuracy of 1 per cent.

The speed of each engine is independently and automatically controlled at any point between 5500 and 7950 rpm with an accuracy of 0.5 per cent.

Manual control of jet nozzle area and fuel flow has been provided.

Switching between manual and automatic control of temperature and speed does not introduce serious transients into the system.

A safe means of checking fuel flow and ignition has been provided.

When the fuel flow has been reduced to its lowest permissible value, the solenoid valve closes and the fuel lines are purged.

Position indicators are provided for determining jet nozzle position and fuel control valve position.

Engine speeds in excess of 8200 rpm shut the engines down and scram the reactor. Power failure of 28-volt supply will automatically shut the engines down.

2. Two Engine Operation*

Each engine may be independently started and placed in parallel operation while in manual control.

Control of paralleled engines may be manual or automatic at the selection of the operator. Operating speed and tailpipe temperature for each engine are selected by the operator when in automatic operation.

In manual or automatic operation on chemical power over-temperatures will result in reduction of fuel flow to the defective engine. In operation on nuclear power, over-temperatures will scram the reactor, and blowers will provide afterheat cooling.

The transfer from chemical power to nuclear power is a stable operation when engines are operated by automatic control. This operation has been demonstrated by use of a common combustor substituted for a reactor.

By-pass valves are provided to isolate an engine from the reactor during startup.

*Parallel operation is not, at present, planned in testing HTRE Core A. However, the second engine can stand by in an idling condition.

Important Features of the Reactor Control System

The following is a summary of important factors which form the basis of the reactor control system.

Each shim-scram rod is driven by its own motor and is mechanically separate and independent of all other units.

All rods which comprise a frame of rods are ganged electrically so that all rods of a frame are synchronized. If one rod lags in position, additional torque is provided by increasing the excitation to its drive motor.

Failure of any rod or its actuator will not prevent normal operation of the remaining rods in a frame.

Each shim-scram rod is spring loaded and is always a potential scram rod.

The dynamic rod position determines whether the shim-scram rods can be withdrawn regardless of whether the transfer switch is in manual or automatic. This condition is included in the withdraw interlocks.

All withdraw interlocks must be closed before shim-scram rods can be withdrawn. These interlocks remain intact throughout the operating range.

Normal control requires that the shim frames operate in sequence. This operation requires that one frame of rods be driven against its limits before the next frame can operate. This sequence is strictly enforced when the shim rod auto-manual transfer switch is placed on Automatic.

For each frame of rods there is a bypass which would normally not be used unless the sequencing circuit involving the frame failed. This provision is also useful to set a desired frame of rods in a fixed position while operating the other frames in sequence.

An auto-manual transfer switch is provided so that shim-scram rods may be controlled either automatically or manually when the power level is greater than 10^{-5} N. In the automatic position the dynamic rod servo controls the motion of the shim-scram rods in such a way as to maintain the dynamic rods in the neutral position band. When the transfer switch is placed in the manual position, the operator controls the shim-scram rod position but cannot withdraw them if the dynamic rod is on the insert side of the neutral position band and unless all withdraw interlocks are closed.

There is a frame selector switch provided so that a given frame of rods may be selected for manual control, and one additional switch position is provided for manual operations of shim frames in sequence. This selector switch is bypassed when the transfer switch is placed on Automatic.

Individual positioning of shim-scram rods is provided. No restriction is placed on the time this control can be used except the usual withdraw interlocks. Position of selected rods can be controlled only by the reactor operator although rod selection is accomplished by another person at the shim rod monitor panel.

Manual insertion of the shim-scram rods is provided in all ranges of operation. The operator may manually insert all rods simultaneously or by frames in sequence.

Automatic operation of the shim-scram rods is prevented below 10^{-5} times full power.

The dynamic servo loop is in operation at all times. Normally the operator has no control over the dynamic rods. The servo alone governs the position of these rods.

A manual control for the dynamic rods is provided for initial startup.

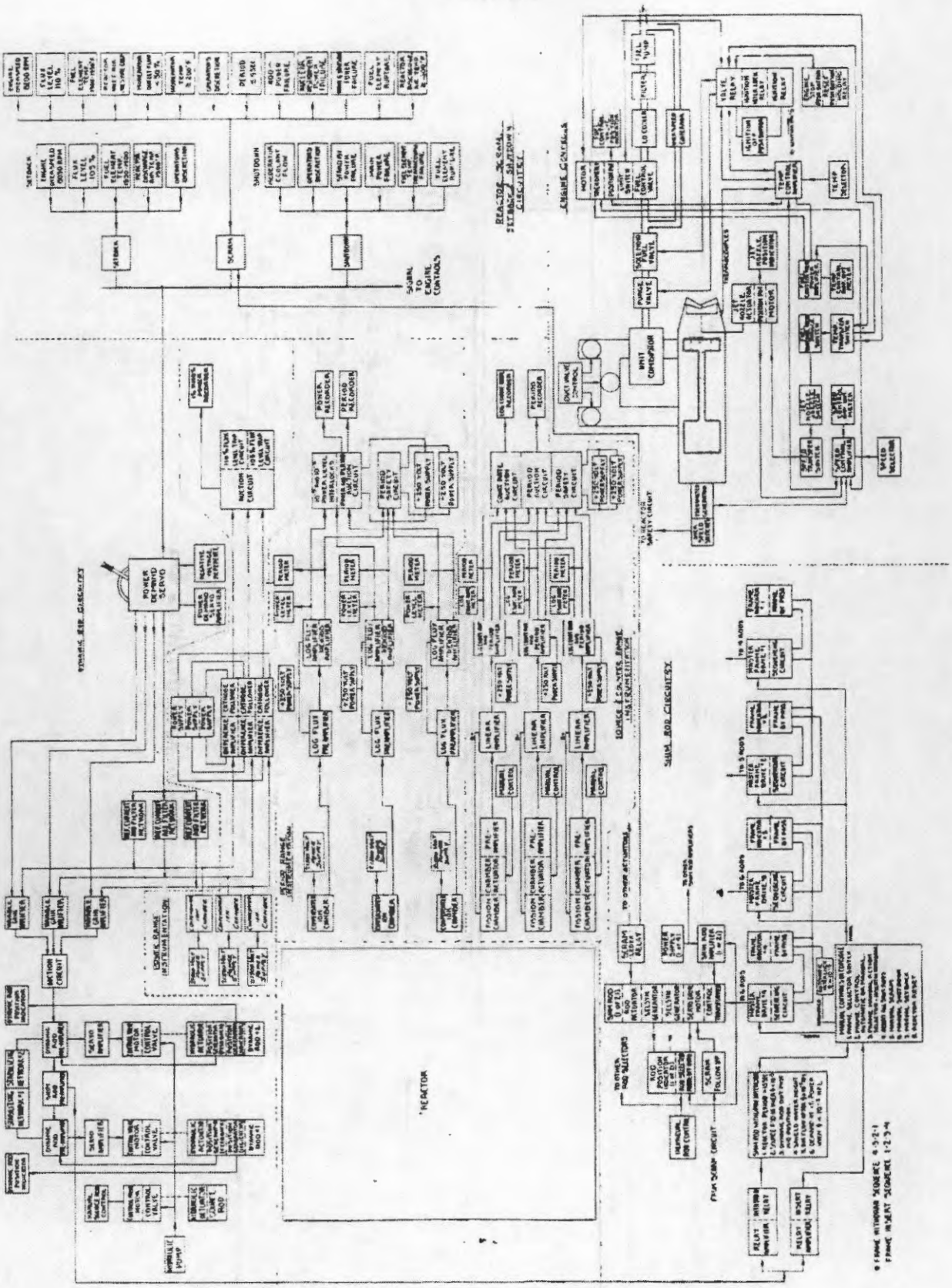

Fig. 22 - HTRE control system

SECRET

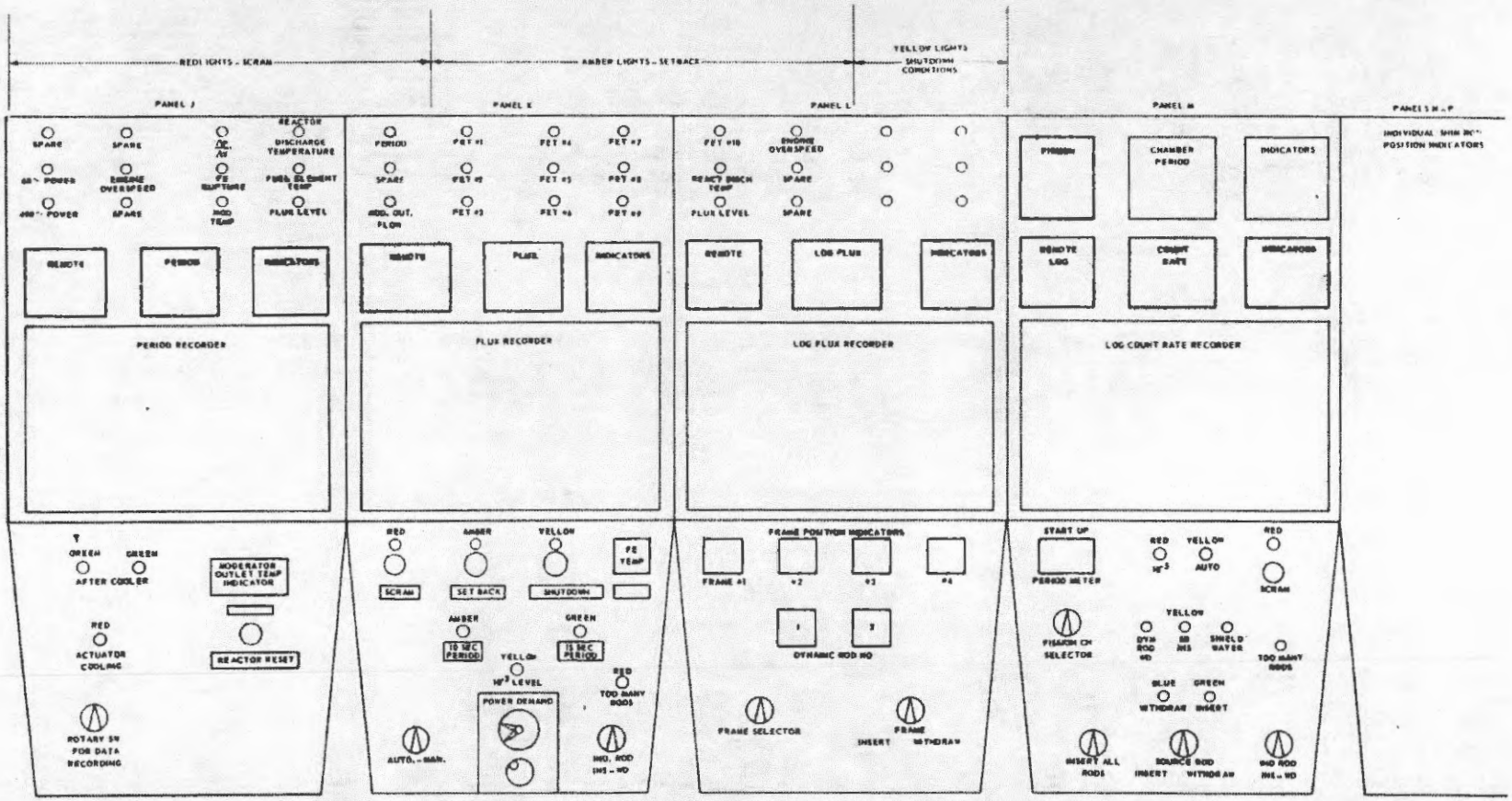

Fig. 23 - Control panels for HTRE Reactor

SECRET

The dynamic rod servo is capable of regulating the power level within a two-decade range from 1 to 100 per cent N. The demand potentiometer is calibrated linearly from 1 to 100 per cent.

A triplicate of all nuclear sensors, ie, ion chambers and fission chambers, is provided so that operation may continue on remaining channels should any one channel fail. Three fission chambers in the top plug supply startup instrument signals; three gamma compensated chambers, located in the CTF, supply period range signals; and three linear chambers supply the power range signals to both the servo and safety-trip power level. Essential units in these channels are designed for fail-safe operation.

The source rod is manually controlled at all times by direct excitation of the pilot valve motor.

Each physical condition that initiates a scram energizes a red light on the annunciator panel until the operator acknowledges by pressing the reset switch.

Each shim rod has a position read-out to 0.01 inch and the dynamic rod to 0.1 inch.

Indicating lights are used to determine when rods are fully withdrawn, inserted, or in a scram condition.

Three corrective measures are provided to prevent a hazardous accident. An automatic shutdown prevents continued operation when certain components, which are necessary only as a standby or as secondary units, are not operating. A power setback is provided when the reactor is approaching unsafe operation, and a scram is provided when the reactor enters an unsafe operating region.

Stack gas activity is monitored but does not automatically scram the reactor. Under these conditions, the reactor is manually shut down or manually scrammed depending on the level of the activity. Airflow must continue to supply afterheat cooling even though engines are shut down.

Whenever the reactor is scrammed, the engines also shut down as a safety measure.

The auxiliary air supply is available for afterheat cooling and is running whenever the power plant is operating. During a scram, airflow from blowers is admitted via pressure-sensor-operated valves.

Numerical values for the control rods are given in Section 1.45 (Table 1). A diagram showing a plan view of the control rod actuator positions is given in the appendix (Figure 44).

Power Plant Operating Procedure - The operating procedure for the HTRE must include the procedures for several different types of operations:

Operation on chemical power only
- Engine startup
- Power operation
- Operating during abnormal conditions
- Shutdown

Operation on nuclear power
- Engine startup
- Reactor startup
- Transfer of power from chemical to nuclear
- Power operation
- Operation during abnormal conditions
- Shutdown

Operation on Chemical Power Only - Before engine startup, a complete check of the operation of the control system will be made. The duct valves to the reactor will be closed and the bypass duct valve opened. The variable area exhaust nozzle will be completely open. The starting motor will be energized and the turbojet brought up to idling speed using manual control of the fuel valve. After adjusting the speed and temperature settings of the automatic control to those existing under manual operation, the system may be transferred to automatic operation.

After the turbojet has been started, the duct valves to the reactor may be opened and the bypass valve closed to force all air through the reactor.

The speed and/or temperature of the turbojet may be changed by adjusting the automatic control. The temperature and speed controls establish the desired operating point within the regulating limits given previously.

Prevention of overspeed is very important in the operation of turbojets, and for a set speed slightly above the 100 per cent rpm value the fuel flow to the engine will be reduced. At a set value above the rated speed, the fuel flow to the engine is completely cut off.

The responsibility of avoiding compressor stall lies with the operator as no means are provided for stall detection or automatic prevention. Rapid acceleration is unnecessary, and operator caution is relied upon to keep the engine out of stall conditions.

Speed and temperature may be set independently, so it is possible to select an engine speed that is too high to be compatible with the selected temperature. Under such conditions, the exhaust nozzle will be wide open, but the engine speed will still be below the selected value. It is also possible to select an engine speed which is too low for the selected temperature. In this case, the exhaust nozzle would be completely closed, but the engine speed would still be above the selected value.

Normal shutdown will require that both the speed and temperature automatic controls be set at the lowest values at which the engine can idle. The automatic control should then be switched to manual operation, and the fuel flow can be completely stopped.

Operation on Nuclear Power - Engine startup will be identical to that used for operation on chemical power only.

Before the reactor is started, the system will be thoroughly checked to insure that it will operate properly. Shim rod withdraw interlocks are provided to prevent shim rod withdrawal and reactor startup until the proper startup conditions exist. The dynamic rods are withdrawn as soon as the main loop is turned on and the shutdown or scram reset switch is depressed. In order to check the scram circuit, several shim rods in frame are withdrawn and scrammed. These shim rods are then withdrawn manually. The flux level gradually builds up as the shim rods are withdrawn. The reactor is tested for criticality by rapidly moving the source and noticing the effect on the flux level. If the flux level continues to decrease after source position change, the reactor is subcritical; if it increases, the reactor is critical and the source may be removed from the core. As the flux level increases, the period meter begins to give steady indications of reactor period; and at 10^{-5} of the flux at full power, the control of the shim rods may be transferred to automatic operation. An interlock prevents further withdrawal of the shim rods in both the manual and automatic position unless air from the operating turbojet is passing through the reactor.

Automatic operation of the shim rods increases the power level from 10^{-5} to 10^{-2} times full power with a reactor period of 10 to 15 seconds. As the power approaches 10^{-2} times full power, the dynamic rods begin to insert and maintain the power at this value. The

dynamic rods are positioned by a servo system which operates from ion chambers in the shield plug. The reactor power as shown by the ion chambers is compared with the demand power, and the resultant error signal is used to reposition the dynamic rods. The shim rods are automatically withdrawn or inserted to keep the dynamic rods within their neutral position band at their central position in the reactor core. The power level is raised from 10^{-2} to full power by changing the master demand potentiometer which calls for withdrawal of the dynamic rods.

When desired, the power may be raised from 10^{-5} to full power by manual withdrawal of the shim rods. When going above 10^{-2} times full power, it is impossible to raise the power above that called for by the master demand potentiometer because of the interlock which prevents withdrawal of the shim rods when the dynamic rods are inserted beyond their central position.

In order for the reactor to supply part of the power to the turbojet, the reactor power is increased. As the power is increased, the temperature of the air flowing through the reactor is increased and the chemical fuel to the engine is reduced to keep the tailcone temperature constant at the preset value. As more power is added to the air by increasing the reactor power, the chemical fuel is reduced to the minimum required to maintain flame propagation. The solenoid valve shuts off the burner, and insertion of a bias in the temperature reference for the fuel valve position prevents instability about the transition point.

After the engine is entirely on nuclear power, the tailcone temperature loop loses its effectiveness in maintaining constant tailcone temperature. As the flux level increases, the temperature increases; but the engine operates at constant speed. There is a limited range over which the reactor power may be increased without driving the exhaust nozzle against its open limits.

The temperature of the fuel elements may be lowered by increasing the airflow through the reactor. This is done by increasing the speed of the turbojet. Regulation of the nuclear power and the engine speed on a predetermined schedule will make possible a variety of test conditions.

The reactor safety system has been designed to prevent dangerous conditions or damage to the reactor. Any minor malfunction will initiate a reactor setback while other more dangerous conditions will scram the reactor.

If a malfunction that increases the reactor power above the designed maximum value occurs, the maximum allowable fuel element temperature will be exceeded before excessive turbine temperatures are registered. However, a slight overtemperature of the fuel elements as registered by a thermocouple attached directly to the fuel element will initiate a power setback of the reactor. If the temperature goes high enough, the reactor will scram. Any malfunction that lowers the airflow through the reactor will also cause the temperature of the fuel elements to increase.

The normal shutdown procedure is to reduce the reactor power to 1 per cent by means of the master demand potentiometer, and then complete the shutdown by depressing the automatic shutdown switch. This calls for the insertion of the dynamic rods and the sequence insertion of the shim rods. As the reactor power is reduced, the turbojet is transferred from nuclear to chemical power so that when the reactor is shut down, the turbojet is entirely on chemical power. The turbojet can then be shut down and the reactor cooled by means of the auxiliary aftercooling units.

1.45 SUMMARY OF PHYSICAL DESIGN AND DESIGN CHARACTERISTICS OF THE REACTOR

Table 1 lists the major physical, nuclear, and thermodynamic characteristics of Core A. These figures are current, and some changes may be expected in those portions likely to be affected by data from the MTR, burner rig testing, flow (air and water) testing, and critical experiments.

TABLE 1

HTRE CORE A SPECIFICATIONS AND DESIGN DATA

Core Components	
Fuel Tubes	
Number of tubes	37
Length	55.00 in.
Material	Aluminum (61S-T6)
Outside diameter	4 in.
Wall thickness	0.080 in.
Control Rod Guide Tubes	
Number of tubes	24
Material	Aluminum (61S-T6)
Length	90.50 in.
Outside diameter in core and plenum	1.25 in.
Outside diameter in transition	1.75 in.
Wall thickness in core and plenum	0.083 in.
Core Water Exit Tubes	
Number of tubes	6
Material	Aluminum (61S-T6)
Outside diameter	2.75 in.
Wall thickness	0.250 in.
Tube Sheets and Outer Shell	
Tube sheet material	Aluminum (61S-T6)
Tube sheet thickness (max)	1.25 in.
Tube sheet thickness at fuel tubes (top)	1.00 in.
Tube sheet thickness at fuel tubes (bottom)	0.88 in.
Tube sheet outside diameter	59.00 in.
Tolerance on hole location	0.005 in. of true position
Pressure shell material	Aluminum (61S-T6)
Pressure shell thickness	0.625 in.
Insulation	
Fuel tube insulation material	Thermoflex RF-1200 GE Spec A50T 2000 B-55
Fuel tube insulation thickness (compressed)	0.1 in.
Fuel tube insulation cover material	310 stainless steel AMS 5521
Fuel tube insulation cover thickness	0.010 inch, rigidized
Exit tube sheet insulation material	Refrasil, 14 lb per cu ft GE Spec A50T 2000 B-54
Exit tube sheet insulation thickness	0.25 in.
Exit tube sheet insulation cover material	310 stainless steel AMS 5521
Exit tube sheet insulation cover thickness	0.030 in., hot side

TABLE 1 (Cont.)

Reflector	
End	12.5 in. water-aluminum matrix
Side	4 in. beryllium
	12 in. water
Dimension across flats, inside	30.758 in.
Plug	
Maximum diameter	96.00 in.
Steel Upper Plug	
Diameter top section	96.00 in.
Diameter of midsection	88 in.
Diameter of lower section	76 in.
Total steel shield thickness	12.50 in.
Total plug height	67.750 in.
Steel plug height	52.750 in.
Aluminum Transition Section	
Diameter	63 in.
Wall thickness	0.750 in.
Material	Aluminum (61S-T6)
Height	15.00 in.
Method of attachment to steel plug	48 bolts and Flexitallic gasket
Over-all Dimensions and Weights	
Over-all height - core, plug, and actuators	206 in.
Actuator height	57.28 in.
Height of core and plug	148.75 in.
Active core length	29.125 in.
Over-all core length	55 in.
Over-all core diameter	59 in.
Active core diameter (across flats)	30.758 in.
Active core diameter (across corners)	34 in.
Total assembly weight (wet)	49,000 lb
Weight of core (dry)	2940 lb
Weight of plug, actuators, etc. (dry)	36,060 lb
Total weight (dry)	39,000 lb
Weight of core (wet)	6490 lb
Weight of plug, actuators, etc. (wet)	42,510 lb
Fuel Elements and Fuel Element Cartridges (Preliminary Design for A1a Reactor Assembly)	
Nose Assembly (ring assembly, 3 rings)	
Over-all length	14.31 in.
Maximum diameter	3.55 in.
Tail Assembly (5 rings and pull ring)	
Over-all length	12.735 in.
Pull ring OD	4.20 in.
Maximum diameter	3.52 in.

TABLE 1 (Cont.)

Fuel Assembly	
Active core length	29.125 in.
Method of support	4 rails on outside ribbons
Diameter of elements and rails	3.586 in.
Number of elements	18
Interstage spacing	0.125 in.
Fuel Elements	
Outside diameter	3.346 in.
Shape of elements	Concentric ribbons
Material of meat	UO_2 (93.4% enriched) and Nichrome V
Cladding material	Nichrome V
Cladding thickness (each side)	0.004 in.
Density of 40% UO_2 meat	9.32 gm-cm^{-3}
Density of 30% meat	9.11 gm-cm^{-3}
Maximum allowable temperature (Nichrome V)	2100°F
Maximum operating temperature (Nominal)	1700°F

	Stages 1-6	Stages 7-12	Stages 13-18
Number of ribbons	11	16	20
Spacing between ribbons	0.128 in.	0.083 in.	0.064 in.
Average ribbon thickness*	0.0165 in.	0.0138 in.	0.0129 in. 0.0127 in.†
Hydraulic diameter	0.252 in.	0.1632 in.	0.1233 in.
Specified heat transfer area (37 tubes per stage)	51.15 ft^2	70.0 ft^2	88.75 ft^2
Radius to inside of inside ribbon	0.197 in.	0.193 in.	0.188 in.

Control System

Absorber Rods	
Rod diameter (OD)	0.50 ± 0.05 in.
Steel wall thickness	0.049 - 0.052 in.
Boral diameter (OD)	0.398 - 0.401 in.
Length of absorber	30 in.
Composition of absorber	50% B_4C, 50% Al
Rod length (total)	80 in.

Shim-scram Actuators		
Number of shim-scram rods	Frame 1	4
	Frame 2	5
	Frame 3	6
	Frame 4	6
	Total	21
Penetration in active core		30 in.
Accuracy of positioning		0.01 in.
Maximum velocity of shim-scram rods on shim		1 ft/min
Scram time for shim-scram rods as scram rods		200 ms

*Based on 65 lb uranium (93.4%) total reactor loading.

†Assuming all ribbons contain a 40% mixture.

TABLE 1 (Cont.)

Dynamic Actuators	
Number	2
Penetration into active core	30 in.
Null position	15 in. inside core
Speed of response (30-inch movement)	750 ms
Accuracy of positioning	0.1 in.
Source Rod Actuator	
Number	1
Moderator System	
Heat release to moderator system	9.24% total power
Nuclear heating (7.5% total power)	1423 Btu/sec
Conduction from air stream	330 Btu/sec
Total	1753 Btu/sec
Nominal water flow rate	600 gpm
Water inlet temperature (plug)	150°F
Water exit temperature (plug)	180°F
Water inlet temperature (core face)	153°F
Water exit temperature (core face)	172°F
Flow velocity in control rod tubes	11 ft/sec
Flow velocity in core	0.6 ft/sec
Total system pressure drop	10 ± 2 psi
Water specifications	

Analysis	Grade A*	Grade B†
Total Solids	3 ppm max	8 ppm max
Al	0.02 ppm max	0.05 ppm max
Ca, Mg, Na	0.5 ppm max	2.0 ppm max
CO_2	1.0 ppm max	2.0 ppm max
SiO_2	0.5 ppm max	2.0 ppm max
Cl	0.1 ppm max	0.25 ppm max
SO_4	0.2 ppm max	0.5 ppm max
Cu	0.01 ppm max	0.025 ppm max
Fe, Ni, Co	0.05 ppm max	0.20 ppm max
B, Cd	0.02 ppm max	0.10 ppm max
pH	5.5-7.0	5.5-7.0
Specific Resistance at 75°F	750,000 ohm-cm, min.	100,000 ohm-cm, min.
pH Control	HNO_3	HNO_3

Thermodynamic Design Data	
Engine	One X39
Compressor pressure ratio	4.95
Altitude	5000 ft (NRTS)
Air weight flow	60.9 lb/sec

*Grade A designates a high purity water for use in apparatus subject to corrosion by water and designed for operation in water. Water should be used for final flushing and for charging of such units.

†Grade B designates an intermediate purity water which may be used for preliminary flushing operations on apparatus subject to corrosion by water and designed for operation in water.

TABLE 1 (Cont.)

Thermodynamic Design Data (Cont.)

Core inlet air temperature	386°F
Core inlet pressure	57.1 psia
Core exit temperature	1450°F
Core exit pressure	51 psia
Core inlet mass velocity in fuel elements	25.86 lb/ft^2/sec
Core exit mass velocity in fuel elements	27.01 lb/ft^2/sec
Max fuel element operating temperature (nominal)	1700°F
Total heat transfer area	1236 ft^2
Core inlet Mach number	0.092
Core exit Mach number	0.154
Frontal area for air and fuel elements	380.6 in^2
Core pressure drop	6.1 psi
Core pressure ratio	0.893
Reactor power to air	15950 Btu/sec
Total reactor power	17700 Btu/sec

Nuclear Data

Uranium inventory	70-80 lb
Average neutron fluxes	
Thermal: Water	3.64×10^{13} n/cm^2/sec
Fuel	8.68×10^{12} n/cm^2/sec
Ratio	4.20
Fast:	1.86×10^{14} n/cm^2/sec
Excess reactivity $\Delta k/k$	
Equilibrium xenon poisoning	2.3%
Maximum xenon poisoning	3.0%
Moderator temperature (150° to 70°F)	1.2%
Per cent thermal fissions	68.5%
End reflector savings	5.4 in.
Radial reflector savings	6.6 in.

Control system capacity:*

Position Ring Number	Number of Rod Positions in Ring	Value per Rod Position % k_{ex}	Value per Ring %
1	3	0.67	2.01
2	3	0.63	1.89
3	12	0.45	5.40
4	6	0.20	1.20
Totals	24		10.50

Core volume fractions:

Water	0.39
Aluminum and insulation equivalent	0.0607
Nichrome V	0.0516†
Uranium	0.005103†

*Position Rings numbered in order of increasing radius. Two dynamic rods located in Ring 3. Values are preliminary measurements in TRA-II assembly except for the value of position Ring 4, which has been extrapolated.

† Based on 80 lb of enriched uranium

TABLE 1 (Cont.)

Distribution of neutron and gamma heating among components
(Values are in per cent of total operating power)

Component	Neutron Moderation	Core Gamma	Extra-Core Gamma	Total
Core				
Water	1.88%	1.14%		3.02%
Aluminum		0.42		0.42
Uranium 235		0.89		0.89
Nichrome		1.45		1.45
Reflector				
Side 4 in. Be		1.20		1.20
10 in. H_2O	0.35	0.71		1.06
End				
Top	0.15	0.51	0.26%	0.92
Bottom	0.15	0.51	0.26	0.92
Core plug		0.05	0.04	0.09
Shield		0.74	0.04	0.78
Total	2.53%	7.62%	0.60%	10.75%

1.5 OPERATION OF THE REACTOR

1.51 IET ORGANIZATION

The operation of the power plant will be handled by a group of specially selected and trained people. At present people are being trained or have been trained at ORNL, the Hanford Works, and within ANPD in reactor and component operation.

Power Plant Test Personnel

Power Plant Test Supervisor - The power plant test supervisor has complete authority over the actions of all personnel, including visitors within the IET facility whether or not there is a test in progress. Any questions regarding the operation of facility equipment or power plant equipment will be referred to him for decision. He has personal responsibility for marking off the items on the check list. All emergency actions will be carried out under his direction. The test operations will be carried out under his direction.

Reactor Operation Engineers - Two men will operate the reactor portion of the console. Their responsibility includes startup, setting of special control rod configurations for test, monitoring the outputs of the nuclear sensors, and changing power level.

Engine Operations Engineers - Two men will operate the turbojet engine side of the console. Their responsibility is to start the engines, monitor their operation, change engine speed and temperature, and adjust them for transition to nuclear power.

Auxiliaries Operators - Two men will handle separate jobs and interchange at intervals. One will operate the periscope panel, open the remotely operated gate to allow the power plant and locomotive, or the latter alone, to enter the area, guide the locomotive in, check the coupling, maintain radio contact with the locomotive operator, manipulate the fire fog nozzles as required, and monitor operation of the power plant through the periscopes. The other man will fill the shield and moderator tanks on the facility, fill and drain the core and shield tank on the dolly, check out the dolly equipment, and monitor operation of it.

Instrument Technicians - Two instrument technicians from the instrumentation group will be assigned to the IET group to monitor the instruments and replace or repair parts in case of malfunction.

Health Physics Engineer - One man will be assigned to the IET facility to make air sampling measurements throughout the building, monitor weather recorders, stack activity, room radiation level, make other special radiation level measurements as may be required, and make recommendations as to operations.

Equipment Operators - Probably three men will be required to put into operation and monitor the operation of the steam boiler heating units; air conditioning fans, pumps, and compressors; diesel-electric generator; air compressor; motor-generator sets; and demineralizer.

Other personnel will be in the IET facility during operation. One or more members of the test program and analysis group will be taking and computing test data in the instrument room.

1.52 CHECK LIST - PRIOR TO STARTUP

A. During Shutdown

1. Key Switch prevents power from being applied to reactor controls.
2. Key Switch prevents power from being supplied to System 44* pump.

B. Connecting power plants

1. Operate periscope through full swing
2. Open test building door (remote)
3. Open track gate (remote)
4. Couple dolly to coupling station (remote)
5. Decouple locomotive (remote)
6. Close track gate (remote)
7. Check dolly coupling (manually for HTRE)
8. Check engine coupling
9. Couple piping and wiring to plug (manual)
10. Adjust floodlights for best periscope view of power plant (manual for HTRE)
11. Check locking of all instrument plugs in dolly plug.

C. Prior to Startup

1. Check all stations of intercommunication system
2. Determine trend and status of weather
3. Heating and ventilating system on and space pressures to tolerance
4. Furnace oil tank level supply high
5. Boilers operating - steam pressure OK
6. Diesel fuel tank level supply high
7. Diesel generator operating on the line
8. Engine fuel tank level supply high
9. Engine lube oil level supply high
10. Instrument power on
11. Air compressor on
12. Air receiver pressure 200 psig
13. System 44 storage tank filled
14. System 44 storage tank above 60°F

*System 44 refers to the moderator

C. Prior to Startup (Cont.)

15. System 33* storage tank filled
16. System 33 storage tank above 60°F
17. System 55† operable
18. Supervisory circuits show continuity
19. Fire alarms operable.
20. Engine fuel pumps in fuel storage building - operating pressure OK
21. Sump pumps operable
22. Radio communication with locomotive and dispatcher's panel OK
23. All personnel inside building or at A & M area - guard gate closed
24. Power distribution panel selection for emergency operation
25. Argon flow to ionization chambers
26. Supply of argon on hand
27. All health physics instrumentation OK
28. Cock, withdraw, and re-cock all shim-scram rods by frames (withdrawal of one frame will not cause reactor to go critical)
29. All instrumentation operating

D. Dolly Systems

1. Switch on dolly power circuits
2. Switch on dolly panel power
3. Check operability of dolly auxiliary power plant
4. Check operability of dolly fans
5. Check operation of engine duct valves

E. Startup Filling

1. Facility system 33 valves closed
2. Switch on system 33 pump at auxiliaries instrument panel
3. Open fill valve on dolly systems panel
4. Monitor tank level indicator
5. Switch off system 33 pump at auxiliaries instrument panel
6. Close fill valve
7. Start system 33 circulation
8. Open systems 33 and 44 cooling water valve in equipment room
9. Set system 33 cooling water temperature controller
10. Facility system 44 valves closed
11. Monitor CRM
12. Switch on system 44 pump at auxiliaries instrument panel
13. Switch on system 44 pump at control console
14. Switch on system 44 pump at service room annex
15. Open fill valve in service room annex by hand
16. Monitor number of gallons in service room annex
17. Check dolly tank level
18. Shut off fill valve
19. Stop pump from control console
20. Stop pump from facility instrument panel
21. Start system 44 circulation
22. Set system 44 water temperature controller
23. Check operability of dolly system 44 auxiliary pumps

*System 33 is the shield water system

†System 55 is the demineralized water system

1.53 DUMMY TEST

Prior to loading the reactor with enriched fuel elements, the following test will be performed in addition to the regular check list.

Shield and Moderator System

1. Fill that part of system 44 that is on dolly.
2. Check circulation through facility and heating ability. Record data and calculate heat losses.
3. Check circulation through dolly system recording data.
4. Check emergency operation of dolly circulating system.
5. Check industrial water circuit operation and capacity.
6. Drain system back to facility.
7. Fill that part of system 33 that is on dolly.
8. Check circulation through facility and heating ability. Record data and calculate heat losses.
9. Check circulation through dolly system recording data.
10. Check operation of make-up.
11. Drain system to facility.
12. Check industrial water cooling capacity.

Reactor Controls and Instrumentation

1. Cock each shim-scram rod.
2. Run rods full travel, recording position
   a. Individually
   b. In frames
   c. Together
3. Scram rods.
4. Simulate signal for counting rate meter, flux, ln flux and period, noting set back and scram points.
5. Check scram for each cause; check set back for each cause, simulating signal in each case.
6. Check feedback of hash from dolly equipment to instrument power leads.
7. Operate source rod.

Engines

1. Check operation at several points on bypass.
2. Increase pressure drop and omit bypass.
3. Check pressures and temperatures throughout exhaust system at several extreme operating points.
4. Check dp/dt setback or scram.
5. Run two engines; get effect on exhaust system.
6. Check automatic-manual control.
7. Simulate stack activity during engine operation.
8. Check airflow interlock with flux.
9. Check time for aftercooling blower to reach full speed after No. 4.

1.54 METEOROLOGICAL CONTROL DURING OPERATION

Because possible radiation levels to personnel in the surrounding area can be very high in the event of a nuclear accident (see "Reactor Hazards" section), it will be necessary to restrict operating times to periods when the wind direction is not toward any nearby inhabited area and the dilution of the atmosphere is sufficiently high.

A study of the wind roses in conjunction with a map of the area indicates that operable weather conditions exist approximately 50 per cent of the time. The preferred wind

directions are from the south and southwest, which fortunately are the most prevalent wind direction Lapse conditions are preferred because of the greater atmospheric dilution which results, although some operation might be allowed with a mild inversion.

Meteorological control would not need to be as strict at startup as it would be later when the reactor has a quantity of fission products stored in it.

Recommendations as to suitability of the weather conditions will be provided by the USWB which will use its standard sources of weather information as well as the information supplied by the tower in the IET.

1.55 INITIAL STARTUP PROCEDURE

The initial startup of the HTRE will be performed in the traditional manner of making critical experiments, ie, fuel elements will be added in discrete steps, with all moderator water being removed before the addition of the next fuel elements. This is done in the interest of safety.

For the initial startup a frame will be used to support the core and plug assembly on a dolly of the same size as that which mounts the Core Test Facility. Only the nuclear instrumentation wiring, the control wiring, and the moderator pipes will be connected through the coupling station to the IET facility and its control console.

The following steps will be adhered to during this initial startup.

1. Practice loading the reactor and filling the core with water according to the procedure outlined below but with cartridges of dummy (ie, natural uranium filled) fuel elements.
2. Make a complete check of all connected instrumentation and equipment.
3. Determine the background level of the source in the core but without fuel elements.
4. Load the center seven fuel cartridges into the core, starting from the center. Fill the core with water and measure the multiplication with the shim-scram rods in and with the shim-scram rods out. Insert shim-scram rods and empty the water from the tank before the next addition of fuel cartridges. This insertion should be made by scramming the rods with the moderator in the reactor, thus checking the safety circuits.
5. Load an additional six fuel cartridges into the central region of the core, fill the latter with water, and measure the multiplication with the shim-scram rods in and out. Insert control rods and empty the water from the core.
6. Repeat step 5 adding 4 additional cartridges to establish a curve of inverse multiplication versus number of fuel cartridges.
7. Load additional fuel cartridges into the core in numbers such that the multiplication with shim-scram rods out extrapolated from the multiplication curves will not be more than twice the previous multiplication with the shim-scram rods out (within the limits of the smallest increment, one cartridge).
8. As criticality is approached, the source will be withdrawn and inserted to aid in determining whether a chain reaction exists.
9. If criticality is obtained at less than the full complement of fuel cartridges, an estimate of the safety margin available with all cartridges inserted can be made from the poisoning available in the shim-scram rods, using the control rod calibrations obtained during the Evendale critical experiments, and the measurements of reactivity of the individual fuel cartridges also obtained at Evendale. Thus, it can be estimated whether the reactor can be safely loaded with the full complement of cartridges.
10. When criticality has been established and an operating level of one watt is reached, the test will be shut down.

A normal startup of the complete power plant will be made in the following manner:*

1. The check list will be completed.
2. Start turbojet on bypass loop.
3. Bring engine up to approximately 6500 rpm on chemical power and reverse duct valve positions so compressor discharge air flows through reactor.
4. Insert source
5. Withdraw control rods until criticality is reached.
6. Manually maintain reactor on a 50-second period to 10^{-5} per cent power.
7. Manually maintain reactor on 15-second period up to 1 per cent power.
8. On automatic control of 15-second period bring reactor up to transition point, that is, the power at which the turbojet engine will sustain itself without chemical fuel.
9. Purge fuel nozzles of remaining fuel.
10. Set power plant at desired test conditions.

The normal shutdown of the power plant will be accomplished in the following manner:

1. Start dolly aftercooling blower.
2. Decrease reactor power to point below transition speed and start chemical combustion in engine.
3. Insert all rods (shut down button).
4. Maintain engine above idling speed after reactor is subcritical (for aftercooling).
5. Lock reactor control power off.
6. Shut down turbojet engine.

The filling of the reactor core with moderator during critical experiments will be accomplished with facility equipment according to the items mentioned in the check list and described below.

Prior to test, a 2000 gallon tank in the tank building will be filled with demineralized water. At the time the filling operation is to start, a power plant operator will be stationed at the reactor operating panel to monitor the count rate meter. Another man will be located in the service room annex, Room 116A, where the pump and flow meter are located. Before pumping starts, he will manually operate valves to bypass the output from the 100-gpm pump through a 1-inch pipe, a manual throttling valve, and a positive displacement integrating flow meter before it passes through the coupling station to the reactor core. To start this pump, three switches in series must be in the "on" position. The first is located on the auxiliaries instrument panel in the instrument room. The second is located on the control console near the count rate meter and the third is the lockout switch at the pump itself.

The procedure then is for the first switch to be thrown "on." By the intercommunication system the operator at the control console maintains contact with the man at the pump and flow meter. The second switch (at the control console) is thrown "on." The operator at the pump, having manually checked all valves, starts the pump and monitors the number of gallons which are pumped into the reactor. A previous calibration of the facility and reactor plug volume allows an accurate determination of the number of gallons that are in the core itself. The filling continues at a rate determined by the manually operated throttling valve until the system is filled. If, by some chance, the reactor should tend toward criticality, the pump can be shut off by the man watching the count rate meter. The second switch is located at the meter for that purpose. If the pump is not stopped after the reactor is full, the overflow passes out the drain pipe. After filling the reactor, shutting off the pump, and setting up the valves for normal operation, the man in the service room

*These are tentative plans. Some changes may be made later after more data are obtained from investigations now in progress.

annex returns to the auxiliaries instrument panel and dolly systems panel for monitoring operation during test.

After the critical experiments are complete, a modified filling procedure will be used. The valves in the service room annex will be set so that the moderator pump output of 100 gpm goes directly to the coupling station through a three inch pipe without bypassing through the flowmeter or throttling valve. The operator at the auxiliaries instrument panel controls the filling from that station and determines that the system is full by monitoring the surge tank level indicators on the panel.

1.56 PROGRAM OF EXPERIMENTS

On satisfactory completion of the critical experiment, the core will be moved to the assembly and maintenance building, mounted in the CTF, and returned to the IET facility for the Heat Transfer Reactor Experiment.

The information required from the HTRE is twofold.

1. To demonstrate the heat transfer ability of the direct air cycle reactor power plant
2. To demonstrate operation of a turbojet engine from a nuclear heat source

Essentially the experimental program will be divided into three parts: zero power tests (up to 10^{-5}%), low power tests (10^{-5} to 1%), and high power tests(1 to 100%).

Zero Power Tests

1. Criticality check
2. Radiation intensity
3. Qualitative controllability check
4. Power calibration of fission and ion chambers
5. Control rod calibration check
6. Water temperature coefficient of reactivity
7. Fuel element temperature coefficient of reactivity (preliminary check)

Low Power Tests

1. Quantitative controls test of reactor without engine
2. Shielding survey
3. Determination of power level of power plant from heat balance
4. Fuel element temperature coefficient

High Power Tests

1. Power plant control system response
2. Heat balance
3. Transitioning of engines from chemical to nuclear power and back
4. Fuel element heat transfer coefficient
5. Airflow distribution
6. Fuel element temperature distribution
7. Power plant performance characteristics
8. Fuel element and flux transients
9. Shielding check
10. Afterheat measurements
11. Xenon buildup characteristics.

1.57 EMERGENCIES

Emergencies Due to Failure of Equipment

Operation of the power plant is dependent upon proper operation of considerable facility equipment. In order to prevent an emergency from taking place, an alarm system is in-

stalled to provide notification that operation of the equipment is proceeding inside or outside of certain established limits.

Emergency conditions that exist in various parts of the IET building are summarized on an alarm panel in the control room. These conditions include improper air compressor operation, ventilating system room pressures not within prescribed limits, primary power failure, diesel generator failure, or presence of combustible gas. Indication as to the open or closed condition of the hatch door, ramp door, or blast door is also shown on this panel.

Following is a description of possible emergencies which can occur, and of the various facility warning and alarm systems.

Utility Electrical Power Failure - The utility electrical power system undergoes sporadic voltage dips and power interruptions. A diesel generator is installed in the facility to supply power during a test, assuming approximately half load. In the event of a voltage dip or power failure in the utility system, additional load is automatically thrown on the diesel generator. In this manner, all necessary equipment within the facility is kept operating.

When utility power is again available, one or more switches must be manually actuated to put the load back on the utility system. There are four main electric circuits. One circuit which includes welding receptacles, refrigeration pumps, test cell heaters, and a few building lights is permanently connected to the utility circuit. Stoppage of this equipment due to power failure has no effect on the operation of the facility. The three other circuits can be set either for continuous power from the diesel or for an automatic switch to diesel power if the utility power fails. Operation is planned with two of these circuits powered continuously by the diesel generator. Instrument power, lights, sump pumps, air exhausters, etc., are included. The other circuit will be on utility lines until a power failure, at which time it will automatically switch over to emergency diesel power.

A control panel mounted close to the diesel generator, besides giving indication of speed, temperatures, and pressures, has an alarm horn that indicates either low oil pressure, high water coolant temperature, or low fuel level.

If the facility diesel generator should fail, the reactor will scram and a diesel generator on the power plant dolly will supply power to the aftercooling blower.

Failure of X39 Engine - Except for power leakage (of the order of 10 per cent) by thermal conduction and absorption of gamma and neutron energy in the shield and moderator circuits, the primary means of dissipating the heat developed in the core is in operating an X39 engine.

Although this is a reliable engine, there is a possibility that it will fail. The dolly will have two engines completely installed, so that either engine can be run from the reactor heat. During power plant operation one engine will be on nuclear power, while the other will be running at idling speed on chemical power. If the engine on nuclear power fails, the reactor scrams (engine failure shows as loss of compressor discharge pressure). A blower mounted on the air inlet ducts forces air through the core to prevent overheating during aftercooling. Full blower capacity is reached in 8 seconds after the starting impulse is given. Calculations show that, with a normal engine coastdown, fuel element temperatures will not exceed 1750°F. Component tests show this is not dangerous to the fuel element. Two blowers are installed. Operation of only one is needed during HTRE No. 1. The engine which is kept at idling speed is available to provide aftercooling during emergencies.

In case of an engine failure in which the engine stops suddenly without coasting down, the reactor scrams and the dolly blower, as previously mentioned, would build up to full speed in 8 seconds. During that time the fuel element temperature will reach no higher than 2300°F.

Failure of Engine Fuel Supply - Engine fuel is pumped from a tank in the IET area to the engine. A fuel line from the tank in the administration area is an alternate fuel source. The failure of both supplies would be of no consequence during nuclear operation, but during aftercooling it would become necessary to use either or both the dolly blowers in place of the engines.

Failure of Dolly Moderator Pump - A duplicate pump connected in parallel is available as standby in event of failure of the moderator pump. A normal shutdown will take place after such an occurrence (as soon as the test point has been recorded). If both pumps were to fail during a power run, the reactor would set back and then scram due to excessive moderator temperature.

Failure of Facility Systems for Moderator or Shield Water - These pumps are used only for filling and draining and are not in use during power plant operation. Their failure would thus have no effect on the safety of the power plant.

Failure of Industrial Water Supply - Industrial water cools the moderator and shield water through a liquid-to-liquid heat exchanger. Upon interruption of the industrial water supply, the primary liquid temperature rises until power setback and scram occur.

Failure of Demineralized Water System - During a power plant operation, demineralized water is supplied as makeup to the moderator system. If this supply ceased, the drop in level in the tank would be noted and the test halted as soon as the data were taken for the point set at the time. No nuclear runaway would result if the tank level dropped. The shielding effectiveness of the tank however, would be reduced.

A green pilot light at the demineralizer indicates the effluent has a specific resistance of more than 100,000 ohms. When the resistance falls below that value, a red pilot light shows and a bell brings attention to this condition.

Failure of Facility Air Supply - A facility air compressor supplies air for starting the X39 engines and for operating the X39 bypass valves.

When malfunctioning of the compressor (high air discharge temperature and low or high oil pressure) is indicated, a horn sounds and lights appear on an alarm panel next to the air compressor. A button is provided on the panel to stop the compressor.

If failure occurs, however, there is no immediate effect on operation. However, an orderly shutdown will be made as soon as the data are taken for the test point in progress. There is a possibility that while shutting down and transferring to chemical power an engine might not make the transition. The air receiver has 275 cubic feet capacity of 200-psi air which is sufficient for the air starter to turn over the engine for one minute. Another engine and two aftercooling fans can be used for backup if the engine fails to restart.

Operation of the bypass valves will not normally be required while the power plant is being shut down. If an engine should fail at this moment, however, an air supply would be required for operating the bypass valves in order to put the other engine on stream. The air receiver has adequate storage capacity. If this capacity were not available, the dolly blowers could handle the afterheat at this point.

Remote shutoff valves which control the draining and filling of the core and shield are air-operated. Their inoperation due to lack of air supply does not contribute to a nuclear hazard.

Failure of Facility Heating System - Heat is supplied for the facility by two oil-fired steam boilers. Steam coils within the moderator and shield water tanks in the tank house maintain the temperature of the liquids above 60°F. During periods of shutdown freezing of the moderator and shield systems on the dolly is prevented by circulating through a heat exchanger in the facility which keeps the liquids above freezing. In the event of failure of one of these boilers, the capacity of the other boiler is adequate. In the event that this one failed also, the dolly system could be drained into the tank in the tank building to prevent freezing in the test cell. If for some reason the moderator and shield water in the CTF froze suddenly, no nuclear damage would result. Undoubtedly the moderator passages would fail. When the moderator again melted, leakage into the lower plenum chamber would result and the water would drain to a collection tank. A large amount of leakage would overflow the collection tank and drain outdoors.

The steam boilers will have a fuel level gate and steam pressure gauges to show proper operation. No special alarms are indicated or sounded due to malfunction of equipment.

A control panel for the three component parts of the heating and ventilating system is mounted on the aisle side of the building column in the heating and ventilating equipment area. In general, red and green lights indicate that compressors, fans, or pumps are not operating. High pressure in the equipment room is indicated by amber lights.

Leakage of Combustible Gas - In the event that a combustible gas should escape in the IET building, two combustible gas detectors are located in the service room and one in the coupling station. The building ventilating system would normally prevent a combustible mixture from accumulating. However, if such a mixture does form, this fact is indicated on a panel near the demineralizer. A horn sounds to attract attention to this fact.

Fire Alarm Systems - The building fire alarms are part of the over-all ANPD and NRTS system. Rate of rise detector systems in the fuel pump house (Building 625), the coupling station (Room 117, Building 620), and the service room (Room 116, Building 620) and a fixed temperature system in the electrical equipment room (Room 101A, Building 620) and the diesel room (Room 101, Building 620) sound audible alarms in the IET building and are recorded at ANP in service building 603 and gate house 601, and at Central Facilities Fire Headquarters Building 666 and Communications Building 668. Water flow is automatic except to the coupling station and service room, in which case it is turned on from the control room alarm panel. The latter event is also signalled to the locations mentioned above. The fog nozzles in the test building are not connected to the fire system network.

Unusual Emergencies

The facility equipment failures listed previously may be considered as "normal" emergencies. Backup equipment is available in each of these cases to relieve the emergency. However, emergencies other than those initiated by equipment failures must also be considered.

Uncontrolled Fire - Consider the case in which engine fuel leaks into the test cell and catches fire. If the water fog system were inoperable and the fuel could not be shut off, an uncontrolled fire would result. Since the floor is pitched toward open trench drains to the outside, no large amounts of fuel could accumulate. However, the fire could burn all power and instrument leads. Motors and valves would be damaged. The piping and tanks on the dolly are stainless steel and would not melt. On loss of electrical power the reactor will scram. Since the shim-scram rod actuating motor is two phase, shorting of wires will not cause withdrawal of the shim-scram rods. Heat from the fire might cause a faulty weld to break open. This could result in losing the shield water or moderator water, but a reactor runaway does not seem possible.

Turbojet Compressor or Turbine Failure - Due to overspeed, material faults, or lack of balance, compressor or turbine blading may fail and throw sections of the compressor or turbine outward. Instrument wires and pipes could be severed and tanks penetrated. As in the previous case, shield and moderator water could be spilled on the floor. The instrumentation would become inoperable and failure of shim-scram rod power would scram the reactor, but reactor afterheat can be sufficient to melt down the fuel elements so that they will then fall to the bottom of the cocoon.

Explosion - It is possible for jet fuel to vaporize within the tailcone so as to form an explosive mixture. Nevertheless, there has never been a case of an explosion at AGTD or at ANPD in an engine tailcone. If an explosion did occur, it should dissipate itself through the exhaust pipe, and if it were really severe, it would lift the explosion hatch in the exhaust pipe. If, by some means, the exhaust pipe were closed off so that an explosion occurred in the tailcone, it is possible that control, instrument, and pipe lines would fail. Although shield and moderator would leak out, there are no forces present to remove the control rods.

Earthquake - The damage that could be expected from an earthquake again would result in disruption of air, fuel, water, power, and instrument lines. The CTF would not topple over. Sharp tremors might jar loose the safety rods if the reactor had not already been scrammed.

Flood - Flooding the reactor is inconceivable due to the location and terrain. Water cannot be retained within the area of the test cell.

Personnel Errors - The only means of causing a reactor runaway seems to be by withdrawal of rods which would result in flux, log flux, and period trips when limits of the latter are reached. Three sensors are installed at all times, and operating rules will require that two of each be operating at all times or the power plant will be shut down.

Sabotage of the air supply equipment would be possible and could result in a meltdown of the reactor fuel elements.

1.58 SECURITY MEASURES

A 9-foot-high exclusion fence made of No. 9 wire woven in 2-inch mesh surrounds the IET Facility. Extension arms at the top of the fence carry three lines of four-point barbed wire. An astronomic time switch supplies power to a fence lighting system. Lamps of 6000 lumen are located on poles at intervals of approximately 125 feet.

There are two gates into this area; one is at the road entrance which is operated by a guard in the exclusion guard house, and the other gate stretches across the railroad tracks and is remotely operated from the periscope panels.

During power plant operation the exclusion guard house is untenantable. Before startup the guard closes and locks the gate and returns to the Administration Area. After that the only access to the IET facility is via the shielded locomotive and the special personnel hatch and tunnel.

Protection of the remotely-operated gate is supplied at all times by a supervisory signal which is recorded at the ANP Gatehouse Building (601) and the Central Facilities Communications Building (668). An open gate is indicated in the IET control room by a red light and a buzzer.

A watchman reporting system is also provided for use when the area is tenantable. Two electrical stations are provided, one in the exclusion guard house and the other at the ramp

door of the main control and equipment building. Signals from these stations are recorded at the ANP Gatehouse Building (601) and the Central Facilities Communications Building (668). Nine outdoor mechanical tour stations are also provided.

All persons legally entering the area must have been granted a prior special security clearance in addition to the normal "Q" clearance. An exchange badge system will be used at the main gate for those entering when no power plant is operating, and a similar arrangement has been made at the assembly and maintenance building for those entering via the locomotive during power plant operation.

1.59 HANDLING OF HTRE IN HOT SHOP

Removal of Reactor Assembly from CTF Tank

When it is necessary to examine or replace fuel elements in the core, the HTRE will be brought back to the hot shop. The control rod actuator hood and blowers are removed, all reactor instrumentation leads to the core are disconnected, and two sections of 6-inch pipe are removed. Then the 98 reactor-assembly-plug flange screws are removed. The above operations will be performed manually if possible, but they can be done with the remotely operated equipment if necessary.

The next step is to assemble the two halves of the core removal fixture and to bolt it in place. The core removal guide is then unlocked from the upper position and lowered and bolted to the reactor assembly. The 2-inch moderator lines are then connected, and the reactor assembly is raised with the 100-ton crane to the upper position in the fixture and locked in place.

The reactor-assembly plenum chamber is enclosed with two vacuum cleaner hoods and one of the vacuum cleaners is started and will continue to operate as long as fuel elements remain in the assembly. The other vacuum cleaner serves as a standby unit.

The upper section of the core removal fixture is unbolted from the lower section while the crane hook remains in the sling lifting eye. The reactor assembly and upper section of the removal fixture is lifted and fastened on pedestals on the turntable.

Removal of fuel elements will be done with a remotely operated machine which will go under the free end of the reactor, locate the fuel tube, insert a rod to release the fuel element, and withdraw the fuel element into a guide tube. The fuel element will then be transferred to the storage pool or to the special cubicle for examination. Storage in the pool will be in special racks to prevent accidental accumulation of a critical assembly.

Reassembly can be performed with this same equipment simply by reversing the above procedures.

Maintenance of reactor parts such as control rods, control rod actuators, and instrumentation is possible without removing the reactor from the core test facility. If a poison rod is to be removed from an active core containing moderator fluid, the source rod must be removed first and be replaced with a poison rod.

Other accessories such as the ducting and jet engines may be removed with remote handling equipment, although these operations will usually be performed manually. Reassembly of these parts is not possible with the remote handling equipment.

Disassembly and reassembly of the CTF tank components is possible with the remote handling equipment.

1.6 WASTE DISPOSAL

Gaseous wastes such as A^{41} and N^{16}, airborne solids, and erosion products from the reactor will be exhausted to the atmosphere through the exhaust stack. Radiation hazards associated with this procedure are discussed in a later section. Operation of the reactor will be subject to meteorological control to prevent these hazards from becoming too great.

Since the fuel element materials are not to be reprocessed at this installation, the only liquid wastes to be disposed of are minor amounts of contaminated liquids from the reactor moderator and shield, solutions used in the cleanup of contamination in the hot shop, and small amounts of chemical wastes from the inspection cubicle and laboratory. The contaminated fluids from the hot shop will be filtered to remove the particulate activity and, if the activity levels are too high for disposal to the water table, they will be concentrated in the waste evaporator in the hot shop building and then permanently stored. The same concentration procedure is available for wastes from the inspection cubicle and laboratories as well as the wastes at the IET which can be piped back to the hot shop.

Because of the nature of the water flow in the water table,* it is not possible to depend upon any significant dilution of radioactive liquid wastes that reach the water table. The only significant reduction in contamination arises from radioactive decay during their passage from the point of entry to the point where they may be removed from wells and springs. The estimated average rate of travel is 33 feet per day, but there may be local variations so that the recommended value for use in calculations is 330 feet per day. At this "fast" rate wastes introduced to the water table at the IET would reach the STR site in 272 days.

Radiochemical analyses will therefore be required for those mildly contaminated liquids which are above the MPC (maximum permissible concentrations) for drinking water and which are to be put into the water table. The analyses will have to be complete enough to identify the radioactive elements so that calculations can be made to determine the expected concentrations at a future time when these waste liquids will have travelled in the water table to a point where withdrawal and consumption is possible.

*Letter to L. E. Johnston from R. L. Nace with report on conclusions of a conference on NRTS waste problems.

2. HAZARDS

2.1 ANALYSIS OF RUNAWAYS

2.11 SUMMARY OF RESULTS

These calculations evaluate the events inside the reactor and determine what is ejected into the atmosphere as a result of a runaway in the HTRE Core A reactor. The methods of calculations, a comparison of various runaways, and a correlation of physical events causing runaways are discussed. Table 2 gives a summary of the results.

TABLE 2

SUMMARY OF RUNAWAY CALCULATIONS

	Step ($\Delta k/k$)	Maximum Core Pressure	Total Energy	Fission Fragments Created	Fission Fragments Ejected From Core
Maximum Accident	1.45%	100 atm	7.9×10^5 kw sec	5×10^{19}	7×10^{18}
Probable Maximum Sabotage	5.3%	3150 atm	3.52×10^6	2.25×10^{20}	2.25×10^{20}

2.12 METHODS OF CALCULATION

Above-prompt-critical runaways for the HTRE Core A reactors may be analyzed in three stages: (1) before fuel element vaporization, (2) the vaporization of fuel element leading to the shutting down of the reactor, and (3) the delayed-neutron-sustained after-reaction. The first stage is characterized by the power level of the reactor rising many decades from a low level (assumed one watt) to a level where the total energy generated has raised the temperature of the fuel elements to the point of vaporization (2732°C). The only effect on reactivity during this stage is the effect initiating the accident. Once the total energy generation has reached a certain point (2.5225×10^5 kw-sec), the fuel elements start vaporizing and the vapor pressure thus produced inside the reactor ejects most of the fuel element vapor into the atmosphere. This loss of fuel from the reactor decreases the reactivity and effects the shutdown of the runaway. The power level is reduced to a level at which the delayed neutrons can sustain it. In this subcritical condition, power generation gradually dies out.

The First Stage - Before Fuel Elements Vaporize

Each runaway is analyzed for a step change in reactivity with the delayed neutrons being lumped into one group. With no temperature coefficient an analytic solution for this case is obtained. The runaways are then analyzed assuming the contribution due to delayed neutrons is constant and that reactivity increases linearly. The runaway induced by the linear change in reactivity is then said to be equivalent to a runaway induced by a step change in reactivity when each has the same period at the start of vaporization of fuel elements. Thus,

it is possible to interpret the calculations in terms of the speed of the physical event causing the accident, even though the actual calculations are completed assuming a step change in reactivity.

The Second Stage - Vaporization of Fuel Elements and the Resulting Shutdown of the Reactor

The second stage of the runaway is analyzed using the following model of the reactor.

1. The reactor is characterized by a certain power density distribution such that if q is the power density in fraction of total power per unit mass of fuel element, then M(q) dq is the mass of fuel elements that have a power density between q and q + dq and qM(q)dq is the fraction of the total power between q and q + dq.
2. The fuel element vapor is distributed uniformly in the void space inside the reactor.
3. The temperature through the Nichrome V fuel elements is constant.
4. Fuel elements which are undergoing vaporization have the same temperature as the fuel element vapor, and this temperature is determined by a Clapeyron-type equation.
5. The solid fuel elements inside the reactor have only internal energy.
6. The vaporized fuel elements inside the reactor have kinetic energy as well as internal energy. Also, after the fuel elements vaporize, they expand to a pressure P and a volume of $1/\rho$ (ρ = density) per unit mass; thus, a unit mass of fuel element does work in expanding equal to P/ρ.
7. The vapor which has flowed outside the reactor has internal energy, kinetic energy, and does flow work on the gas already outside. The gas flow rate out of the reactor is determined by the equations of adiabatic flow of a perfect gas through a nozzle. The conservative assumption was made that the vapor flowed into the void space above and below the reactor and that this void space was closed off from the atmosphere. Hence, the flow depended on the difference in the vapor density inside the reactor and the vapor density in the void space.
8. No fuel element vapor escapes the reactor until the original air in the reactor has been ejected.
9. No fuel elements vaporize until the fuel element temperature is high enough to maintain vaporization with one atmosphere of fuel element vapor pressure.
10. The runaway is stopped by fuel element vapor leaving the reactor. This effect on reactivity is assumed to be proportional to the total flow out.

The Third Stage - The Delayed Neutron Sustained After-Reaction

For the more severe runaways, the reactor is strongly subcritical at the beginning of the third stage. By assuming the reactivity does not decrease any further during the third stage, one obtains an overestimate of the power in the third stage. This overestimate is considerably smaller than the power developed in the first and second stages and hence is quite acceptable.

For the less severe runaways in which only a small fraction of the fuel elements vaporize and flow out of the reactor, the effect of further decreases in reactivity must be taken into account. In the third stage the reaction is sustained by delayed neutrons and is slow enough that the decrease in reactivity due to ejection of fuel elements is directly proportional to the power. For this type of runaway it can be shown that the runaway will change reactivity so that it is below delayed critical by the same amount it was above delayed

critical.* This theorem can then be applied to estimate the total power in the after-reaction for low intensity runaways.

2.13 COMPARISON OF RUNAWAYS RESULTING FROM VARIOUS REACTIVITY INCREASES

The characteristics of the runaways are best interpreted graphically. Figure 24 shows the number of fission fragments produced and the number ejected as a function of step change in reactivity. Figure 25 shows the total energy developed in a runaway as a function of step change in reactivity.

Maximum power level in a runaway as a function of step change in reactivity is shown in Figure 26.

Figures 27 and 28 show respectively the maximum temperature and the maximum vapor pressure of fuel element vapor as a function of step change in reactivity. Note the very high pressures developed which would result in the bursting of the reactor for all runaways other than the smallest (step change of 1% or less).

Figures 29 and 30 show respectively the power level and time at which vaporization of fuel elements begins as a function of step change in reactivity.

Figure 31 shows a plot of rate of linear increase in reactivity versus equivalent step change in reactivity.

2.14 CORRELATION OF PHYSICAL EVENTS CAUSING RUNAWAY WITH REACTIVITY INCREASES

Increases Due to Accidents

1. Failure of control rods - Under operating conditions there are two dynamic rods worth 0.45 per cent each which may be withdrawn at a speed of 40 inches per second. Also, there are 21 shim-scram rods with an estimated value of 960 per cent† which are limited to a speed of 1 foot per minute. Hence, withdrawing all rods at their maximum speed results in a linear increase in reactivity of 1.264 per cent per second or an equivalent step change in reactivity of 1.45 per cent. This represents the maximum accident to the HTRE Core A reactor.

2. Substitution of nonpoisonous rods - Careful check of the reactor assembly as a routine part of the startup procedure should eliminate this danger, but an accident from this cause is less severe than accident 1.

3. Loss of airflow - Loss of airflow would result in the slow melting of fuel elements which would drop to the bottom of the cocoon surrounding the reactor. The viscosity of the molten Nichrome would be such as to possibly allow the uranium oxide particles to settle to the bottom. Since the afterheat in the uranium particles would be large enough to burn a hole through the cocoon, the uranium oxide could possibly fall into the borated shield water below, and, if the geometry be right (sphere), the assembly would be 9.4 per cent supercritical. This would be a very fast reactor and probably would result in the uranium oxide melting and vaporizing before the heat generated would have a chance to get to the water. Since the possibility of this sequence of events is so unlikely, no estimate of the magnitude of energy generated or the numbers of fission fragments released is made.

*KAPL 646

†Measured value from TRA-II experiments is 9.0 per cent.

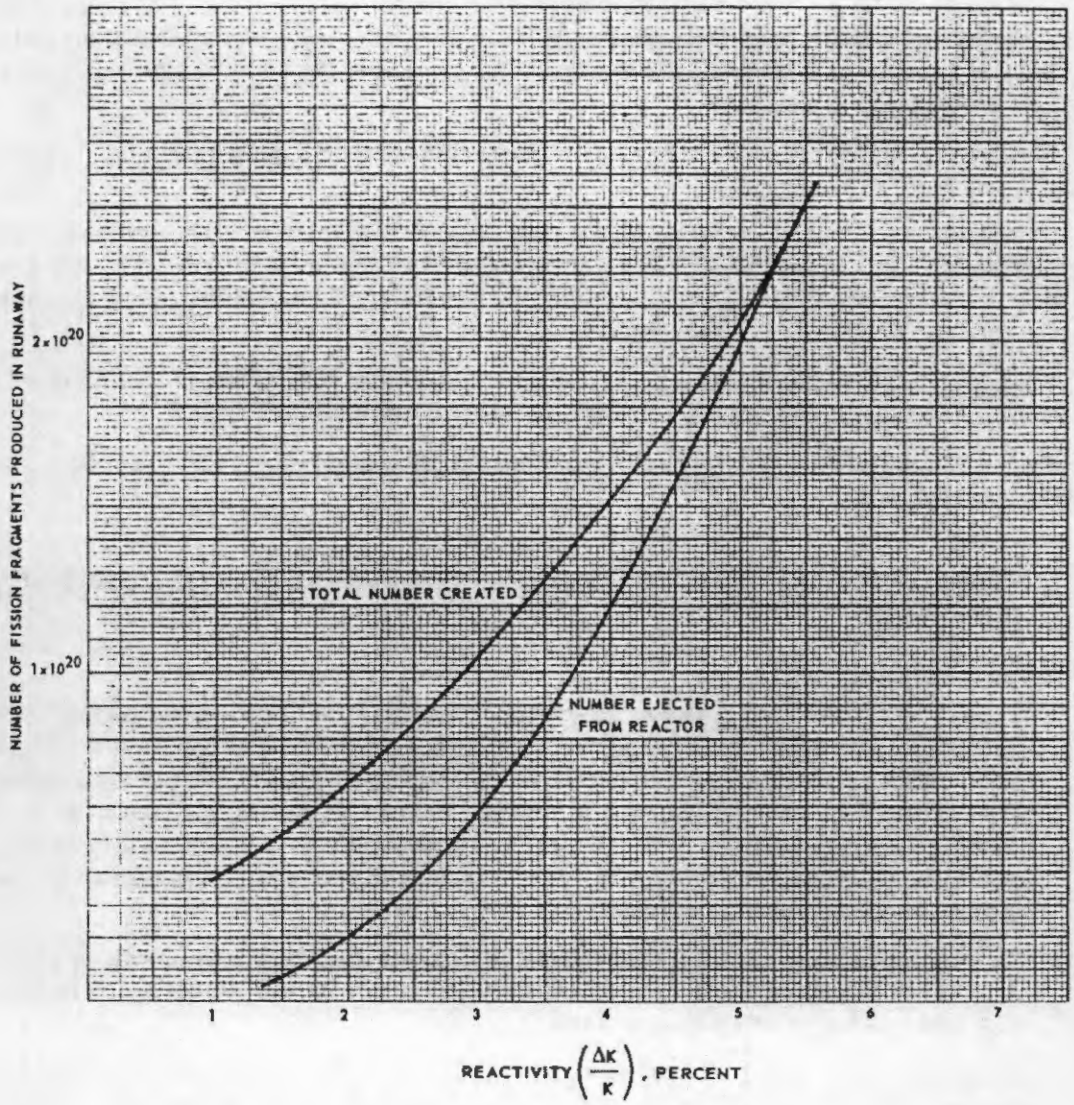

Fig. 24 - Number of fission fragments produced as a function of step change in reactivity

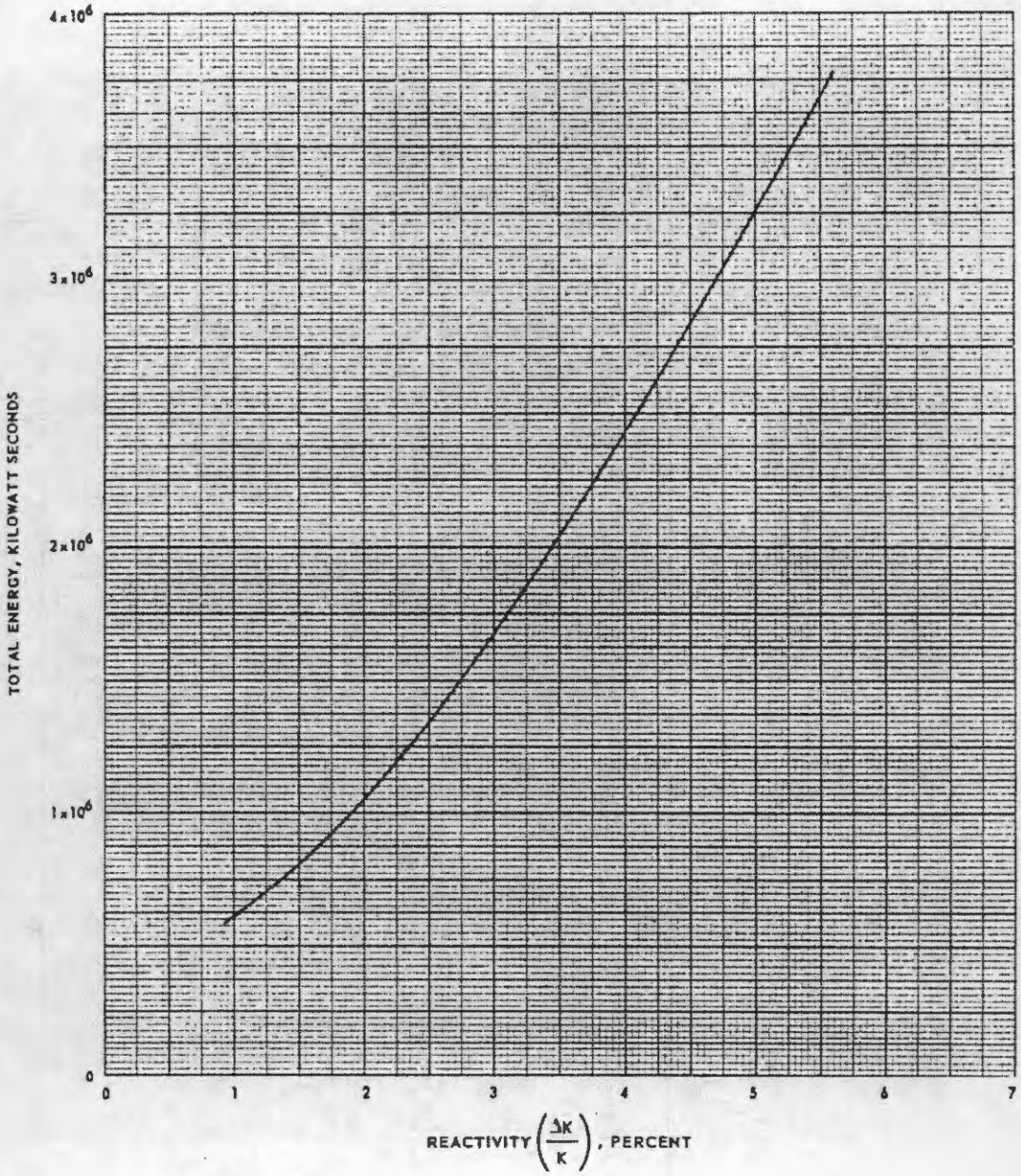

Fig. 25 - Total energy developed in a runaway as a function of step change in reactivity

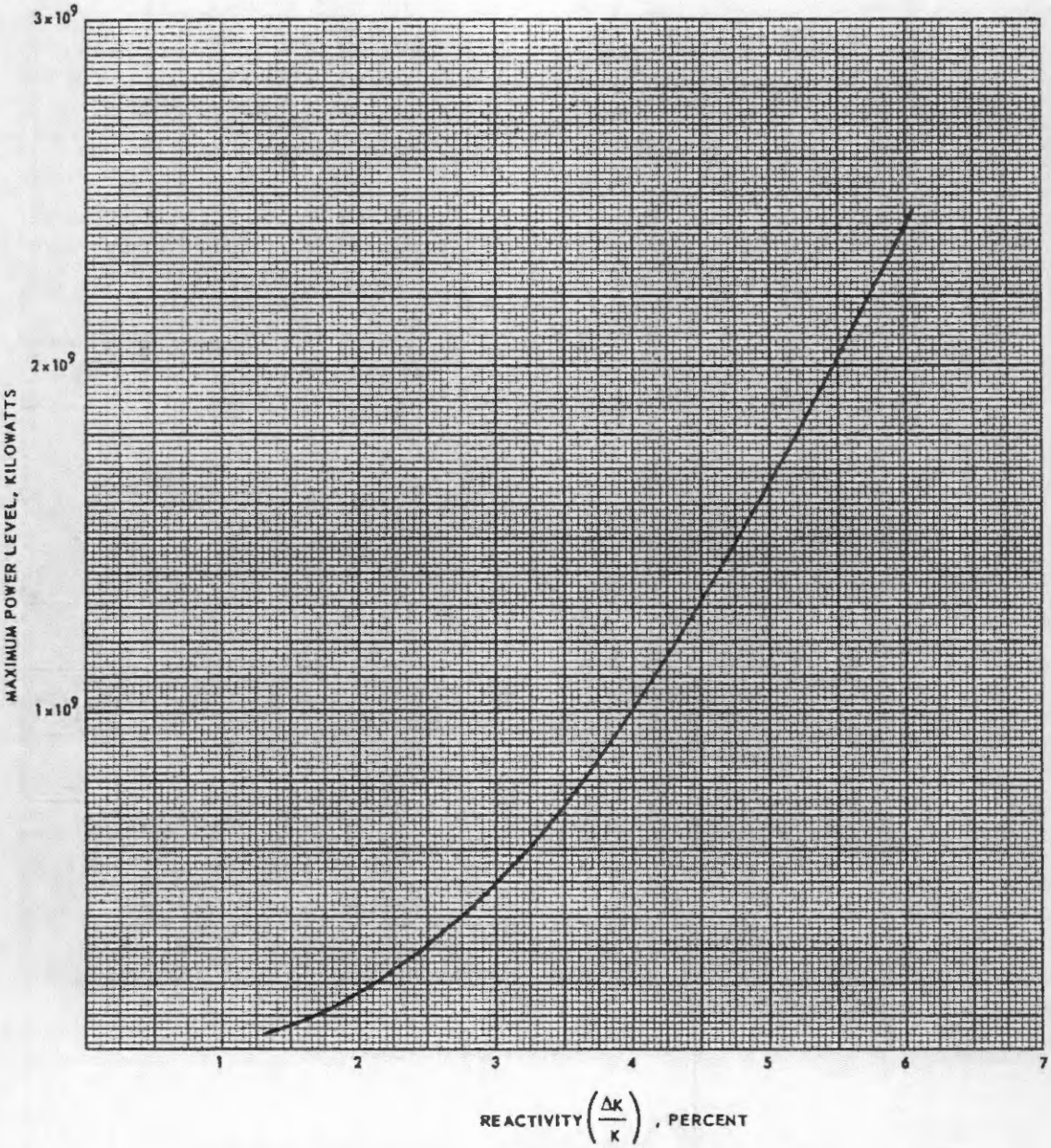

Fig. 26 - Maximum power level in runaway as a function of step change in reactivity

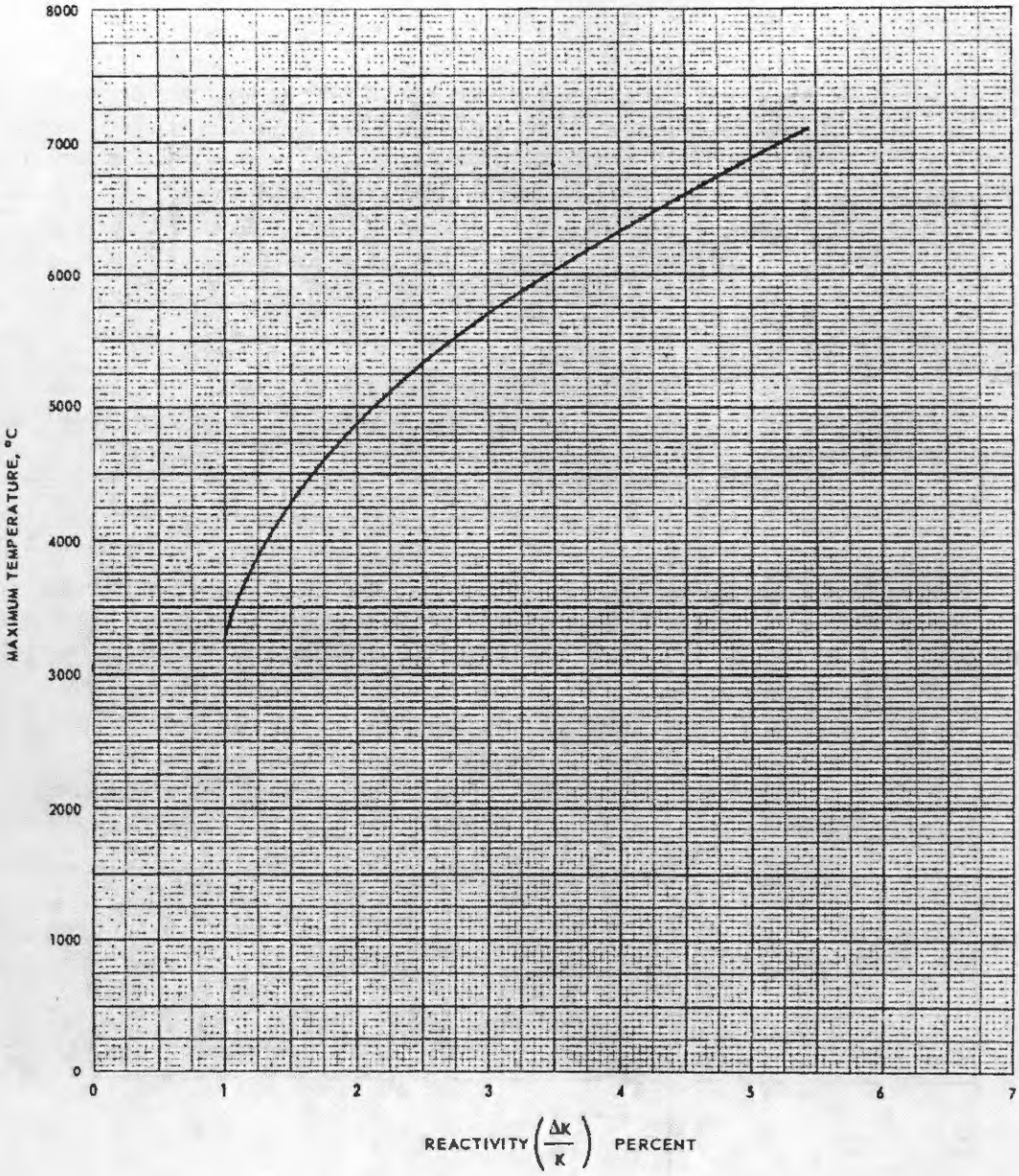

Fig. 27 - Maximum temperature inside reactor as a function of step change in reactivity

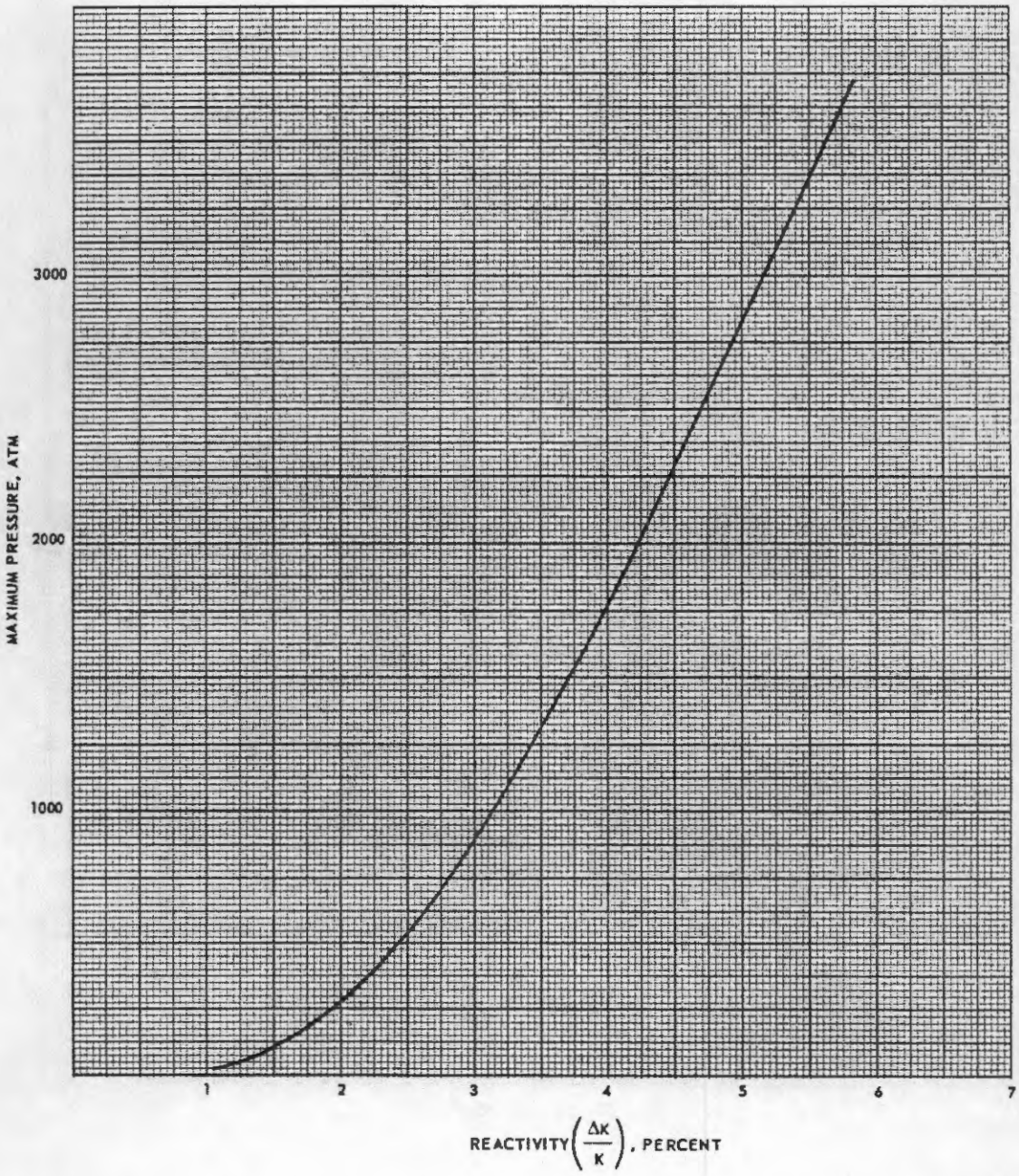

Fig. 28 - Maximum fuel element vapor pressure as a function of step change in reactivity

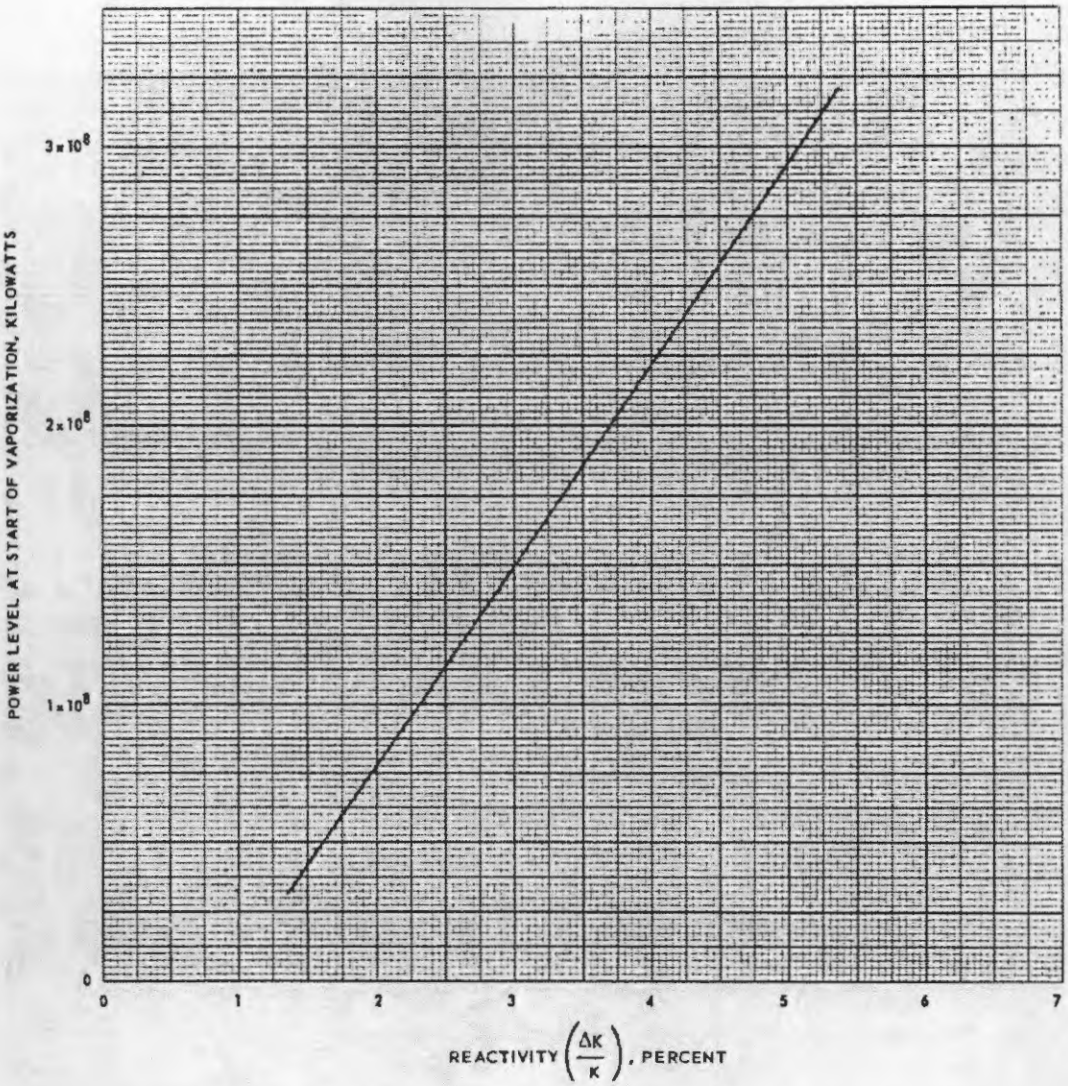

Fig. 29 - Power level at start of vaporization of fuel as a function of step change in reactivity

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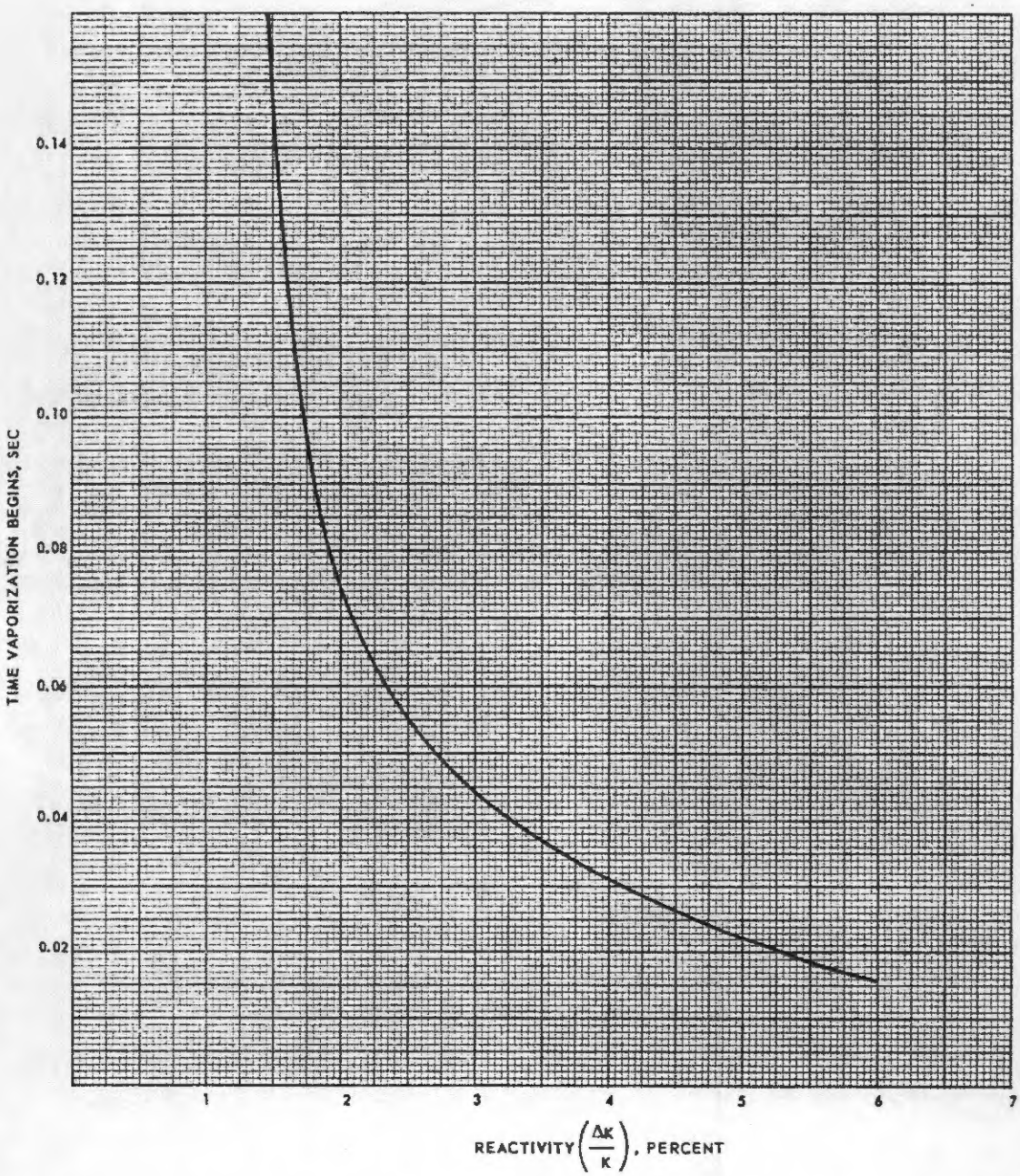

Fig. 30 - Time at which vaporization of fuel elements begins as a function of step change in reactivity

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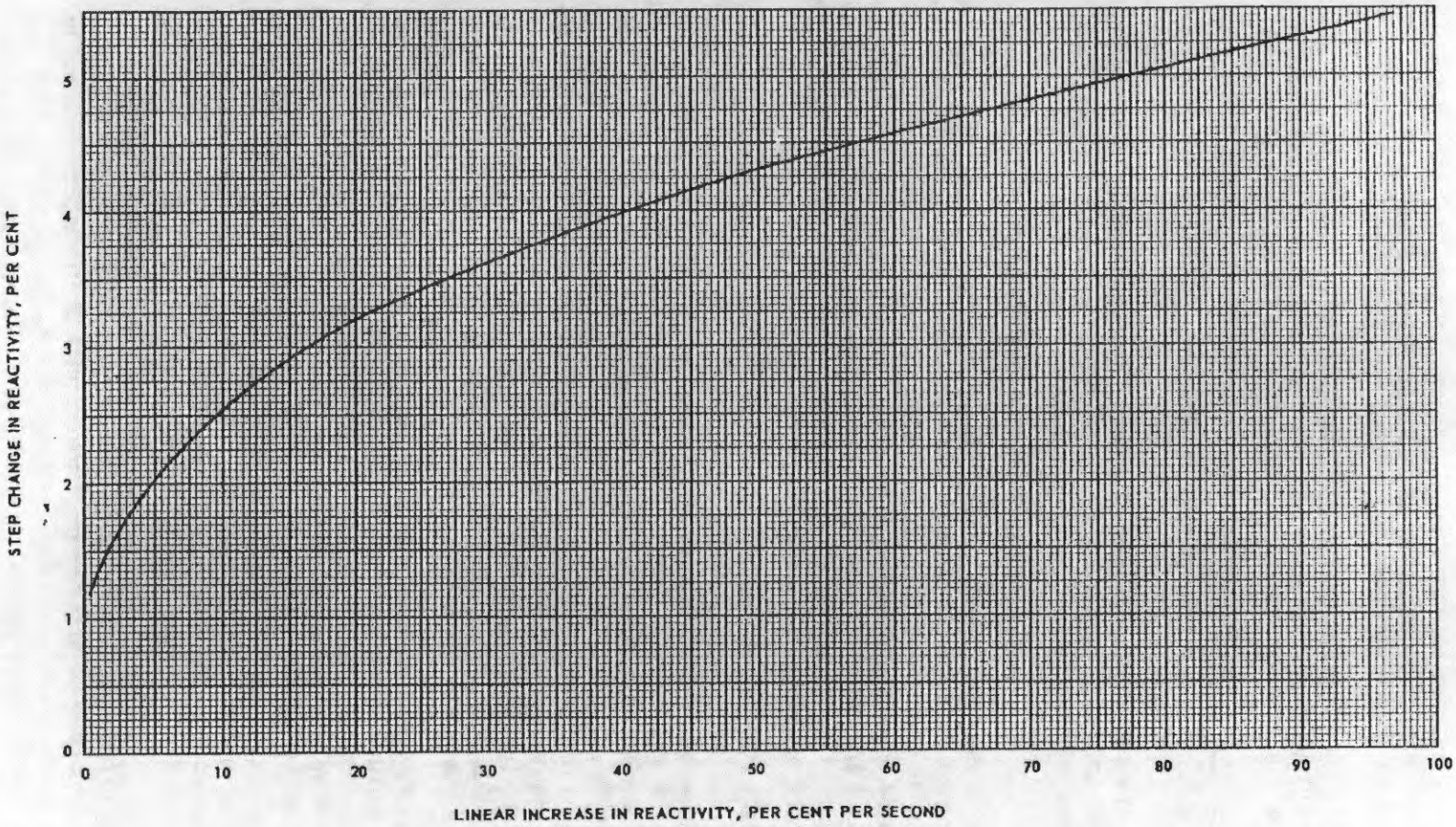

Fig. 31 - Equivalent step change in reactivity (α t) versus linear increase (α)

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Increases Due to Sabotage

1. Driving out all control rods - If a saboteur using explosives can drive out all rods (dynamic and shim) in 200 milliseconds, the resulting linear increase in reactivity is 52.5 per cent per second, equivalent to a step change of 4.38 per cent.

2. Filling fuel tubes with water - If a saboteur can close off the bottom open ends of the fuel tubes and then can fill the tubes with water in 1 second, the linear increase in reactivity is 40 per cent per second, equivalent to a step change of 4.00 per cent.

3. Combining 1 and 2 - This results in a linear increase in reactivity of 92.5 per cent per second, equivalent to a step change of 5.3 per cent. This represents the probable maximum sabotage.

4. Implosion - This possibility is not given serious consideration since the necessity of maintaining a precise reactor geometry and the difficulty of handling a large amount of high explosives are thought to be out of reason.

2.2 OTHER HAZARDOUS FEATURES

Major releases of the stored fission products are possible without the necessity of having a reactor runaway. The worst of these is the result of a major meltdown of the reactor which can occur if all means of air circulation is lost suddenly at a time when the reactor has a substantial content of fission products. The temperatures reached in the fuel elements in such cases are sufficient to melt the fuel elements and boil out the more volatile of the fission products even though the reactor has been shut down. The resulting hazard in this case would be due almost entirely to the I^{131}.

Accidents of this nature are extremely improbable due to the multiple failures in power supplies, motors, and other equipment which would have to occur before all cooling would be lost. One possible way it could happen would be if the jet engine wrecked itself so thoroughly that it destroyed or at least ruptured the inlet air ducts thus eliminating the cooling fans. This might be possible through the failure of the compressor blades* from overload or by introduction of some foreign object into the compressor inlet. However, the casing of the jet is so designed that it normally will contain the debris caused by the wrecking of the compressor. Another possibility is that all airflow from the compressor could be stopped by improper operation or failure of the valves in the ducting. In this case the wreckage may be so violent as to wreck the ducting. Needless to say, the design and construction of the valves and their controls is such that this is a remote possibility.

Other accidents resulting from failure of components in the core proper can induce releases of a much smaller amount of activity. One such failure could be the collapse of a portion of a fuel element due to the temperature and airflow stresses. After such a collapse, portions of the element still producing nuclear power would be insufficiently cooled, and the temperature would rise in local "hot spots." If the temperature rises high enough, to about 3000°F, oxidation can set in at a very high rate, and since this oxidation reaction is exothermic, it might continue uncontrolled even though the reactor has been scrammed in the meantime. Experiments have been conducted to determine the amount of damage to the core which could occur if this uncontrolled burning took place in one tube of the reactor. The experiments were conducted with a one-tube full scale mockup of the core complete with insulation, simulated fuel elements, and water-cooled aluminum fuel tube. Combustion was initiated in an atmosphere of pure oxygen at atmospheric pressure by igniting a fuse of ordinary steel wool which in turn ignited the fuel elements. Once oxidation had started, the flow of oxygen was increased and the reaction occurred at a vigor-

*See data on reliability in the engine section.

ous rate. The fuel elements were completely oxidized in about 15 seconds, and generated an average of about 1.5 megawatts during the experiment.

Examination of the aluminum tube after the burnup indicated complete removal of all of the fuel and insulation and no damage to the aluminum except at a point near the bottom end. Apparently, a small pool of molten slag had been held up by a pile of solidified slag for a long enough period to melt a hole in the aluminum at this point.

It seems from the results of this experiment that there is very little chance of major damage to the core or other fuel element tubes due to the development of local hot spots in any one tube. However, operating the reactor in a manner such that several tubes could develop hot spots at the same time is certainly possible.

Complete removal of one tube from the reactor means a loss of 2.7 per cent of the stored fission products. However, it is unlikely that all of this material would travel up the exhaust stack. A reasonable guess is that during a burnup of this kind about 1 per cent of the total reactor fission products would be released.

Other smaller ruptures of the fuel elements are possible and will probably happen. Fast acting rupture detection equipment which samples air directly from the reactor is capable of detecting very small ruptures amounting to 10^{-8} of the reactor per second with low backgrounds (Nichrome oxides, etc.) and 10^{-6} of the reactor per second for any foreseeable background and will be the cause for shutting down the reactor if the release builds up to dangerous levels or appears to be causing significant damage to the reactor.

3. HAZARDS TO THE SURROUNDING AREA

3.1 HAZARDS CALCULATIONS FOR MAJOR RELEASES OF ACTIVITY

The radiation hazards to persons exposed to the radioactive cloud following nuclear runaways and accidents have been calculated using the equations developed from Sutton's diffusion equations as given in the appendix. These equations are:

1. For the total dose in rads due to passage of an instantaneously emitted cloud

$$D_\gamma = \frac{4 \times 0.474\, FB(t)\, G\mu_a'\mu}{u} [I_1 + K\, I_2]$$

$$= 3.85 \times 10^{-4} \frac{F\, B(t)}{u} [I_1 + 1.6\, I_2]$$

$$D_\beta = \frac{4 \times 0.526\, F\, B(t)\, G\, \mu'\mu}{u} I_1$$

$$= 3.70 \frac{F\, B(t)}{u} I_1$$

2. For the dose in rads to the lung following inhalation*

$$D_L = \frac{2R \times 0.526\, FE(t)}{\pi u} \times 100 \times \frac{e^{-\frac{h^2}{a^2}}}{a^2}$$

$$= 1.16 \times 10^{-2} \frac{FE(t)}{u} \frac{e^{-\frac{h^2}{a^2}}}{a^2}$$

3. For the thyroid dose in rads, assuming I^{131} content of the inhaled material is soluble,†

$$D_\tau = \frac{2R\, FE(t)_i}{\pi u} \times 1000 \times \frac{e^{-\frac{h^2}{a^2}}}{a^2}$$

$$= 0.221 \frac{FE(t)_i}{u} \times \frac{e^{-\frac{h^2}{a^2}}}{a^2}$$

*100 = rads to lung per joule expended in the lung. This assumes that the average lung weighs 1000 grams.

†1000 = rads to thyroid per joule of energy from I^{131} absorbed in the blood stream. This allows for transfer of only 0.2 of the total I^{131} to the thyroid. The thyroid weighs 20 grams.

4. The dose in rads during the first day due to maximum fallout

$$D_\gamma = \frac{2\pi^{1/2} \times 0.474\, F\, [E(t) - E(1d)]\, G\, \mu_a'\, \mu}{ex} \left[I_D + \frac{K}{2} I_S \right]$$

$$= 1.26 \times 10^{-4} \frac{F\,[E(t) - E(1d)]}{x} [I_D + 0.8\, I_S]$$

$$D_\beta = \frac{2\pi^{1/2} \times 0.526\, F\,[E(t) - E(1d)]\, G\, \mu'\, \mu}{ex} I_D$$

$$= 1.21 \frac{F\,[E(t) - E(1d)]}{x} I_D$$

5. Total dose in rads possible due to maximum fallout

$$D_\gamma = 1.26 \times 10^{-4} \frac{FE(t)}{x} [I_D + 0.8\, I_S]$$

$$D_\beta = 1.21 \frac{FE(t)}{x} I_D$$

6. The dose rate in rads per hour due to fallout after passage of the cloud

$$D_{R\gamma} = \frac{2\pi^{1/2} \times 0.474\, FB(t)\, G\, \mu_a'\, \mu \times 3600}{ex} \left[I_D + \frac{K}{2} I_S \right]$$

$$= 0.454 \frac{FB(t)}{x} [I_D + 0.8\, I_S]$$

$$D_{R\beta} = \frac{2\pi^{1/2} \times 0.526\, FB(t)\, G\, \mu'\, \mu \times 3600}{ex} I_D$$

$$= 4.34 \times 10^3 \frac{FB(t)}{x} I_D$$

In these equations, F is the fraction of the total amount of fission products released, and the following values were used for the special cases of dose and dose rates due to fission products from a reactor disaster. The average energy of the gamma rays was taken to be 0.7 Mev, and the corresponding absorption coefficients are

$\mu' = 9.7 \times 10^{-3}\ m^{-1}$ for NTP conditions

$\mu_a' = 3.75 \times 10^{-3}\ m^{-1}$ for NTP conditions

$\mu = 7.8 \times 10^{-3}\ m^{-1}$ for average conditions at the NRTS

$K = 1.6$

The average energy of the betas was taken to be 0.4 Mev with a maximum energy of 3 Mev. An absorption coefficient which fits the energy absorption data for up to 90 per cent of the total energy is

$\mu' = 0.56\ m^{-1}$ for NTP conditions

$\mu = 0.46\ m^{-1}$ for average conditions at the NRTS

The quantity $B(t)$* is the total power emitted by the reactor fission products at the time t after a runaway or accident after the reactor has been operated for 1900 hours at an average power of 10^7 watts plus 100 hours at an average power of 2×10^7 watts. This is equivalent to operating at full power during all of the acceptable meteorological conditions available in a period of two months.

$$B(t) = 10^7 \times 0.0686 \{t^{-0.2} - (t+7.2 \times 10^6)^{-0.2}] + [t^{-0.2} - (t+3.6 \times 10^5)^{-0.2}\} + 0.0137\, A\, t^{-1.2}$$

where A is the energy in joules in the nuclear runaway.

The quantity* $E(t)$ is the energy yet to be emitted at the time t for the same operating conditions.

$$E(t) = 10^7 \times 0.0858 \{[(t+7.2 \times 10^6)^{0.8} - t^{0.8}] + [(t+3.6 \times 10^5)^{0.8} - t^{0.8}]\} + 0.0686\, A\, t^{-0.2}$$

Values of $B(t)$ for the maximum sabotage, maximum accident, and for the total release without a runaway are given in Figure 32. Values for $E(t)$ are given in Figure 33; however, in this case there is no visible difference in the three cases for the range of time plotted. The additional energy from the accidents has no effect on E(t) for the range of time of interest.

The value of $E(t)_i$, the energy release from the I^{131} in the fission products, is

$$E(t)_i = \frac{P \times y}{E} \left[\frac{(1 - e^{-\lambda T_1}) + (1 - e^{-\lambda T_2})}{\lambda}\right] E' e^{-\lambda t}$$

$$= 4.44 \times 10^8\, e^{-10^{-6} t} \text{ joules}$$

where

P = power level = 10^7 watts
y = fission yield of I^{131} = 0.03
λ = decay constant of I^{131} = 10^{-6} sec^{-1}
T_1 = time of operation at 10^7 watts = 7.2×10^6 sec
T_2 = time of operation at 2×10^7 watts = the last 3.6×10^5 sec
E = energy per fission = 194×10^6 ev
E' = average energy of I^{131} betas = 0.22×10^6 ev
t = time since release of cloud, seconds

The radiation hazards due to the maximum sabotage, $F = 1$, were calculated using very adverse weather conditions which exist when there is a strong inversion. Sutton's equations probably do not fit the facts too accurately for this condition, but the calculated doses are probably about correct. It is assumed that the emission is at ground level with a wind velocity of 1 meter per second; n is 0.5 and c is 0.035. Values of the various doses due to passage of clouds directly over points at distances from 100 to 10^5 meters from the reactor are given in Table 3. The value of A is 3.5×10^9 joules. The distance to the public highway northeast of the IET is about 10^4 meters, and the distance to Idaho Falls is about 10^5 meters.

The radiation hazards due to the maximum accident runaway were calculated assuming that the meteorological conditions were such that a mild inversion exists with a wind velocity of 3 meters per second and Sutton's parameters n = 0.333 and c = 0.0604. This condition is about the minimum during which operation would be allowed even with favorable wind directions.

*Calculated from the Way-Wigner formula. Phys. Rev. 73 (1318) 1948.

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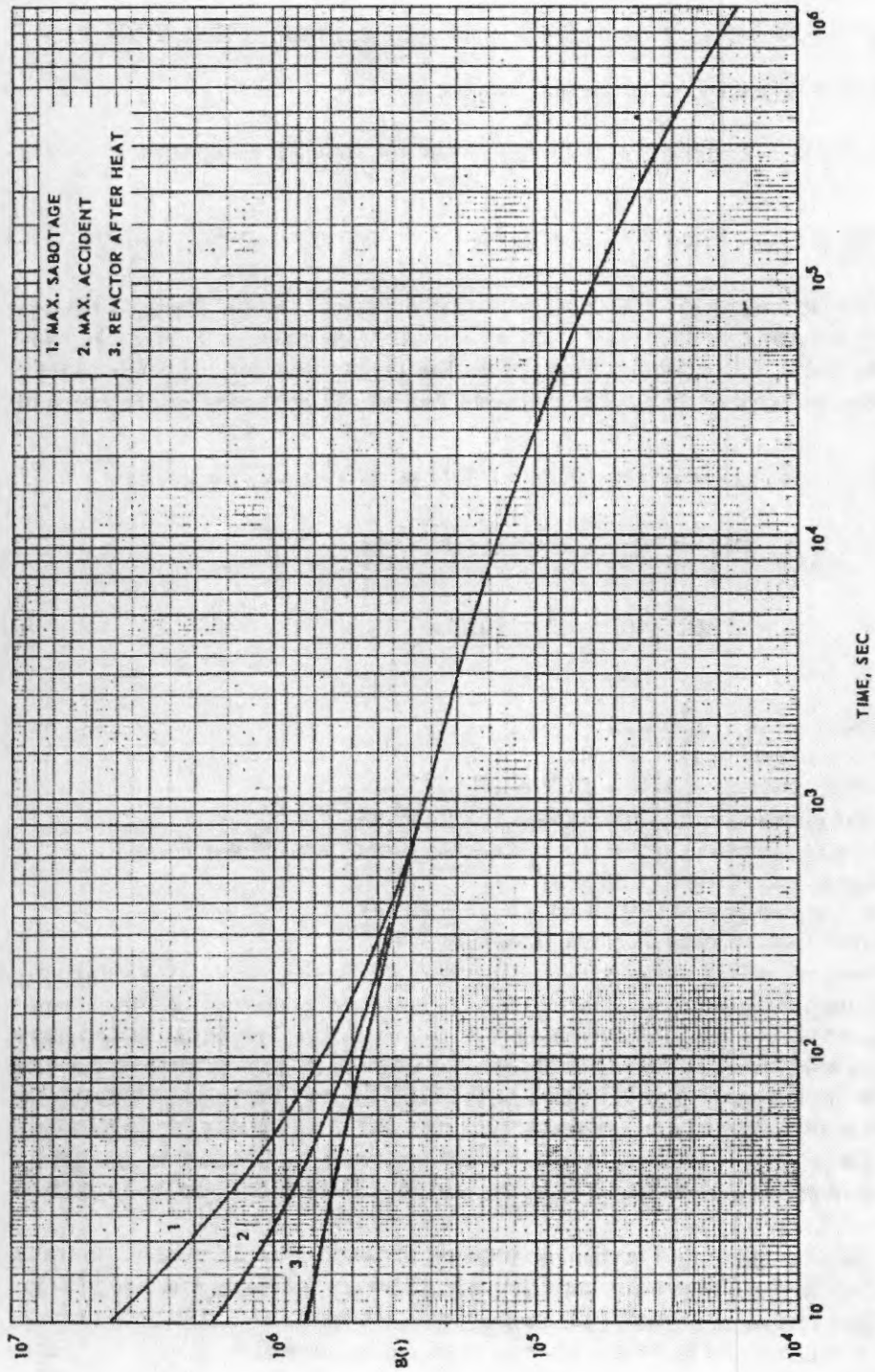

Fig. 32 - B (t) versus time

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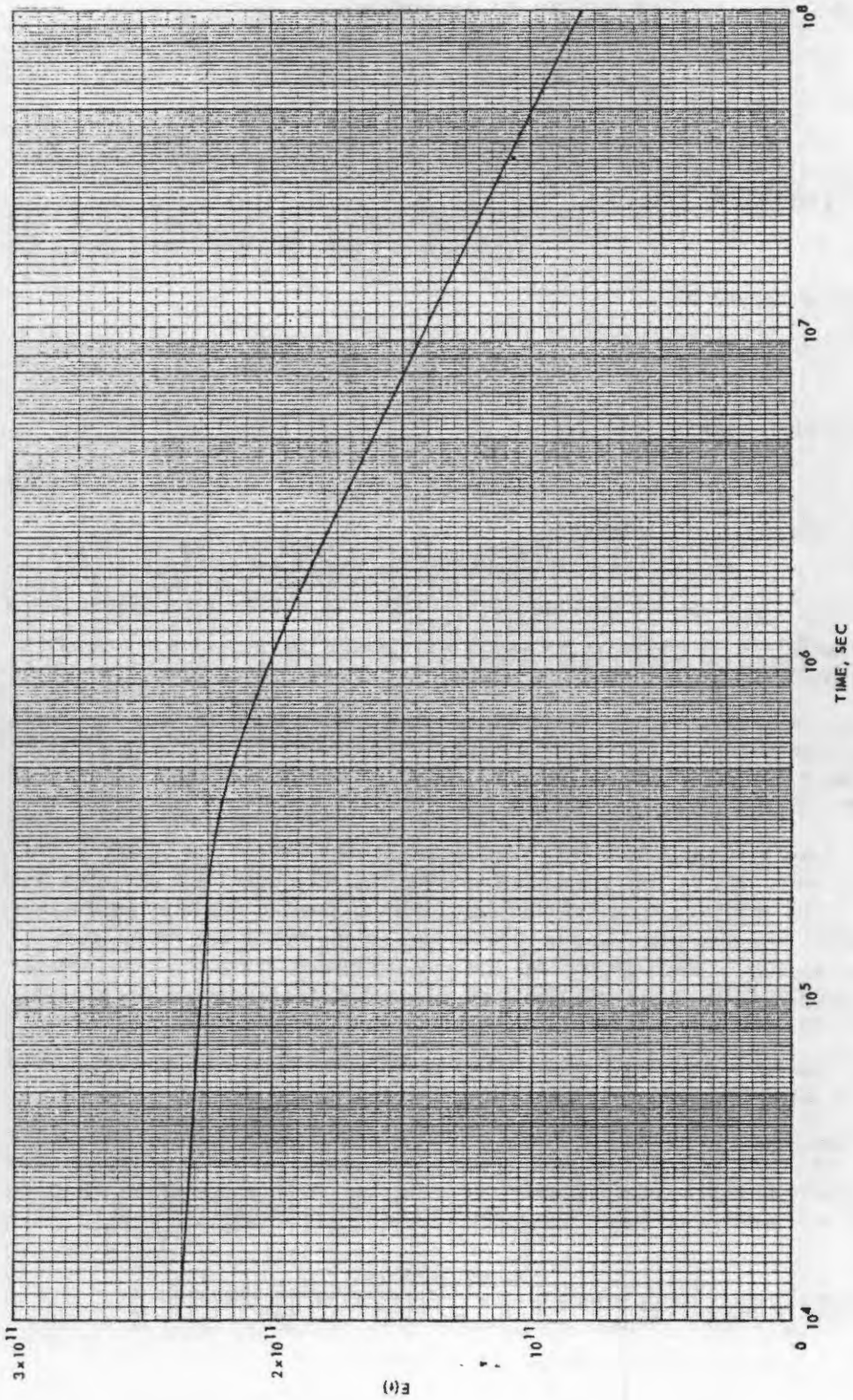

Fig. 33 - E (t) versus time

TABLE 3

RADIATION LEVELS FOLLOWING MAXIMUM SABOTAGE RUNAWAY

Distance, meters	10^2	10^3	10^4	10^5
Dose during cloud passage, rads				
Gamma	3.9×10^4	3.0×10^3	270	14
Beta	4.3×10^6	1.2×10^5	2.0×10^3	26
Dose following inhalation, rads				
Lung	2.7×10^9	8.6×10^7	2.7×10^6	8.4×10^4
Thyroid	8.1×10^7	2.5×10^6	7.9×10^4	2.3×10^3
Dose during first day due to rainout, rads				
Gamma	8.3×10^5	3.9×10^4	840	---
Beta	5.1×10^7	1.6×10^6	2.0×10^4	---
Total possible dose, rads				
Gamma	3.4×10^7	1.6×10^6	5.5×10^4	240
Beta	2.1×10^9	6.8×10^7	1.3×10^5	2.4×10^3
Dose rate at time of rainout, rads/hr				
Gamma	2.8×10^5	5.6×10^3	97	0.78
Beta	1.7×10^7	2.3×10^5	2.3×10^3	18

The value of F is 0.14; the value of A is 7.9×10^8 joules; and emission is assumed to be at ground level. The results are given in Table 4.

The radiation hazards due to the burnup of one reactor tube, F = 0.01, are calculated for the same meteorological conditions as for the maximum accident but with emission taking place from the stack with an effective height of 61 meters with $n = 0.333$ and $c = 0.053$. The results are given in Table 5.

These doses and dose rates have been calculated assuming that the worst condition applies to each case, that is, for the cloud doses and inhalation doses it is assumed that there is no loss of activity in the cloud because of fallout. For the inhalation doses it is assumed that the retention in the lung is 100 per cent. If the factor for retention of insoluble uranium oxide in the lung* is used, the lung and thyroid doses would be reduced by a factor of about 8. The doses and dose rates were calculated for the rainout assuming the maximum exponential fallout rate for each distance is discussed in the appendix.

The actual case would probably provide results in which the cloud doses are reduced by fallout and the ground deposits are also less than calculated.

If a cloudburst of 1 inch of rain over an area of 10 square miles removed most of the contamination from the cloud and washed it into one of the nearby dry river beds so that contamination was sent directly to the water table, then the concentration of beta emitters in this water, undiluted by its travel in the water table, would be approximately,

$$\text{Concentration} = \frac{0.526\, B(t) \times 10^7}{10\,(5280 \times 30.5)^2 \times 2.54 \times 1.6 \times 10^{-12} \times 0.4 \times 10^6 \times 3.7 \times 10^4} \quad \mu c/cc$$

$$= 3.4 \times 10^{-4}\, B(t) \quad \mu c/cc$$

† National Bureaus of Standards Handbook 52.

TABLE 4

RADIATION LEVELS FOLLOWING MAXIMUM ACCIDENT RUNAWAY (F = 0.14)

Distance, meters	10^2	10^3	10^4	10^5
Dose during cloud passage, rads				
Gamma	841	58	3.7	0.08
Beta	6.3×10^4	790	9.0	0.09
Dose following inhalation, rads				
Lung	1.8×10^7	4.1×10^5	9.0×10^3	180
Thyroid	5.8×10^5	1.2×10^4	260	5.3
Dose during first day due to rainout, rads				
Gamma	9.0×10^4	2.8×10^3	52	0.04
Beta	4.1×10^6	8.0×10^4	1.1×10^3	0.74
Total possible dose, rads				
Gamma	3.7×10^6	1.2×10^5	2.2×10^3	34
Beta	1.7×10^8	3.7×10^6	4.7×10^4	680
Dose rate at time of rainout, rads/hr				
Gamma	3.7×10^4	530	5.2	0.04
Beta	1.7×10^6	1.5×10^4	120	0.08

TABLE 5

RADIATION LEVELS FOLLOWING ONE TUBE BURNUP (F = 0.01)

Distance, meters	10^2	10^3	10^4	10^5	4.75×10^3
Dose during cloud passage, rads					
Gamma	1.1	0.64	0.27	0.007	0.484
Beta	---	---	0.633	0.009	1.33
Dose following inhalation, rads					
Lung	---	0.073	50	18	1.1×10^3
Thyroid	---	0.0022	1.5	0.52	32
Dose during first day due to rainout, rads					
Gamma	6.4×10^3	230	4.4	0.0031	
Beta	3.3×10^5	6.7×10^3	97	0.062	
Total possible dose, rads					
Gamma	2.6×10^5	9.7×10^3	180	2.9	
Beta	1.4×10^7	2.8×10^5	4.1×10^3	59	
Dose rate at time of rainout, rads/hr					
Gamma	2.6×10^3	44	0.44	0.0034	
Beta	1.2×10^3	1.2×10^3	9.9	0.068	

The nearest point at which this water could be removed is at the STR, and it takes the water about 270 days to travel that far at which time $B(t) = 90$ so that the concentration in the water at the STR would be about 0.03 μc/cc -- a value which is considerably above the MPC.

This method of calculation does not allow for the settling out or filtering out of the particulates which would be included in the cloud.

The cloudburst could wash this rainout material into Mud Lake, 11 miles east of the IET which has an area of about 4 square miles or 10^7 square meters. If it is an average of about 1 meter deep, then the initial concentration of beta emitters would be

$$\text{Concentration} = \frac{0.526\, B(t) \times 10^7}{10^7 \times 10^6 \times 1.6 \times 10^{-12} \times 0.4 \times 10^6 \times 3.7 \times 10^4}$$

$$= 2.2 \times 10^{-5}\, B(t) \quad \mu\text{c/cc}$$

One hour after the maximum sabotage $B(t)$ is 1.9×10^5 so that the average concentration assuming uniform distribution is 4.2 μc/cc.

The dose rate in rads/hr from total of beta and gamma emitters is

$$D_R = \frac{B(t) \times 10^7 \times 3600}{10^7 \times 10^6 \times 10^2} = 3.6 \times 10^{-5}\, B(t) = 6.8$$

3.2 RADIATION HAZARDS DUE TO AIRBORNE CONTAMINANTS DURING NORMAL OPERATION

During normal operation of the HTRE some radioactive materials will be dispersed to the atmosphere through the exhaust stack. These materials are erosion products from the reactor itself, and the gases and normal airborne dusts which are activated by neutron absorption during their passage through the reactor.

The production rate for any one radioactive species is

$$M = 6.02 \times 10^{23}\, \frac{WFS\sigma \times 10^{-24}\, \phi}{A}$$

or

$$C = \frac{\lambda M}{3.7 \times 10^{10}} = 1.63 \times 10^{-11}\, \frac{\lambda WFS\sigma\phi}{A}$$

where

C = activity in curies/sec
W = weight of material in the reactor, grams
F = fractional abundance of particular isotope
S = fractional amount of element present
σ = cross section in barns
ϕ = neutron flux, neutrons/cm^{2}sec
λ = disintegration constant, sec^{-1}
A = atomic weight of isotope

This equation can be used to calculate the rate of release of the activated gases and airborne dusts which spend little time in the reactor.

The amount of air in the reactor during operation depends on the average temperature and pressure and the available volume. The pressures and temperatures are:

	Pressure, lb/in^2	Temperature, °F	Temperature, °R
Inlet	54.8	426	875
Outlet	47.4	1400	1859
Average	51.1		1367

The average density is then

$$\rho = \frac{P}{RT} = \frac{51.1 \times 144}{53.4 \times 1367} = 0.101 \text{ lb/ft}^3$$

and since the available volume is 5.7 ft^3 the weight of the air is 0.575 lb or 261 gm. The data on dust concentrations and compositions are given in the appendix (Meteorology), and the largest amount likely to be present for these calculations is assumed to be 1 mg/m^3 or 3×10^{-5} gm/ft^3 so that the amount in the reactor is 1.7×10^{-4} gm at any one time. However, this amount is too low to provide any significant activity.

For the erosion products which are not liberated as fast as they are activated the total number of curies after operation for a time t is

$$V = \frac{C}{\lambda}(1 - e^{-\lambda t})$$

The rate of erosion of the reactor core determines the rate at which the radioactive material is emitted. If this rate of erosion is called R, the activity released is

$$C' = R \times V = \frac{1.63 \times 10^{-11} RWFS\sigma\phi(1 - e^{-\lambda t})}{A}$$

Tests of fuel elements operated at high temperatures indicate very little loss of the surface oxide film. Maximum oxide stringer penetration amounts to about 0.7 mil, but the average is much less. For these calculations it is assumed that the oxide layer is eroded off at a rate of 0.1 mil per 100 hours of operation and since there are 4 mils of cladding on each surface,

$$R = \frac{0.1}{4 \times 3.6 \times 10^5} = 6.94 \times 10^{-8}$$

The weight of the cladding is about 214 lb or 9.75×10^4 gm.

Table 6 gives the values of W, F, S, the number of curies released per second, and the *MPC* for these activated materials assuming that the reactor had run at a power of 10^7 watts for the first 1900 hours and at 2×10^7 watts for the last 100 hours.

The limits for uranium contamination on the surfaces and sealed edges of fuel elements are such that there should be no more than 5.24×10^{14} fission products released to the cooling air per second.

TABLE 6

Reaction	F	S	σ	λ	C	MPC	$\frac{C}{MPC}$
A^{40}, n-γ, A^{41}	1.0	0.013	1	1.07×10^{-4}	2.0×10^{-3}	5×10^{-7}	3.6×10^{3}
O^{16}, n-p, N^{16}	1.0	0.23	1.4×10^{-5}	0.0943	7.1×10^{-3}	10^{-7}	6.0×10^{4}
Si^{30}, n-γ, Si^{31}	0.03	0.015	0.12	7.34×10^{-5}	2.6×10^{-6}	(10^{-6})est.	2.6
Cr^{50}, n-γ, Cr^{51}	0.044	0.20	11	3.0×10^{-7}	1.4×10^{-3}	8×10^{-6}	1.8×10^{2}
Mn^{55}, n-γ, Mn^{55}	1.0	0.005	13	7.4×10^{-5}	1.7×10^{-3}	3×10^{-6}	5.7×10^{2}
Fe^{58}, n-γ, Fe^{59}	0.003	0.01	0.83	1.7×10^{-7}	2.4×10^{-7}	1.5×10^{-8}	16
Co^{59}, n-γ, Co^{60}	1.0	0.001	22	4.2×10^{-9}	8.7×10^{-6}	10^{-6}	8.7
Cu^{63}, n-γ, Cu^{64}	0.70	0.001	4.3	1.5×10^{-5}	7.5×10^{-5}	6×10^{-6}	12

W = 261 gm for A^{40} and O^{16}, and 9.74×10^{4} for the remaining isotopes

TABLE 7

Element	λ	γ	MPC, c/m^3	$\frac{y}{MPC}$	Critical Organ
Sr^{89}	1.51×10^{-7}	0.047	2×10^{-8}	0.354	Bone
Sr^{90}	8.79×10^{-10}	0.052	2×10^{-10}	0.228	Bone
Y^{91}	1.41×10^{-7}	0.056	4×10^{-8}	0.197	Bone
Zr^{95}	1.23×10^{-7}	0.062	3×10^{-8}(est.)	0.268	Bone
Ru^{106}	2.20×10^{-8}	0.005	3×10^{-8}	0.004	Kidneys
Te^{129}	2.50×10^{-7}	0.002	4×10^{-8}	0.012	Kidneys
I^{131}	1.00×10^{-6}	0.030	3×10^{-9}	10	Thyroid
Xe^{133}	1.51×10^{-6}	0.063	4×10^{-6}	0.024	Whole Body
Xe^{135}	2.1×10^{-5}	0.067	2×10^{-6}	0.703	Whole Body
Cs^{137}	6.66×10^{-10}	0.061	2×10^{-7}	2×10^{-4}	Muscle
Ba^{140}	6.27×10^{-7}	0.062	6×10^{-8}	0.650	Bone
Ce^{144}	2.92×10^{-8}	0.052	7×10^{-9}	0.217	Bone

TABLE 8

VALUES OF $\frac{X}{MPC}$ AND $\frac{\overline{X}}{MPC}$ AT THE DISTANCE TO THE MAXIMUM CONCENTRATION AND AT 10^4 METERS

Condition	Distance	A^{41}		Cr^{51}		Mn^{56}		I^{131}	
		$\frac{X}{MPC}$	$\frac{\overline{X}}{MPC}$	$\frac{X}{MPC}$	$\frac{\overline{X}}{MPC}$	$\frac{X}{MPC}$	$\frac{\overline{X}}{MPC}$	$\frac{X}{MPC}$	$\frac{\overline{X}}{MPC}$
Mild Inversion	10^4	0.034	8.8×10^{-4}	2.1×10^{-3}	5.6×10^{-5}	5.5×10^{-3}	1.4×10^{-4}	0.86	0.022
Lapse	10^4	3.4×10^{-3}	2.7×10^{-4}	1.9×10^{-4}	1.5×10^{-5}	5.3×10^{-4}	4.1×10^{-5}	0.076	5.9×10^{-3}
Strong Lapse	10^4	3.9×10^{-4}	7.9×10^{-5}	2.0×10^{-6}	4.1×10^{-6}	6.0×10^{-5}	1.2×10^{-5}	8.2×10^{-3}	1.6×10^{-3}
Mild Inversion	4.75×10^3	0.070	2.0×10^{-3}	3.7×10^{-3}	1.1×10^{-4}	0.011	3.1×10^{-4}	1.5	0.043
Lapse	1.21×10^3	0.062	6.3×10^{-3}	2.8×10^{-3}	2.9×10^{-4}	9.1×10^{-3}	9.2×10^{-4}	1.1	0.12
Strong Lapse	417	0.051	0.014	2.3×10^{-3}	6.3×10^{-4}	7.4×10^{-3}	2.0×10^{-3}	0.92	0.25

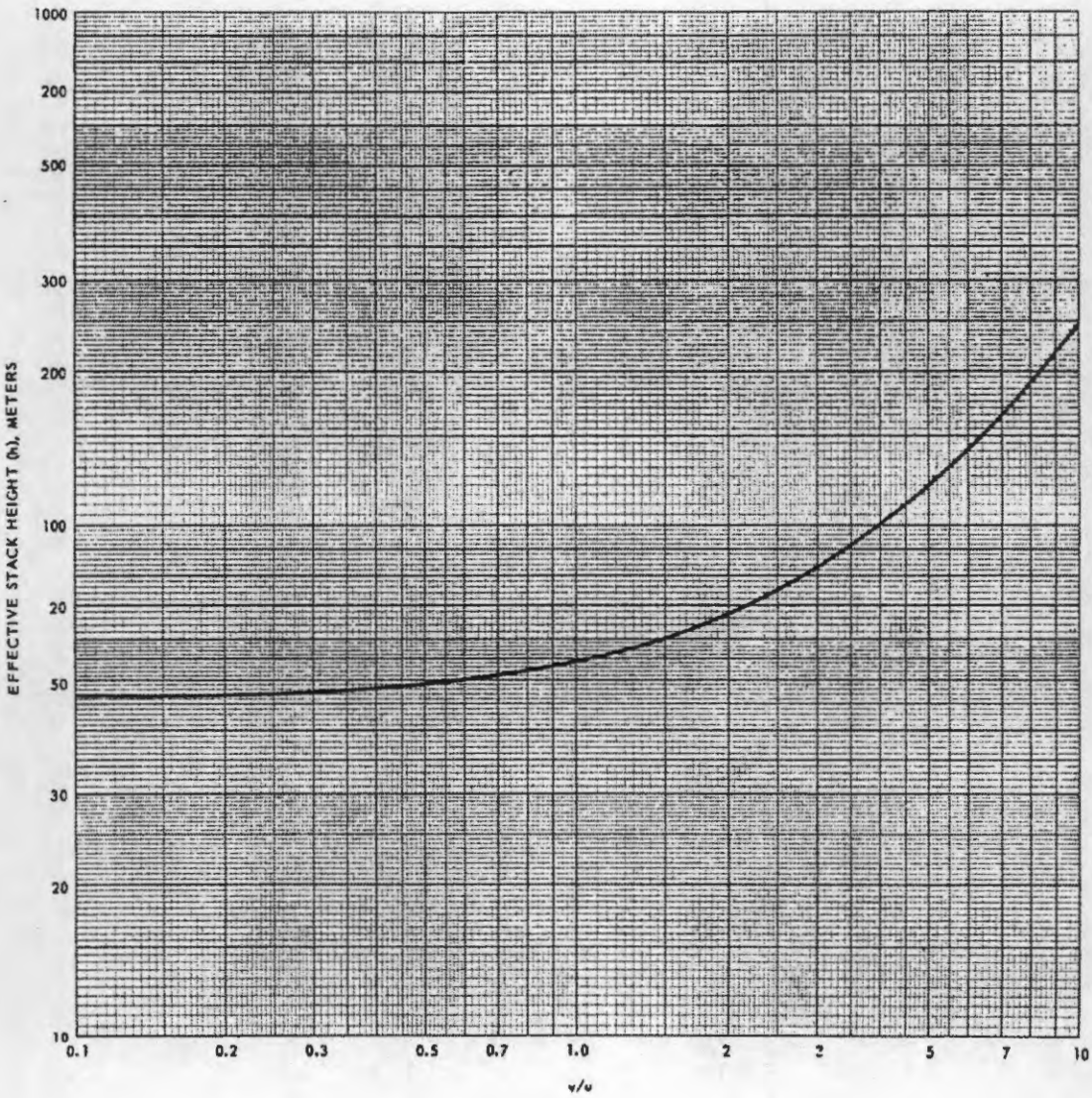

Fig. 34 - Effective stack height versus stack velocity divided by wind velocity

If it is assumed that the two fission products from any fission in this surface material are immediately released to the cooling airstream, the activity released in curies per second of any one fission product will be

$$C = \frac{\lambda y \times 5.24 \times 10^{14}}{3.7 \times 10^{10} \times 2} = 7.09 \times 10^{3}\ \lambda y$$

where

λ = disintegration constant of fission product
y = fission yield of fission product

The fission products of most importance are listed in Table 7 along with the values of λ, y, MPC in air, $\frac{\lambda y}{MPC}$ and the critical body organs affected. The value of $\frac{\lambda y}{MPC}$ is indicative of the relative hazard of the particular fission product, and it is apparent that the main hazard is due to I^{131} which is far worse than the sum of all the others.

The instantaneous concentration X and the average concentration $\overline{X}$* divided by the MPC's are given in Table 8 for the following values of n, u, h_e† and C.

Condition	n	u, m/sec	h_e	c
Mild Inversion	0.333	3	61	0.053
Lapse	0.25	5	54	0.108
Strong Lapse	0.20	7	51	0.223

*The average values of the concentration were calculated assuming uniform emission into an angle of 45°.

†Effective stack heights were calculated from formulas on page 142 in the appendix, and are shown plotted against v/u in Figure 34.

4. APPENDIX

4.1 CORE TEST FACILITY

The Core Test Facility (CTF) consists of shielding, an air supply, and other necessary auxiliaries and services for testing a succession of direct cycle cores, fuel elements, controls, and other components. Such testing is intended to demonstrate the feasibility of the direct cycle system and to verify or evaluate basic design features by direct experimentation.

4.11 COMPONENTS AND SYSTEMS

Shell

The primary function of the CTF tank is to provide shielding for the reactor. It consists of two cylindrical sections connected by an intermediate section of a right truncated cone as shown on Figure 35. The top cylindrical section is approximately 9 feet 10 inches long by 16 feet 6 inches in diameter, the truncated conical section approximately 1 foot 4 inches long, and the bottom cylindrical section is approximately 6 feet long by 15 feet 6 inches in diameter. The assembled height of these sections, including a 1-inch-thick plate on the bottom, is approximately 17 feet 2 inches. All parts of the tank shell except the 1-inch-thick base plate are fabricated of 3/8-inch stainless steel plate.

Fourteen tubes circumferentially located have been provided in the tank wall approximately 8 feet from the bottom for the insertion of nuclear sensing equipment. Other openings have been provided as required for the routing of the shield water pipe and for the drainage of the tank.

Shielding

The shielding contained within the tank shell is made up of borated water, steel, and lead. There are approximately 17,500 gallons of demineralized water (0.5 parts per million solids) to which 0.6 per cent by weight of boron has been added (about 3.55 grams of H_3BO_3 per 100 cc of H_2O). This solution is capable of reducing the neutron level below that which will cause damage or excess induced activity to components external to the shield. The design is such that the radiation level will not exceed 100 mr per hour three hours after shutdown of a 25-hour run at a reactor power of 40 megawatts. The shield water will fill all the space inside the tank shell that is not occupied by the cocoon, duct work, metal shielding, and support structure. It is circulated by means of piping which is located in the lower section of the tank. This piping consists of two manifolds, one inlet, and one outlet, and their attendant piping. Shield water from the facility is introduced through the inlet manifold, and is discharged below the cocoon and in the vicinity of the reactor core area. It is collected near the top section of the tank by 4 pipes which are fastened to the side of the lead and steel gamma shield. These pipes are then connected to the outlet manifold. A connection from this manifold is routed through the wall of the tank to the facility for cooling and recirculation.

The metal shielding consists of several parts. The sides of the reactor will be shielded by a cylindrical shield around the core. This cylinder is 73 1/4 inches high, 67 inches in diameter, and 10 1/2 inches thick. The 10 1/2-inch thickness consists of two cylinders of 0.75-inch thickness of stainless steel plate enclosing 9 inches of lead. This assembly is capped off on top by a 2 1/2-inch-thick stainless steel ring, and on the bottom by a 1 1/2-inch stainless steel ring. There is a gap of 2 1/2 inches between the outside wall of the cocoon and the inside wall of the cylindrical shield. This space is filled with shield water which cools the shield by natural convection so that boiling will not occur.

The bottom of the reactor is shielded by a disc-shaped steel shield upon the outer circumference of which rests a circular side shield. The lower disc-shaped shield is 134 1/2 inches in diameter and 12 1/8 inches thick. It is composed of a low carbon steel core encased in a 3/8-inch-thick stainless steel sheathing.

The cylindrical side shield is the same outer diameter as the base shield and is 12 inches thick at the point where it rests upon the bottom shield. On the outer circumference this thickness is maintained for a height of 30 inches, at which point it reduces to a diameter of 102 1/2 inches. This diameter is maintained to the top of the shield, which is 43 inches in over-all height. The inner diameter is tapered as shown on Figure 35 for clearance reasons. This shield is composed of mild steel clad with 3/8-inch-thick stainless steel plate.

The top shielding is composed of 2 cylindrical sections as shown on Figure 35. The construction of these shields is as described above, ie, mild steel with 3/8-inch-thick stainless steel cladding.

The shielding sections are so arranged within the tank shell in relation to each other that they not only serve as a shielding for the reactor, but also form the structure which supports the cocoon, the reactor core, and related equipment.

Shield Water System - The shield water system is shown in Figure 36. The shield water is collected in the tank at various locations and enters a single ring-type manifold having one 4-inch line leading outside the tank. From this point the water passes through a strainer (hole size 0.103 inch in diameter), and from the strainer it enters two centrifugal pumps operating simultaneously and in parallel. These pumps are rated at 300 gpm operating against a total head of 120 feet of water. From the pumps the water passes through two check valves and then enters the shell side of a 7,250,000 Btu per hour heat exchanger. The heat exchanger is single pass on the shell side and 4 pass on the tube side. The cooling water is supplied at 180 gpm from the facility pumps. It enters the heat exchanger at approximately 60°F and leaves at 140°F. The flow rate of the cooling water is modulated to keep the shield water temperature at the heat exchanger outlet at 150°F. For these conditions (shield water flow equals 600 gpm, heat transferred equals 7,250,000 Btu per hour, T_2 equals 150°F) the temperature at the heat exchanger inlet will be approximately 180°F. The shield water leaves the heat exchanger, passes through a flowmeter, and then re-enters the tank and is distributed through the system. The cooling water leaves the heat exchanger and is carried to a location directly above the facility drainage trench where it is dumped overboard. All of the above system is stainless steel, and all pipes are 304 stainless steel, schedule 10 seamless with welded fittings and standard A5A bolted and gasketed flanges. All castings are radiographically inspected per ASME boiler code, 1952, Sec. 8, Paragraph UW-S1, and are pressure tested where applicable. All welded joints are inspected radiographically and by nonfluorescent penetrant (Mil. I-6866). Where slipon flanges are used, the welds are inspected by nonfluorescent penetrant only because radiographic methods are not applicable. These flanges have two welds between the inside and the outside; therefore failure is extremely unlikely.

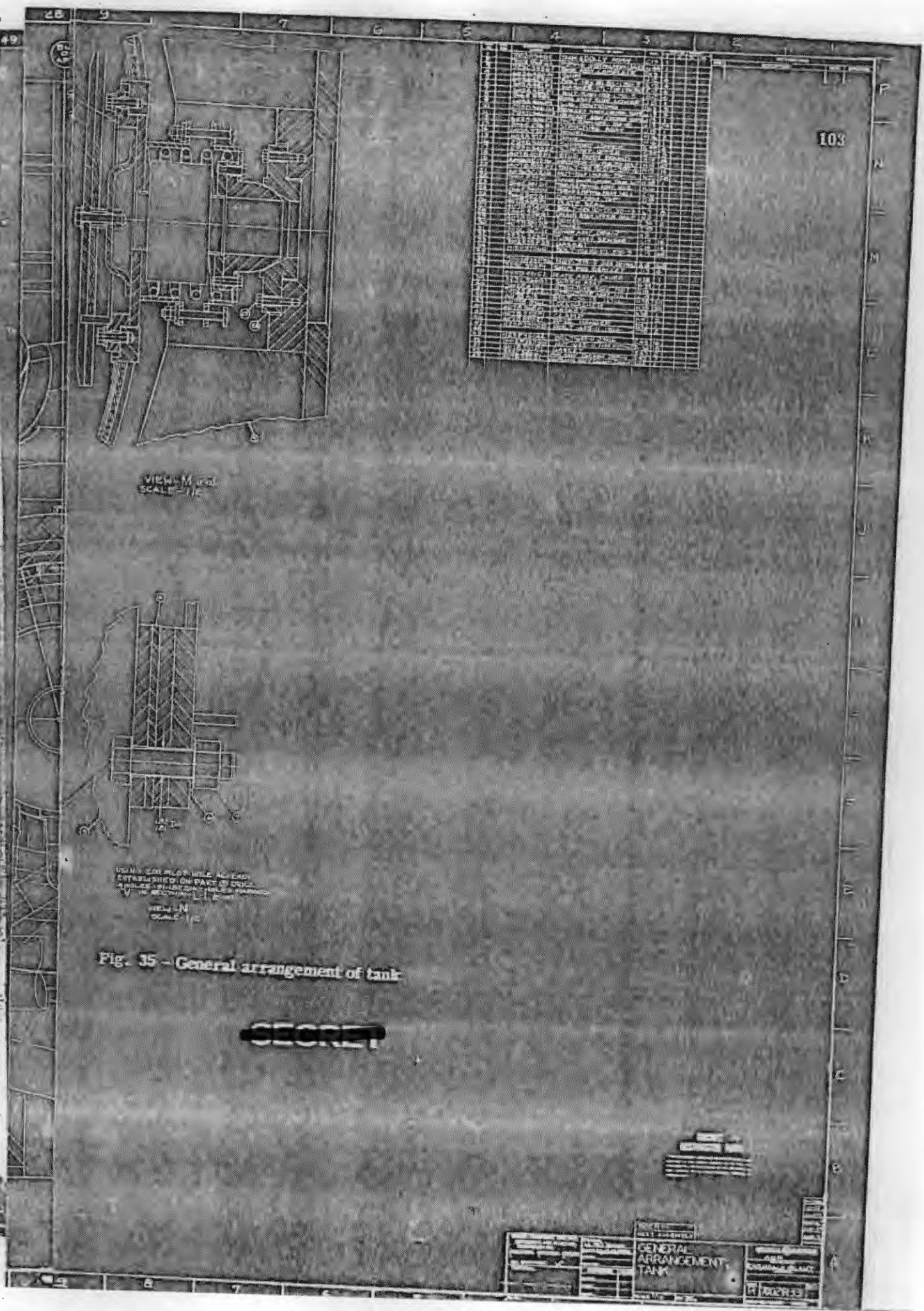

Fig. 35 – General arrangement of tank

[redacted]

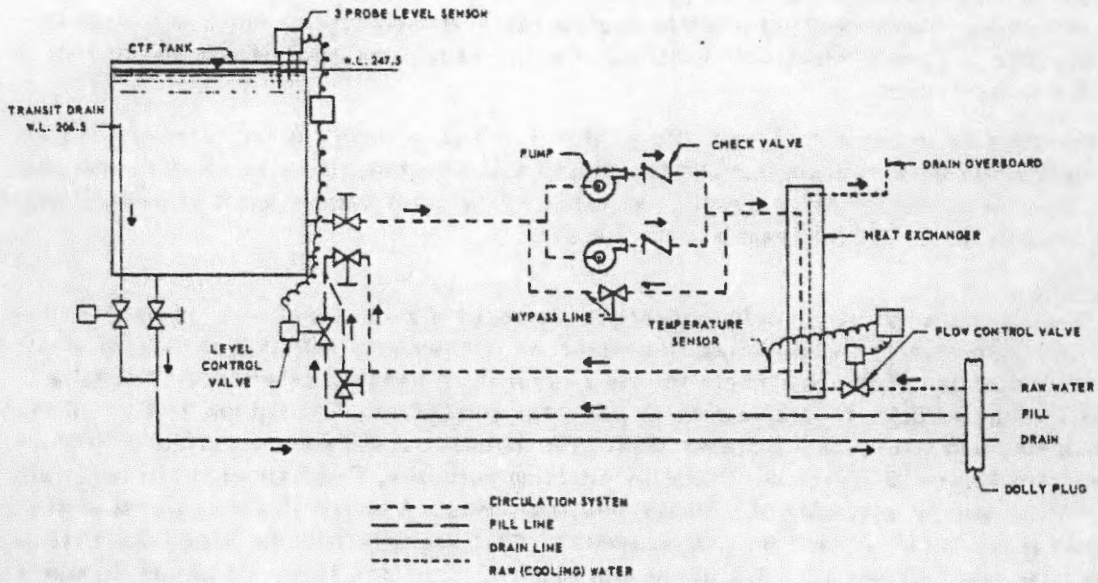

Fig. 36 - Shield water system

The fill and drain system consists of 4-inch stainless steel, schedule 10 pipes running from the facility plug to the CTF tank. The drain line is attached to the bottom of the tank, and the inlet line is attached to the heat exchanger outlet line.

The shield water level is maintained by a three-probe electronic level sensor which operates a 1-inch solenoid valve allowing demineralized water at 90 psi to enter the tank. When the water level falls below the intermediate probe (W. L. 243), the solenoid valve opens and remains open until the water level reaches the upper probe (W. L. 245). If the water level drops below the lower probe (W. L. 242), a warning light in the control room is turned on. The water level control system has a standby circuit which automatically takes over in case of electronic failure and at the same time energizes a warning light in the control room.

In order to drain the tank partially so that it is light enough for the turntable, a pipe is attached to the tank drain line and is equipped with an automatic valve which is operated by controls in the IET control room. Actuation of the valve automatically allows the tank to drain to W. L. 204 for transit to the hot shop.

Cocoon

The cocoon, a watertight cylindrical tank composed of three sections, is mounted within and supported by the shielding. Its centerline is coincident with that of the tank shell. This cocoon forms the receptacle for the reactor core and plug assembly. The walls of the cocoon are made of 1/2-inch-thick stainless steel plate. The bottom is a 1/2-inch-thick stainless steel convex dished head. The diameter of the cocoon varies in steps as shown on Figure 35 to provide offsets for shielding purposes. Two flanged and bolted joints are provided for assembly and disassembly purposes. A bolted flange and seal is provided at the top to support the plug assembly. This seal prevents the compressed air in the inlet plenum from escaping to the atmosphere. Fourteen 10-inch nominal diameter stub pipes equally spaced about the circumference are provided approximately 112 inches above the bottom surface of the dished head. These pipes are welded at assembly to the 14 riser pipes which connect to the cold torus. Fourteen 10-inch nominal diameter internally insulated stub pipes equally spaced about the circumference are provided immediately above the dished head. These are welded to the outlet pipes which transfer the heated air from the reactor to the hot torus. A 14-inch diameter opening is provided in the dished head for the insertion of the cocoon drain system fitting. This fitting bolts to the cocoon dished head and has a spring-loaded spherical seal which mates with a matching surface on the bottom disc shield. Its purpose is to drain any water which may collect in the cocoon during operation. The inner surface of the dished head is insulated. This insulation carries up the cylindrical sides of the cocoon wall for approximately 23 inches.

CTF Cocoon Drain System

A drain system has been provided to remove any fluids which may leak into the air passages of the cocoon. This drain system consists of a 4-inch opening located at the lowest point in the cocoon to which is flanged a flexible connector. The connector mates with and seals against a tapered fitting which is fastened to the lower gamma shield. An opening through the lower gamma shield leads through a pipe to outside the shield tank wall to a 100-gallon sump which is provided with high and low level probes. From the sump the line leads through a normally closed, power-actuated shutoff valve to four interconnected 100-gallon trap tanks slung under the dolly. The four tanks are for the purpose of collecting and containing a small leak which will be drained later in the hot shop. In case of a large leak, the contamination flushed out by the leak is expected to settle to the bottom of the tanks before they overflow. The trap tanks are provided with overflows which dump into a drainage ditch in the IET floor.

Ducting

External Ducting - External ducting for the CTF is designed to carry compressed air from the two X39 compressors to the inlet torus on the tank and return it to the turbine scrolls on the engines with a minimum pressure drop consistent with practical design.

The system must provide a bypass to permit the engines to operate singly on their unit combustors, and it must make provision for remote removal since contamination of the hot ducting is possible during operation. Operation for 1,000 hours is required at the following design conditions:

From the compressor scroll to the 24-inch duct, including the bypass

Airflow	60 lb/sec
Air Temperature	500°F
Air Pressure	53 psig
Duct Diameter	18 in. ID

Bypass to inlet torus

Airflow	60 lb/sec
Air Temperature	500°F
Air Pressure	53 psig
Duct Diameter	24 in. OD

Exit Torus to turbine valve

Airflow	60 lb/sec
Air Temperature	1500°F
Air Pressure	53 psig
Duct Diameter	30 in. OD

Turbine Valve to turbine scroll

Airflow	60 lb/sec
Air Temperature	1500°F
Air Pressure	53 psig
Duct Diameter	20 in. ID

The long lengths of stainless steel ducts and the high temperatures (1500°F) involved in the design present a difficult thermal expansion problem. Since these large expansions must be prevented from causing excessive stresses in the ducts, engine scrolls, and tank tori, a system of expansion joints was designed.

It was desirable to eliminate large structural members in the CTF, therefore the ducts were designed around a system of linked joints. Here the expansion joints act only as hinges in the piping and do not take axial movement.

The cold expansion joints (18 in. and 24 in.) are of the convoluted or non-equalizing type and designed for 1000-hour life or 2500 cycles.

The hot expansion joints (20 in. and 30 in.) are of the nodoid or toroid construction and designed for 1000 hour life or 2500 cycles.

The external ducts for one engine can be remotely removed from the CTF by breaking four Marman type clamps, disconnecting instrumentation lines, and lifting on an eye over the ducting CG. After being placed on a special stand, the contaminated parts of the ducting can be removed by loosening a Marman clamp in the bypass.

A layout of the duct system is shown in Figure 37.

Internal Ducting - Compressed air from the engine compressor is collected by a torus-shaped plenum on top of the tank. This torus is made up of fourteen 24-inch-diameter

straight segments of 1/4-inch-thick stainless steel plate. It is 168 inches in diameter on the centerline and is provided with two 24-inch-diameter flanged openings to connect the torus with the ducts that lead to the unit combustors. A 10-inch nominal diameter stainless steel tube extends downward from the center of each of the 14 segments. These inlet ducts bend through one 60° and three 90° turns and are welded to the stub pipes of the cocoon at the inlet plenum as noted above. Fourteen 10-inch nominal diameter stainless steel outlet ducts are welded to the outlet plenum of the cocoon as noted above. These ducts also bend through three 90° turns and one 45° turn. Each one of these outlet ducts has two expansion joints provided in the vertical straight section to allow for expansion during operation. These outlet ducts, as well as the expansion joints, are insulated on the inside. A torus at the top of the tank collects the air from these 14 equally spaced outlet ducts. This torus is made up of 14 straight segments of 5/16-inch wall thickness stainless steel tube, 30 inches in diameter. It is 209 1/2 inches in diameter on the centerline and is not insulated. Two 30-inch-diameter flange openings are provided to connect this torus with the ducts that lead to the unit combustors. Twelve flanged stub pipes are provided diametrically opposite 12 riser pipes. These are normally closed, but are provided for the insertion of equipment used in inspecting the insulated ducts. Two 30-inch-diameter flanged openings in the torus give access to the two other riser pipes.

Duct Valve System - The purpose of the CTF duct valve system is to control the flow of compressor discharge air through the proper CTF air passages for various operating conditions. The system will provide for paralleling and unparalleling engines to allow operation individually or together through the bypass or the reactor loop. A manual system for positioning each valve separately is to be provided. Provision will also be made for moving the duct valves to the proper position for afterheat removal by the blowers.

Interlocks will be provided to guard against electrical or pneumatic failures or positioning of the butterfly valves in a manner such as to block engine compressor airflow excessively. The basic airflow path for the CTF may be seen in Figure 38.

All duct valves are of the butterfly type, and each valve has an actuator assembly consisting of a main actuator, a static brake for interlock purposes, a dynamic brake for reducing shock at the end of valve stroke, and miscellaneous control accessories. The components are assembled with a mounting and coupling arrangement extending from the butterfly valve shaft. A hinge type coupling allows remote disassembly of the actuator from the valve. The actuator is supported by a constant support hanger from the structure and will remain in place when the ducting is removed.

The control system provides butterfly valve operations of two types, the "Jog" or manual operation of individual butterfly valves and the semiautomatic type which provides for group sequence motion of the valves. All control is initiated from the control console in the main control room.

Jog controls are provided for opening and closing the individual valves, with a "Fast Jog" override to step up operation from the normal jog speed of 20 seconds full stroke to the fast jog speed of less than 1 second.

Sequence controls are provided for automatic paralleling and unparalleling of engines from the common loop. An "Engine Switch" circuit is also provided to interchange the engines in the event of failure of the one which is operating the reactor on a one engine test. A blower position control is provided to move the butterfly valves rapidly to the position required for blower aftercooling. An interlock release is provided for operation at a pressure drop between the compressor and turbine which is higher than the normally anticipated values at which the interlocks will be set.

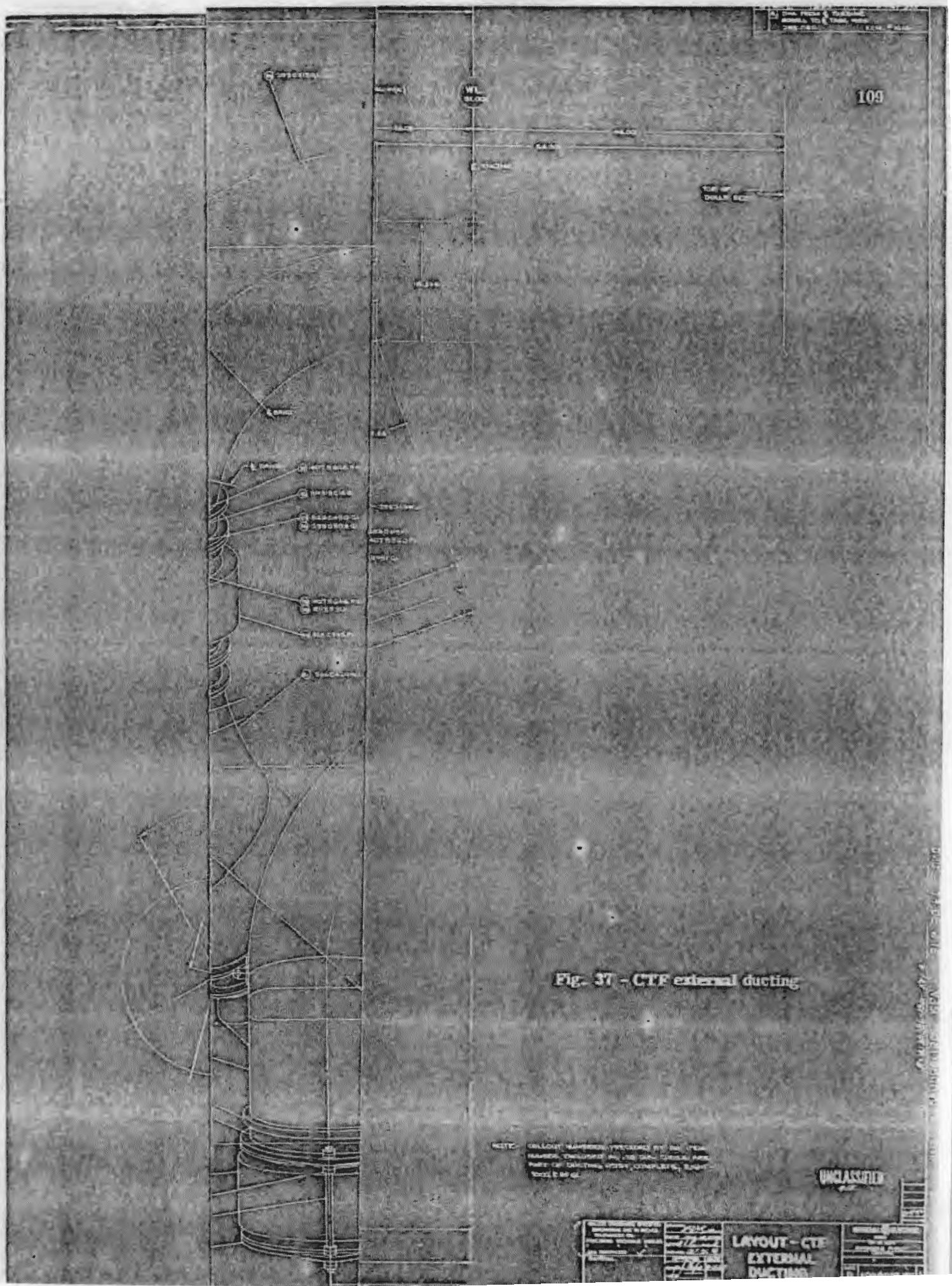

Fig. 37 - CTF external ducting

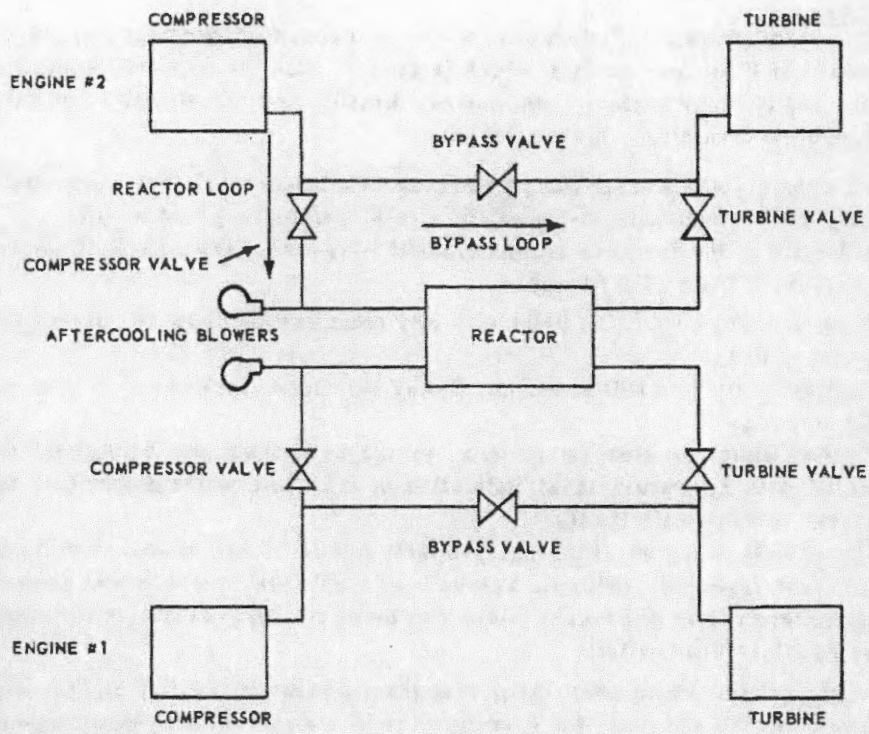

Fig. 38 - Basic airflow path for the CTF

It should be noted that this system endeavors to be fail safe inasmuch as possible. All control relays are in the normally open position, and for butterfly valve motion some of these must be closed by appropriate switching. Limit switches are designed on the same fail safe basis. The actuator components are also fail safe so that in case of any failure, valve motion will either be very slow or not possible. Thus it is not possible to have a valve block compressor airflow excessively except in the event that the operator release the interlock and manually jog a valve further closed.

Moderator System

The main moderator system (Figure 39), which operates during reactor operation, is designed to remove 3540 Btu per second, which is greater than the expected sum of maximum values of 2880 Btu per second from nuclear heating and 660 Btu per second from conduction through the insulation. It consists of:

1. Three 350 gpm stainless steel pumps pumping to a head of 135 feet, each driven by a 3500 rpm, 20-hp, 440-volt, 3-phase, 60-cycle, explosion proof motor
2. One 12 3/4-million Btu per hour stainless steel heat exchanger with 3/16-inch-thick shell and 3/4-inch OD x 17 BWG tubes
3. One thermostatically controlled 6-inch, 3-way stainless steel valve, driven by a 30 lb-ft electric motor
4. One thermostatically controlled 4-inch, 2-way stainless steel valve, driven by a 30 lb-ft electric motor
5. One 500-gallon stainless steel surge tank, vented to atmosphere through the facility and provided with necessary level indication to allow the system operator to keep the tank level between safe limits
6. The necessary stainless steel piping, properly insulated and heated in critical pipe runs to prevent freezing; metering valves to control flow; drain valves to drain the system completely; and expansion joints and loops to compensate for the expansion due to temperature differential

The aftercooling system which operates during transit between the IET and the hot shop is capable of removing the afterheat due to both fluid and core structure gamma absorption, 13 Btu per second, and due to conduction from fuel elements, 61 Btu per second. It consists of:

1. Two 60-gpm, stainless steel pumps, pumping to a head of 85 feet, each driven by a 3500-rpm, 3-hp, 440-volt, 3-phase, 60-cycle explosion proof motor
2. One thermostatically controlled stainless steel, forced draft, liquid-to-air heat exchanger cooled by a fan driven by a 3-hp, 440-volt, 3-phase, 60-cycle explosion proof motor
3. One manually operated stainless steel flow regulator
4. The necessary stainless steel piping similar to the main system, valves, etc.

Auxiliary Blower System

Two 2-speed blowers will be located on a structure above the dolly floor on the front of the dolly. At high speed (3600 rpm, 60 hp) each blower is capable of producing 4 pounds of air per second at 45 inches of water pressure. At low speed (1800 rpm, 7.5 hp) it is capable of producing 2 pounds of air per second at 11 inches of water pressure. The power source is 440 volts, 3 phase, 60 cycles.

A check valve will open with approximately 3 inches of water pressure differential between the blower outlet and the cold torus. Quick disconnects allow the cold torus to be removed without disturbing the blowers. Flexible ducts provide for expansion. Either blower is capable of providing aftercooling of a 20 megawatt reactor after 100 hours of operation.

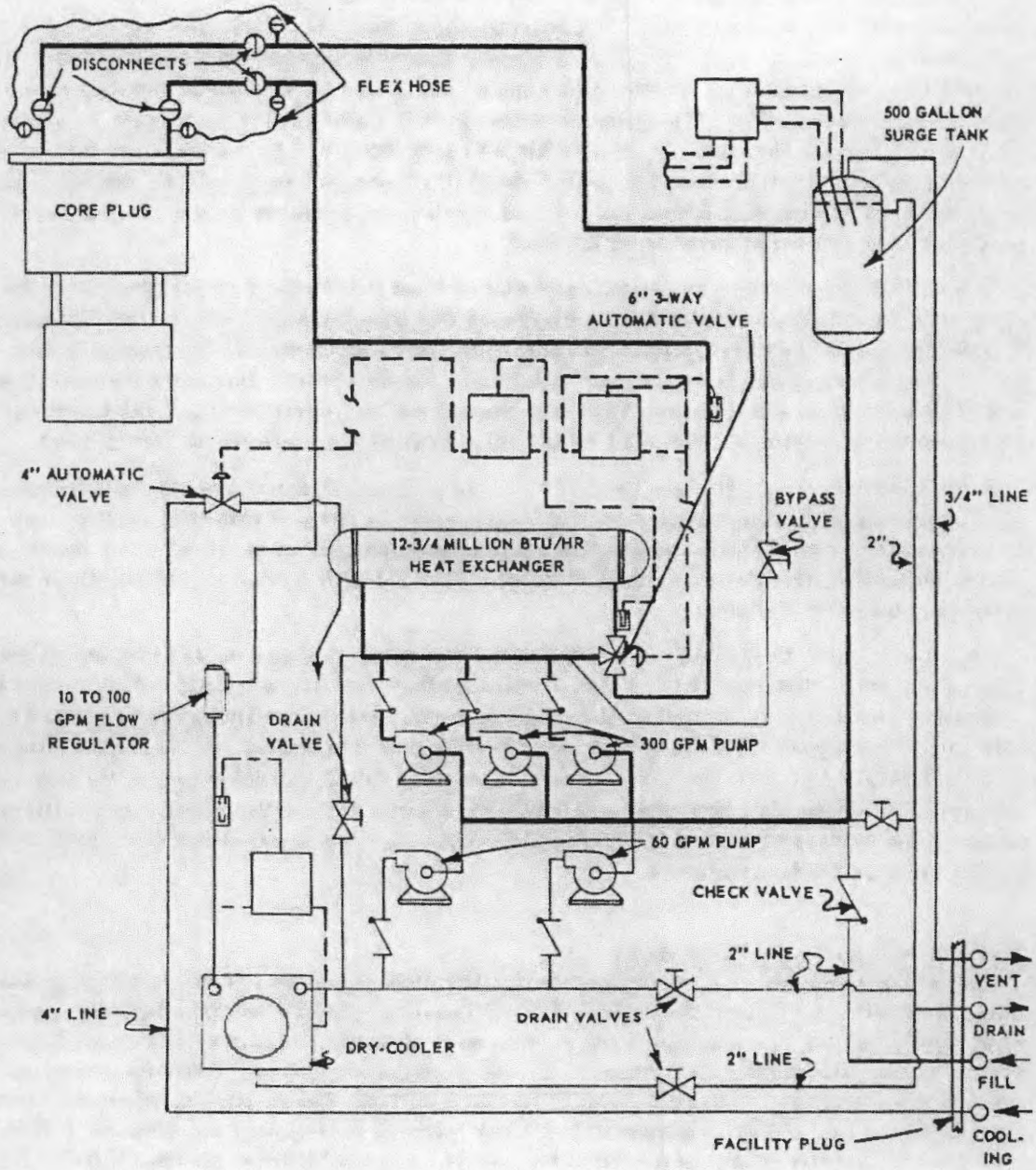

Fig. 39 - Moderator system

Auxiliary Power System

To supply power for operation of systems components on the dolly during transit from the IET to the hot shop, two self-regulated diesel-electric sets and controlling equipment were selected from the Caterpillar Tractor Company. Each diesel-electric set is capable of providing 20-kw, 0.8-pf, 440-volt, 3-phase, 60-cycle power, which is sufficient to operate two 3-hp moderator aftercooling pumps, one 3-hp heat exchanger fan motor, and one 7.5-hp blower motor. The controlling equipment consists of 4 batteries, 2 battery chargers, 2 circuit breakers, 2 local start and stop stations, 2 remote start and stop stations, and a low voltage transfer switch. Most of the controlling equipment is contained in a weatherproof control cabinet. Each diesel-electric set contains its own 22-gallon fuel tank providing 10 hours operation at full load.

The IET facility power or hot shop power will be used for the battery chargers when the dolly is in its corresponding location. Startup of the diesel-electric sets at the IET is as follows: the operator will press both glow plug buttons for approximately one minute (assuming cold weather, otherwise glow plug buttons are not necessary); then both start buttons are pressed to start the engines. Only one running set will carry the load; the other will be a standby. A maximum load of 17 hp is then placed on the main diesel-electric set.

If the main diesel-electric set develops trouble and the voltage drops, the aftercooling load is transferred to the running standby diesel-electric set. From then on the aftercooling load will remain with the standby set until the main set is repaired and a selector switch mounted in the control cabinet is reset. This selector switch can make either set main, and the other standby.

Upon the arrival of the dolly in the hot shop, two quick disconnects are coupled on the front of the dolly. The manipulator then presses both circuit breaker drop out buttons and both diesel stop buttons located on the diesel-electric sets. Facility power is applied to both quick disconnects - 440-volt, 3-phase, 60-cycle power to one disconnect for the aftercooling load and 115-volt, 60-cycle power to the other for the diesel-electric set battery chargers. When facility power is applied to the aftercooling power lines, the auxiliary pumps of the moderator system automatically restart, but the manipulator must press the blower start button for operation.

Turbojet Fuel and Lube Oil Systems

Fuel which is stored in a 50,000-gallon facility tank is pumped through filtering and water-separating equipment through the dolly disconnects and plug and into the dolly manifold. Here it is teed into separate supply lines, each of which contains an additional filter, shutoff valve, and engine disconnect. The fuel then passes into the turbojet inlet connection to the engine-driven pump, which forces it through the oil cooler, where it cools the lubricating oil, and then into the fuel control valve. If operation is on chemical power, a portion is directed to the unit combustor, while the remainder is returned through the facility plug to the facility supply tank. If operation is on nuclear power, the fuel control valve returns all the fuel to the facility tank. This system provides up to 28 gpm of JP3 fuel at 5 to 20 psig at turbojet inlet connection.

The turbojet lube system is self-contained for each turbojet. Each 32-gallon tank contains 28 gallons of oil and cannot be filled above this level. The oil flows from the tank by gravity through a motor-operated shutoff valve and through a disconnect into the turbojet inlet connection. Here the engine-driven pump passes the oil to the gear case and all bearings at a flow of about 3 gpm. The scavenger pump returns the oil through a cooler, out the engine outlet connect at a pressure of 15 to 29 psig, through a filter and flow switch, and back to the tank.

Fuel Drains - In order to drain approximately 1/2 pint of fuel from the engine turbine scroll after the pre-start procedure and to provide for the drainage of a small amount of fuel and lubricant from the pan under the disconnect panel, lines from the turbine scroll and from the fluid disconnect panel (this panel is mounted on the engine directly above the compressor casing) are attached to the engine and extend downward to a position about one foot above the dolly deck and directly above a funnel which is attached to the main dolly structure. The fuel is carried forward by gravity flow to a point above the facility drainage trench where it is dropped overboard. The line attached to the turbine scroll is equipped with a solenoid valve which is controlled from the IET control room. The line from the engine fluid disconnect panel is equipped with a manual shutoff valve. These lines are fitted with flame arrestors as is the funnel into which these lines discharge.

It is necessary to drain a small amount of fuel (less than one drop per second) from the fuel flow divider during operation on chemical fuel. Lines are attached to these flow dividers, and the fuel is carried by gravity down the structure and forward to the facility drainage trench where it is dumped overboard. This line will be equipped with a manual shutoff valve and a flame arrestor at the discharge end.

Coupling to the Exhaust Gas Handling System

The coupling mechanism consists of a circular flange 52 inches in diameter which is attached to the engine tailcone 11.64 inches aft of the rear tailcone flange. When the engine is inserted in the exhaust handling facility, this flange mates with another flange which is spring loaded and is attached to the facility. The actual seal between the two is performed by a 1/4-inch silicone rubber circular gasket similar to an "O" ring. The space between the spring-loaded flange and the stationary ducting of the facility is sealed by a band of silicone-impregnated Fiberglas cloth attached with band clamps to each flange. The springs are designed so that at initial coupling the sealing force is 200 pounds (1.3 pounds per inch of gasket). If the dolly is located within $\pm$ 0.5 inch of true location, the sealing force varies from 100 pounds to 300 pounds. When the engine is in operation and the tailcone has expanded 0.7 inch to the rear, the spring forces are increased to 340 pounds (2.2 pounds per inch of gasket). The range of loads due to variation of initial engine position is 240 pounds to 440 pounds. The load limit of 500 pounds is not reached until the springs are compressed 1.50 inches, which is 0.8 inch greater than the design point.

It is expected that misalignment due to tolerance buildup or change in loading on the dolly will result in engine deflection greater than 0.25 inch at the coupling location. The coupling allows for an initial misalignment (during insertion) of 1 inch. It further allows for an additional 0.5 inch of misalignment taking place during operation or after insertion.

All of the mechanism is constructed of 304 stainless steel, with the exception of the silicone and Fiberglas materials. These components will withstand temperatures up to 500°F. It is anticipated that the flow of secondary air will keep the temperature substantially below this; however, provision will be made to allow for admission of cooling air around the silicone parts.

The coupling mechanism described above is attached to a tapered duct 110 inches long having a diameter of 56 inches at the large (upstream) end and 45 inches at the small end. The engine tailcone extends approximately 80 inches into the large end of this duct. Attached to the forward end of the main tube are four ducts which are part of the secondary air system described below. This entire system is secured to the metal plates forming the roof of the coupling station.

The secondary air system consists of 4 ducts 24 inches in diameter attached to the forward (upstream end) of the main tube. These ducts turn and run parallel to the main tube so that their entrances extend outside of the IET building. At the intakes of these tubes

are spring loaded doors which essentially serve as check valves to prevent contaminated air from flowing out of the system in case of reversal of flow. These valves will be designed to open on pressure differentials of 4 inches of water (maximum).

The pressure recovery system consists of a diffuser having a 2 to 1 area ratio. The throat is 30 inches in diameter and approximately 23 feet long. The diffusing section goes from 30 inches in diameter to 42 inches in diameter and is 9 feet 6 inches long. At the forward end of the throat is a bellmouth which is 1/4 to 1/2 throat diameter from the tail-cone discharge nozzle. It is at this location that secondary air is drawn into the main stream. An expansion joint is placed in the throat of the system to take up expansion in the down-stream ducting.

4.12 X39 ENGINES

Two X39 turbojet engines are installed on the CTF to provide the cooling airflow for the test reactor while utilizing some of the reactor thermal energy. Each engine must operate using either energy from the reactor or from a chemical fuel combustion system.

The X39 engine is a major modification of the J47-GE-11 turbojet engine. The engine has been modified by removal of the combustion section and addition of a compressor discharge scroll, which collects compressor discharge air for ducting to the reactor, and a turbine scroll, which takes the hot air from the reactor and/or the chemical combustor and distributes it to the turbine inlet annulus. Other major changes include reduction of compressor flow capacity to obtain a suitable match between the compressor and turbine and installation of a new engine control system.

Engine Performance Data

Two operating points of the X39 engine are summarized in Table 9. Data given are for estimated performance of the X39 engine in the CTF with HTRE Core A at 5000 feet altitude on a standard NACA day. The exhaust nozzle is open.

Components

The following paragraphs give a description and a statement of the purpose of each of the major mechanical components or sections shown on the engine cross-section drawing in Figure 40.

The purpose of the bulletnose, bellmouth, and inlet section is to convey the engine airflow with a minimum of pressure drop to the compressor inlet and to provide a suitable geometry for measurement of the compressor inlet flow, pressure, and temperature. The compressor inlet is protected with a screen which consists of streamlined wire. All of these components are substantially identical to those used on the standard J47 engine.

TABLE 9

X39 PERFORMANCE DATA

Engine Speed, rpm		Compressor Inlet	Compressor Discharge	Turbine Inlet	Turbine Exhaust
	Temperature, °F	41	425	1440	1120
7950	Pressure, psi	12.2	63	46	15.5
	Airflow, lb/sec	62	61	60.5	61
	Temperature, °F	41	295	1190	980
6000	Pressure, psi	12.2	43	31.5	12.6
	Airflow, lb/sec	46.5	45.5	45	46

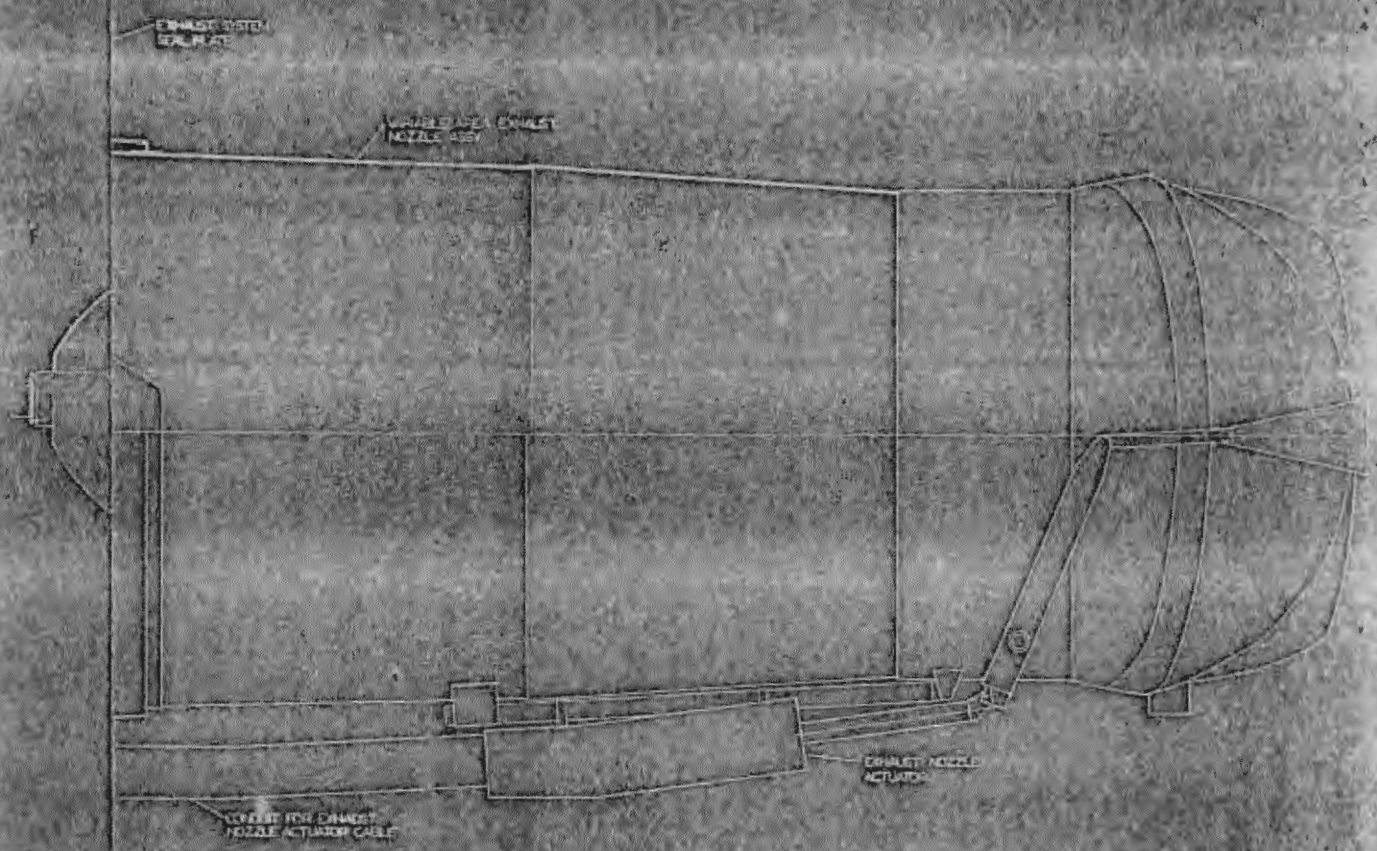

Fig. 40 - Simplified cross section of the X39 engine

[redacted]

The gear case provides mechanical drive for a number of engine accessories by means of gearing from the main shaft. The gear case also provides for application of the engine starter power to the main shaft. All engine control and accessory components requiring a mechanical drive from the engine shaft are mounted on the front face of the gear case. Such components include the engine fuel pump, the lubricating oil pump, the overspeed governor, the overspeed switch, the engine control tachometer, the engine indicating tachometer, and the engine starter. A functional description of the control and accessory components will be given below. The gear case is substantially unchanged from the basic J47 engine.

The purpose of the compressor is to take in atmospheric air and to raise its pressure to about 5 atmospheres at full speed. The X39 compressor is substantially identical to the J47 compressor except that the compressor blade tip diameters have been reduced. This was accomplished by cutting off the tips of the rotor blades and by manufacturing a compressor casing with a smaller inside diameter and with shorter stationary blades. These changes in compressor geometry give a net reduction of compressor airflow of about 25 per cent as compared with the basic J47 engine.

The midframe provides structural support of the compressor casing, the center bearing, mounting pads, and the aft frame. The aft frame is the nonrotating structural member between the center and rear bearings. The J47 midframe is used in the X39 without significant modification. The X39 aft frame is modified to provide for cooling and for structural support of the turbine scroll.

The compressor scroll collects the compressor discharge air. The turbine scroll distributes the air to the turbine inlet annulus. Both scrolls are made from the same basic toroidal form. The compressor scroll has 8 inlet pipes which mate with the midframe openings originally provided in the J47 for the combustion cans. The turbine scroll provides for mounting of the turbine nozzle diaphragm and the tailpipe.

The turbine diaphragm and rotor convert the energy of the hot gases entering the turbine into shaft power. Both components are used without modification.

The purpose of the variable area exhaust nozzle is to provide a duct for the exhaust gases and to allow variation of the exhaust nozzle area for engine control purposes. The exhaust nozzle used on the X39 engine is the exhaust nozzle for the J47-GE-17 reheat engine with the reheat fuel nozzles and flameholders removed. The exhaust nozzle assembly incorporates thermocouples for use in the engine temperature control system and straightening vanes to minimize tailpipe pressure losses resulting from swirl in the gases leaving the turbine.

A number of auxiliary flow systems are incorporated into the X39 engine design. Vents are provided for proper pressure distribution around the oil seals at the various bearings; cooling airflow is provided on the compressor rotor discs and at both the forward and rear faces of the turbine wheel; and air is bled from the compressor discharge for cooling the aft frame. Figure 41 is a schematic diagram of the vent, cooling, and bleed air systems.

The only change made in the bearings and shafting of the J47 in converting it to the X39, mentioned before under the heading of the "Engine Compressor," was the reduction of the compressor blade height by cutting off the blade tips.

The unit combustor is required to provide chemical energy for starting and to make up the difference, if any, between the energy supplied by the reactor and the energy required by the engine at the desired operating point. The unit combustor consists of 10 combustion cans and fuel nozzles in a suitable casing which is mounted as part of the ducting vertically above the turbine scroll inlet. Figure 42 is an outline drawing of the unit combustor.

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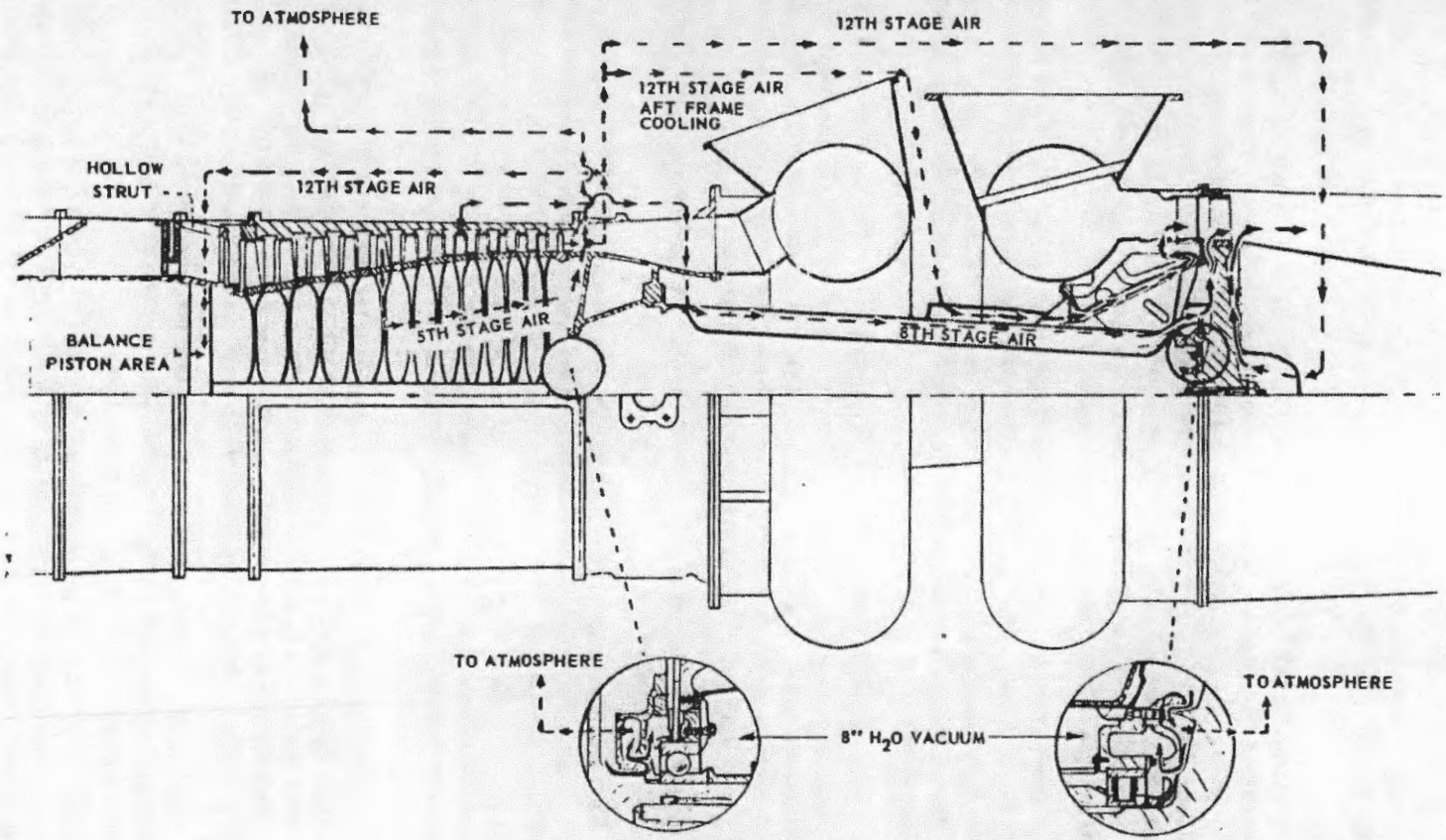

Fig. 41 - Vent, cooling, and bleed systems

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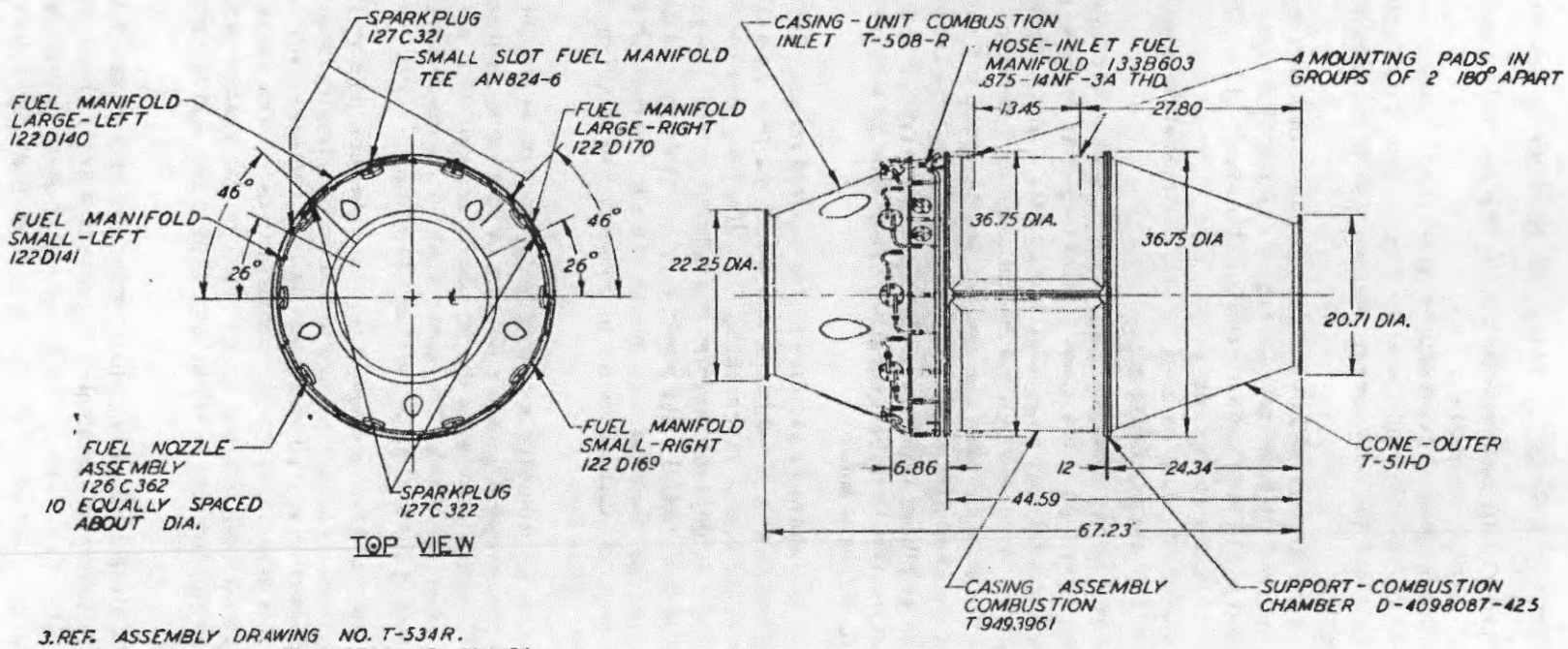

3. REF. ASSEMBLY DRAWING NO. T-534R.
2. WEIGHT OF UNIT COMBUSTOR = 571 POUNDS.
1. ALL DIMENSIONS ARE REFERENCE.

Fig. 42 - Unit combustor

Control System

The X39 engine control system is designed to staisfy the following major requirements.

1. The engine control system shall be independent of the reactor control system except for certain emergency system connections.
2. The engine control system shall provide safe operation of the engine using energy from the reactor and/or energy from chemical combustion. Satisfactory control operation must be provided for both energy sources with either single engine or parallel engine operation.
3. The chemical fuel control system will provide the chemical fuel energy necessary in addition to the reactor energy to operate the engine at the desired operating point. The engine control system will automatically readjust the chemical fuel flow to compensate for changes in reactor energy output.
4. The engine control system will only be used for test cell operation in which a fairly low degree of dynamic accuracy is necessary.

The basic engine control system is composed of two servo loops which are linked thermodynamically by the engine. Operation of the speed control loop is as follows (Figure 43). The signal representing the desired engine speed selected by the engine operator is compared with the signal from the engine-driven control tachometer generator. The error signal representing the difference between the desired engine speed and actual engine speed is amplified by the speed control amplifier, which incorporates a lead-lag circuit for servo stabilization. The amplified speed error signal runs the variable area jet nozzle actuator in the appropriate direction to correct the speed error. The jet nozzle opens to increase speed and closes to decrease speed.

The temperature control loop operates as follows. The desired turbine discharge temperature as set by the engine operator is compared with the signal from the engine exhaust pipe thermocouples. The error signal representing the difference between the desired tailpipe temperature and actual tailpipe temperature is amplified in the temperature control amplifier and the associated fuel control valve power supply. The output of the fuel control valve power supply runs the chemical fuel control valve in the open direction if the tailpipe temperature is lower than that called for or in the closed direction if the temperature is higher than that called for.

The engine control system incorporates a circuit designed to close the chemical fuel control valve if the actual engine speed becomes 150 rpm or more greater than the called for speed. Such a situation might arise when the jet nozzle actuator is in one of its extreme positions, ie, fully open or closed. The speed at which the speed override might become active is determined by the setting of the speed selector.

The ultimate engine protection from overspeed while on chemical energy is achieved by means of a bypassing type overspeed governor which is driven directly from the engine gear case. The ultimate protection against overspeed while on nuclear energy is by means of a double overspeed switch also driven by the engine gear case. One set of overspeed switch contacts is set to open at 8100 rpm and is connected into the reactor power setback circuit. The other set of switch contacts is set to open at 8200 rpm and is connected into the reactor scram circuit.

The purpose of the speed and temperature control amplifiers is to compare the desired and actual speed and temperatures and to amplify the resulting error signal. Both amplifiers use magnetic amplifier components. The power output stage in the speed control amplifier is a pair of relays. The speed control amplifier lead-lag circuit utilizes a capacitor resistance circuit. The temperature control amplifier incorporates a magnetic constant-current reference and magnetic amplifier stages throughout.

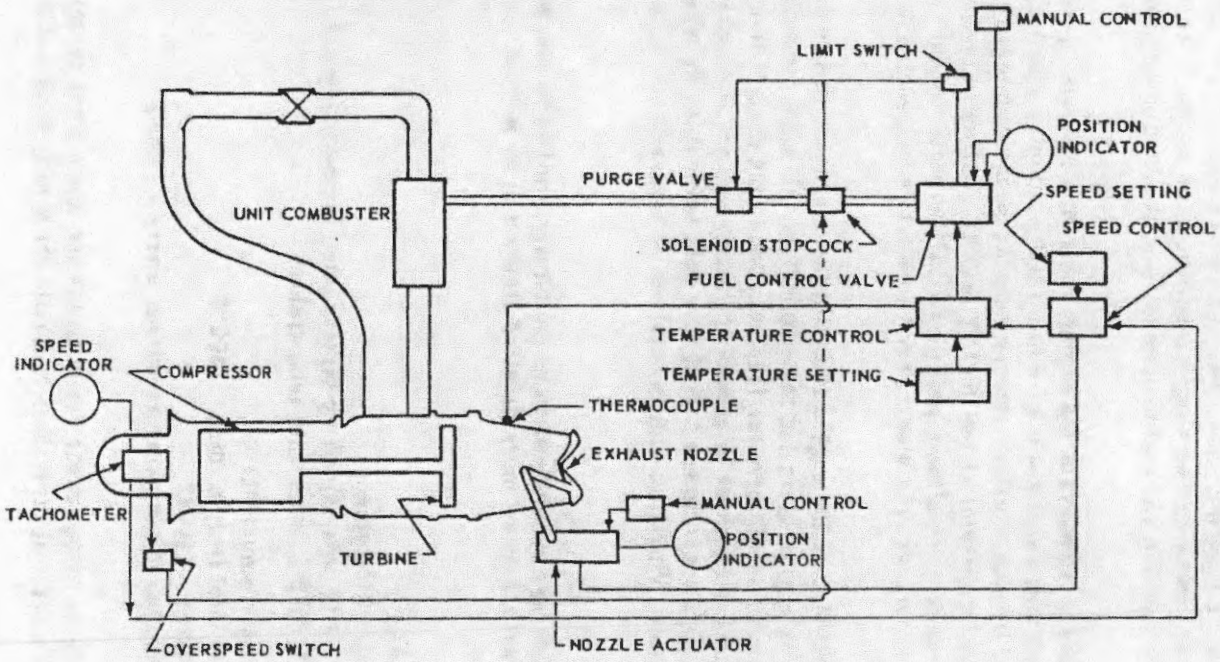

Fig. 43 - X39 control system

The above engine control description applies to the engine automatic control system. A manual system is provided so that the engine fuel valve and jet nozzle positions may be manually controlled for use during starting and emergency operation. Engine control is transferred from automatic to manual by means of two multicontact transfer switches, one for the temperature control loop and one for the speed control loop. Manual control of the fuel control valve and jet nozzle position is effected, with the transfer switches in the manual position, by intermittent or "jogging" operation of switches which supply 28-volt d-c power direct to the fuel control valve and jet nozzle actuator. Each engine is provided with a pushbutton emergency stop switch and pushbuttons for unit combustor ignition test and ignition shutoff.

The engine starter is provided to accelerate the engine rotor to a suitable speed for ignition of the unit combustor and then assist the engine to its self-sustaining speed. Starting power on the X39 is provided by an air turbine starter mounted on the engine gear case and driven by 25 psig air at room temperature from the IET facility. Airflow to the starter is controlled by a combined pressure regulating and electrical solenoid "on-off" valve which is mounted in the engine bulletnose. The starter can be used in emergencies to provide aftercooling of the reactor.

Sensory instrumentation is provided on the engine to assist the operators in safe engine operation and to obtain data on the engine operating characteristics. All engine instrumentation outputs are converted to electrical form for transmission to the control room and data recorders. Temperature data is obtained by means of thermocouples. Pressure data is obtained by means of strain gage transducers. Fuel flow data is obtained by means of a rotary induction type flow meter. Vibration data is obtained by means of induction type vibration pickups.

Operating Limits

The operating conditions which are considered to be physically limiting on the engine are listed below. These and various other more detailed limits will be written into appropriate operating instructions.

Engine Physical Speed

Maximum steady state - 7953 rpm

Maximum transient overspeed - 8400 rpm

Minimum self sustaining speed is determined by turbine inlet temperature and is approximately 3000 rpm for a 1600°F turbine inlet temperature.

Turbine Inlet and Turbine Exhaust Temperatures

Maximum steady state turbine inlet temperature - 1500°F

Normal turbine inlet temperature - 1400°F

Maximum transient turbine discharge temperature during starts - 1600°F

Engine Vibration

The vibration limit at the engine compressor front flange and the turbine scroll rear flange for both horizontal and vertical directions is 5 mils for steady state and 8 mils for transient operation.

Engine Operation Experience

Although a considerable total of X39 engine operating hours has been accumulated, the number of engines and amount of operating time to date do not warrant general statistical conclusions. However, several major aspects of X39 engine operation to date are given below as a general indication of experience. A total of 475 engine operating hours have been accumulated on 8 individual engines. Of this total 62 hours were at rated engine speed. Of the total engine hours, 156 were at a turbine inlet temperature of 1300°F or greater.

In the course of the development testing which gave the operating time listed above, a number of failures of non-rotating parts occurred. However, none of the failures were of such a nature as to bring the engine to a stop.

Due to the close relationship between the X39 engine and the J47-GE-11 engine, which was indicated under the engine description, some data are presented below relative to the reliability of the basic J47 turbojet engine.

The most complete statistical data on failures in the J47 engine are from Air Force service flight operation. The information which is available from GE-AGTD Development Test Cell operation is rather incomplete in nature and is difficult to apply inasmuch as development tests often involve intentional infractions of engine operating limits or rules. One important aspect of the statistics on engine failures in military service which should be noted here is that there is a close correlation between infractions of engine operating limits and failures experienced. This is not to say, however, that all failures are a result of breaking operating rules.

During 3 months of 1954 engines of 3 different models of the J47 operated for a total of approximately 328,000 engine hours with no turbine wheel failures and a total of 93 incidents of compressor damage by foreign objects. The 93 incidents include all types of damage from the most trivial blade nicks to loss of the complete compressor blading. However, none of the compressor failures in the engine model which is basic to the X39 resulted in catastrophic rupture or blowup of the compressor. Several compressor casings were cracked or ruptured, but no incident resulted in high velocity fragments.

The accumulated statistics to November 1, 1954, on turbine wheel failures in the engine type basic to the X39 show an incidence of one turbine wheel failure per 100,000 hours of operating time.

The accumulated statistics to November, 1953, on compressor blade failures in two models of the J47 engine show 12 instances of compressor blade fatigue failure (one or more blades failed in a compressor) in 614,000 engine service hours.

4.13 CTF PERFORMANCE AND DESIGN SPECIFICATIONS

1. Maximum power level	40 megawatts
2. Radiation level at tank side surface	
During operation at 40 megawatts	
Maximum thermal neutrons	2×10^6 neut/cm^2-sec
Maximum fast neutrons	10 rep/hr
Maximum gammas	100 r/hr
Three hours after shutdown and after 25 hours run at 40 megawatts	100 mr/hr
3. NACA standard conditions	
Pressure	12.2 psia
Temperature	41.2°F
4. Design point airflow	
One engine	60.9 lb/sec
Two engines	121.8 lb/sec
5. Reactor outlet air temperature	
Maximum	1500°F
Normal operating	1450°F

6. Design point air pressure available at compressor scroll exit — 58.0 psia

7. Pressure drop - compressor scroll to torus inlet
   - One-engine operation — 0.43 psi
   - Two-engine operation — 0.43 psi

8. Pressure drop - torus inlet to core inlet
   - One-engine operation — 0.5 psi
   - Two-engine operation — 0.7 psi

9. Available pressure drop across core
   - 60.9 lb/sec - one-engine operation — 8.0 psi
   - 121.8 lb/sec - two-engine operation — 6.8 psi

10. Pressure drop - reactor exit to torus outlet
    - One-engine operation — 1.0 psi
    - Two-engine operation — 2.2 psi

11. Pressure drop - torus exit to unit combustion inlet
    - One-engine operation — 0.5 psi
    - Two-engine operation — 0.5 psi

12. Exhaust handling system

	10-Velocity Head Filter	No filter
Primary flow	60 lb/sec	60 lb/sec
Secondary flow (closed nozzle)	17 lb/sec	90 lb/sec
Secondary flow (open nozzle)	5 lb/sec	74 lb/sec

13. Turbojet lube system
    - Flow rate (maximum) — 5 gpm
    - Discharge Pressure — 15 to 45 psig (nom. 25)
    - Operating temperature range — -65°F to 160°F

14. Turbojet fuel system
    - Flow rate (maximum) — 28 gpm
    - Fuel inlet pressure — 5 to 20 psig
    - Outlet pressure to unit combustor (maximum) — 250 psig
    - Operating temperature range — -65°F to 160°F

15. Air systems (Turbojet starting and duct valve control)
    - Maximum flow — 1 lb/sec
    - Maximum pressure — 200 psig

16. Moderator cooling system
    - Circulating flow rate — 850 gpm
    - Heat removal capacity — 3540 Btu/sec
    - Operating temperatures
      - Entering plug — 150°F
      - Leaving plug — 180°F
    - Raw water cooling media
      - Flow rate — 330 gpm
      - Temperature entering heat exchanger — 60°F
      - Temperature leaving heat exchanger — 140°F

17. In-transit moderator cooling system

Circulating flow rate	60 gpm
Heat removal capacity	59 Btu/sec
Operating temperatures	
Entering core	150°F
Leaving core	157°F
Cooling medium	air
Horsepower rating	3 hp

18. Shield cooling system

Circulating flow rate	600 gpm
Heat removal capacity	2000 Btu/sec
Operating temperature	
Entering tank	150°F
Leaving tank	175°F
Raw water cooling medium	
Flow rate	180 gpm
Temperature entering heat exchanger	60°F
Temperature leaving heat exchanger	140°F

19. Argon gas for nuclear sensors

Maximum temperature	100°F
Maximum pressure	100 psig

20. Auxiliary blower system

High speed	
Blowers required	one per engine operating
Flow per blower	4 lb/sec
Pressure	45 in. H_2O gauge
Power requirements	440 volts, 3 phase, 60 cycles
Motor rating	60 hp
Low speed	
Blowers required	1, on standby
Flow per blower	2 lb/sec
Pressure	11 in. H_2O gauge
Power requirements	440 bolts, 3 phase, 60 cycles
Motor rating	7.5 hp

21. Auxiliary power system

Power units required - two; one for operation, one for standby

Alternator rating - 20 kw, 440 volts, 3 phase, 60 cycles, 0.8 power factor

22. Wheel loading on dolly

	Allowed	Actual
Forward static load	45,000 lb/wheel	42,700
Forward moving load	40,000 lb/wheel	40,200
Aft static load	45,000 lb/wheel	37,500
Aft moving load	40,000 lb/wheel	36,300

23. HTRE weights, pounds

	Structure	Fluid	Total
Live plug	39,000	11,000	50,000
CTF tank components	305,000	142,000	447,000
Air pump and auxiliary equipment			
Turbojets, ducts, valves	27,000		
Structure	13,000		
Water equipment	15,000		
Auxiliary power equipment	11,000		
Dolly			66,000
Structure	33,300		
Tanks and piping	3,000	2,000	
Trucks	38,400		
Facility plug	4,600		81,300
Total			644,300

4.2 REACTOR CONTROL SYSTEM

4.21 CONTROL ROD OPERATION

The HTRE reactor has 21 shim-scram rods and 2 dynamic rods to control the excess reactivity which is needed to meet performance specifications. The rod locations are shown in Figure 44. Fuel element depletion and poisoning, as well as moderator temperature effects, make it desirable to have 5 per cent excess reactivity. The control effectiveness of the 21 shim-scram rods has been calculated to be about 9 per cent. Shim-scram rods are arranged in four groups or frames of rods so that each frame contains approximately the same reactivity as any other frame of rods. Each shim-scram rod is provided with its own independent drive actuator and serves the dual purpose of a scram as well as a shim rod.

In the HTRE core the effectiveness of a control rod is greatest near the central axis and diminishes with radial distance from this axis. During reactor startup and subsequent operation, the shim rods are normally withdrawn one frame at a time to maintain reasonable flux symmetry. Therefore the rods of each frame are forced to move in synchronism. If a given rod is lagging, additional torque is applied by its drive mechanism. Frames of rods are withdrawn in a sequence such that a reasonably good radial flux gradient is maintained. When the frames are inserted, the opposite order is followed. This type of shim-scram rod operation is designated as sequence operation and is the basis for normal operation of the shim-scram rods. Sequence operation is mandatory when the controls are on automatic operation.

Special provisions make it possible to operate the shim rods in other than normal sequence. This is done by first placing the automatic-manual transfer switch on manual and then selecting a position on the selector switch. The selector switch, located on the shim rod monitor panel, has three positions. The first position places the rod in the control system for normal operation in frames; the second position selects the rod for individual control; and the third position removes the rod completely from the control system to maintain it in a fixed position. The individual rods can be moved using individual control switches located on the control panel. Individual rod position is indicated on the panel. Up to five rods may then be individually positioned. The withdrawal of shim rods is possible only when all withdraw interlocks are closed. However, the operator may insert shim rods in sequence or simultaneously at all times.

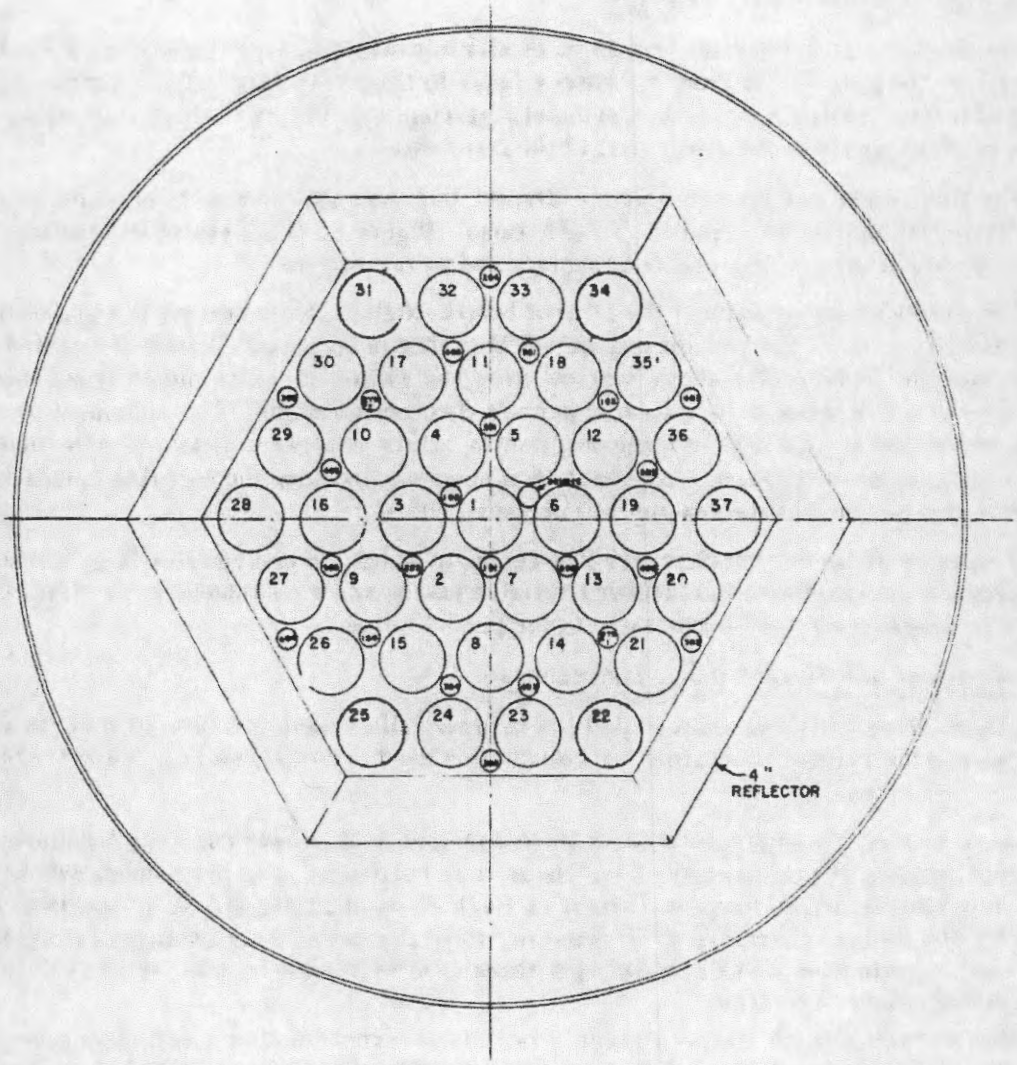

Fig. 44 - Control rod positions in the HTRE core

When first bringing the HTRE critical, manual control of the dynamic rods is provided. The dynamic rod in normal operation is automatically withdrawn when electric power is turned on prior to reactor startup.

The source rod is manually controlled and is used only during startup.

4.22 STARTUP INSTRUMENTATION

The startup instrumentation is defined as all components used for control or indicators in raising the power level from the source range to the power range. The ultimate objective of reactor control is to provide automatic startup; but, in this reactor, manual operation is necessary over the lower part of the flux range.

The flux levels can be conveniently divided into four ranges according to the instrumentation or operation required in each range. Figure 45 is presented to illustrate the ranges, which are source, counter, period, and power regions.

The source range consists of the neutron levels existing in the reactor due to a neutron emitter in the core. The reactor is subcritical in this range since all rods are seated before startup. The counter range extends over the region in which the neutron counting equipment is the primary indication of neutron flux multiplication. The equipment used in this region registers a limited number of fission pulses on scalers and count rate meters. As shim rods are withdrawn, multiplication of neutrons provides the increased count rate. It is in this region that the reactor will become critical.

The period and power ranges cover that region in which the neutron flux is great enough to operate ion chambers and furnish a reliable period and a continuous power level indication. Appreciable heat is generated in the period range.

Source Range and Counter Range Instruments

A large source of neutrons is sealed in a hydraulically driven rod located near the central axis of the reactor. Indicating instrumentation used in this region is given on the block diagram in Figure 46.

Three fission chambers located in the top plug provide pulses resulting from neutron induced fissions at the chamber. Each chamber is positioned in an instrument well by its own mechanical drive. Range selection of fission chamber signals is accomplished by moving the fission chambers to preselected fixed positions. This arrangement permits the fission chambers to be completely withdrawn after startup so that they will not burn out during reactor operation.

Before startup, each fission chamber is fully inserted so that a sufficient minimum reading is available at the count rate meter. Each fission chamber signal is boosted by a preamplifier located at its drive actuator. The preamplifier signal is fed to the linear amplifier located in the control room. The output of the linear amplifier is fed to the count rate meter and period amplifier, each channel being monitored by its own indicating meter prior to the auction circuit. Period and count rate signals of the three channels are auctioned, and the largest readings are indicated on the log count rate recorder and period meter. Each of the three channels is completely independent; if one fails, the other two will continue to provide the necessary information through their normal channels. A period trip circuit is the only automatic safety shutdown in these channels. If the fission pulse rate increases too rapidly in the counting range, this trip circuit will indicate a scram.

Period Range Instruments

Criticality will be achieved in the counter range and the flux will then be raised to the period range by manual control of shim rods. When the flux level enters the period range,

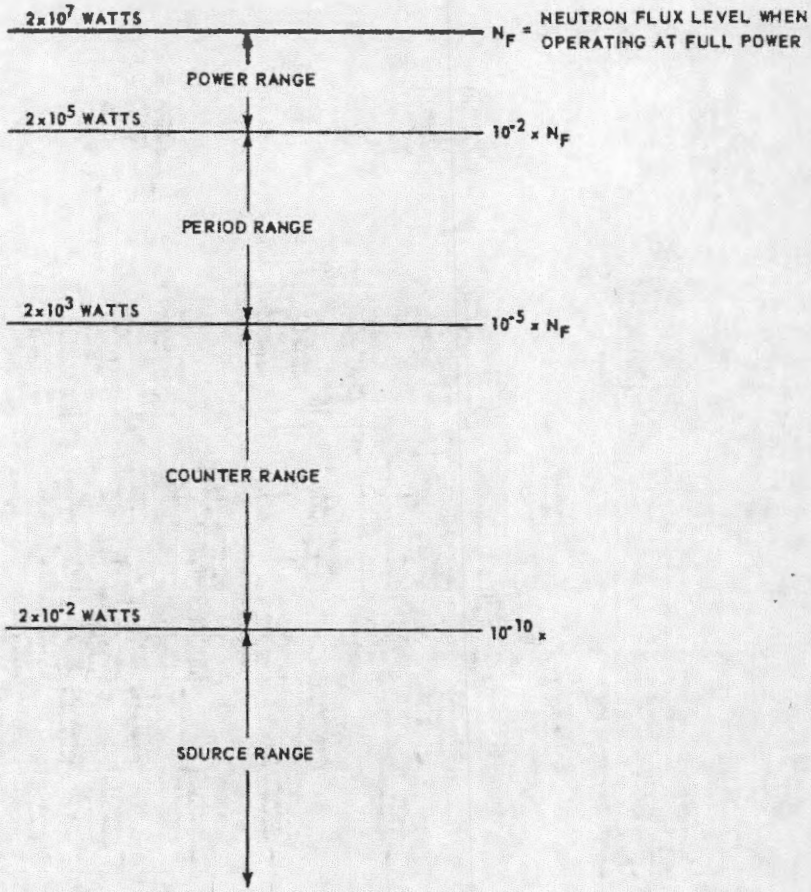

Fig. 45 - Division of neutron flux range

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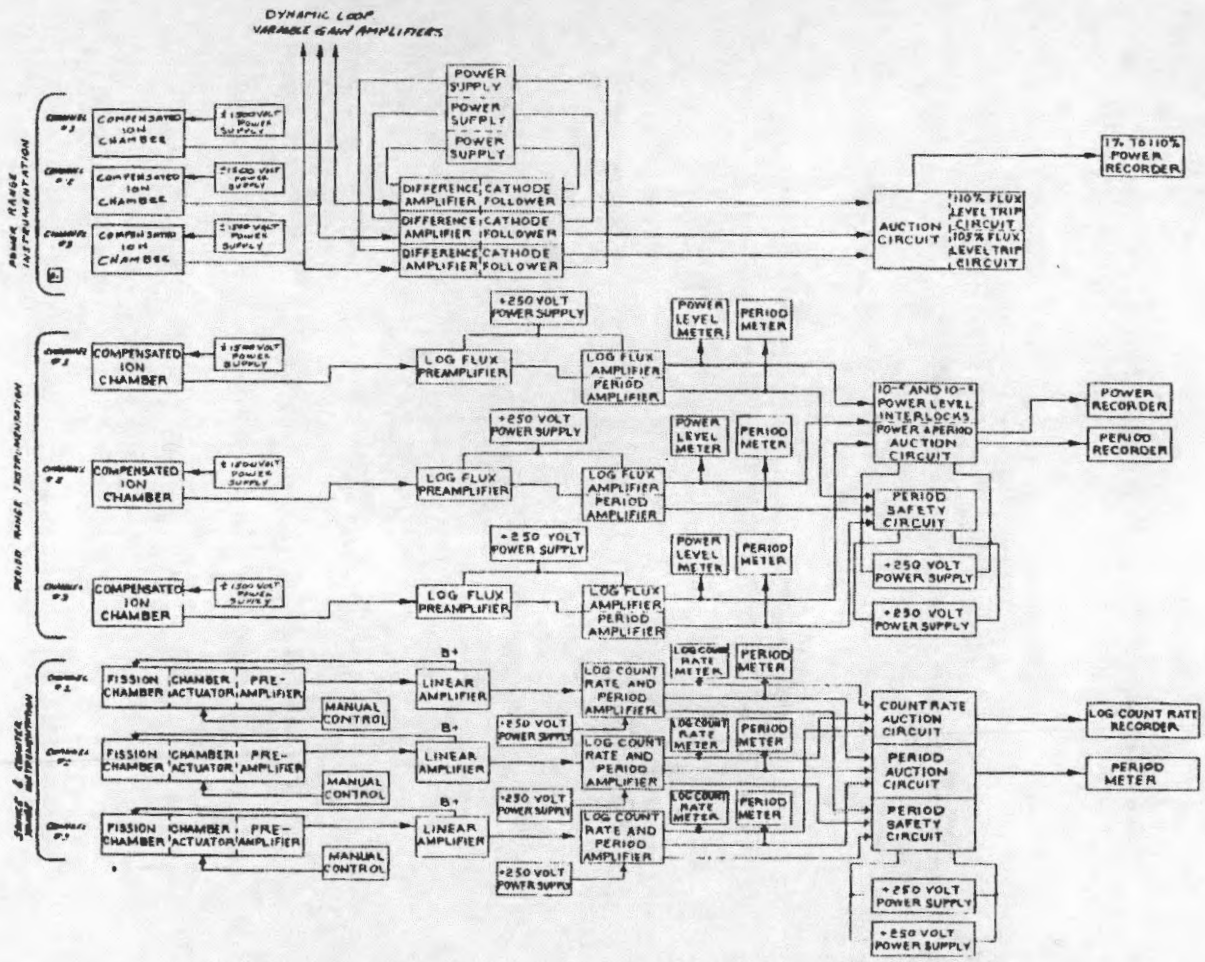

Fig. 46 - HTRE reactor startup and operating instrumentation

SECRET

the ion chambers supply a reliable and continuous period and flux level signal. These signals are then used to control a semiautomatic operation in the period range (ie, control of the rate of change in power level but not the power level).

Figure 46 shows the complete instrumentation used in this range. The three compensated ion chambers shown in the center left position supply the three channels used. The gamma compensated chambers are located in the side of the CTF shield and are constructed to eliminate about 98 per cent of the gamma signal which would exist in an uncompensated chamber. The signal which remains is a good indication of the neutron flux level and not a combination of the neutron plus gamma flux level. The signals are amplified by preamplifiers located on the dolly, and the output is transmitted by coaxial lines to the log flux and period amplifiers located in the control room. Power level and period indication is provided for each channel. These channels provide a period trip level for protection against rapid change in flux level, and, in addition, they are used to control the 10^{-5} and 10^{-2} power level interlocks. Period signals in this range are also used to provide for automatic control of the shim-scram rod withdrawal. When the shim-scram rod transfer switch is placed on automatic and the power level is greater than 10^{-5} times full power, the period signals regulate the withdrawal of shim-scram rods to maintain the period between 10 and 15 seconds. A 5-second period will scram the reactor. A power level and a period recorder are used to record the auction circuit output. Automatic withdrawal of shim-scram rods ceases when the power level rises to 10^{-2} times full power. At this time, the power servo takes command.

4.23 POWER RANGE SERVO SYSTEM

A schematic of the dynamic-rod control system is given in Figure 47. Three linear ion chambers in the top shield plug supply flux level signals at the servo input. Each of the current signals will be calibrated to match a fixed current reference supplied by the magnetic voltage reference power supply A. The difference between the two matched current levels appears as error voltages at the output of amplifiers K1. Potentiometers A, B, C, and D are ganged and driven in response to the power demand setting. Potentiometer D determines the reference current while A, B, and C maintain a relatively fixed gain factor in the reactor servo loop. The impendance matching amplifiers, K2, provide a means for setting the loop gain in the field and matching the electronic amplifiers to the magnetic preamplifiers. The diode units are used to select only the highest signal of the three amplifiers for controlling rod position. Therefore failure of one channel will not prevent operation of the other two.

Two magnetic preamplifiers are used for boosting the current level and for matching this error signal against rod position feedback. There are two dynamic rods, each with its own controlling magnetic amplifier and hydraulic drive unit; therefore one unit will not interfere with the operation of the other. As can be seen from the schematic, the magnetic amplifiers supply a 2-phase servo motor which in turn controls the pilot valve. The rod position is fed back by a rod-driven synchro transmitter whose stator is connected to that of a corresponding control transformer located in the magnetic preamplifier. With this arrangement, a given error signal at the magnetic preamplifier calls for a definite rod displacement and eliminates one integration in the servo loop. The two rods are electrically synchronized by matching their feedback positions against the common control winding signal at the input to the magnetic preamplifiers.

There is in addition a third magnetic preamplifier used as a discriminator to control the two shim - scram rod follow-up relays. The ± error signal when exceeding adjustable limits operates these relays, which, in turn, control the shim rod motion by sequence operation.

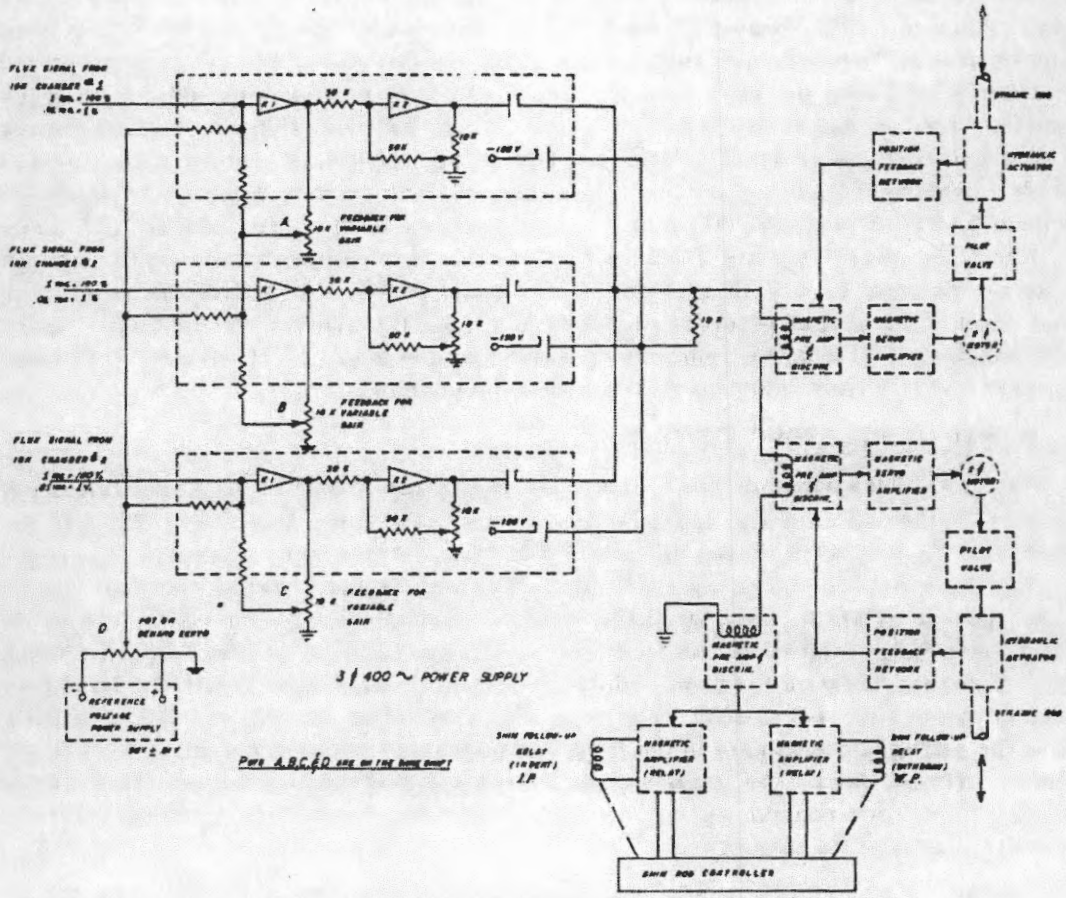

Fig. 47 - HTRE reactor servo control loop

4.24 OPERATING PROCEDURE FOR REACTOR CONTROLS

Reactor Startup

In order to start the reactor, electric power is turned on in the startup instruments and power range servo system. As soon as the servo power is on, the dynamic rods automatically withdraw from the reactor. Since the combined dynamic rods contain about 0.9 per cent $\Delta k/k$ and since the reactor is subcritical by a greater amount prior to startup, the reactor will not go critical by withdrawal of the dynamic rods alone. The dynamic rods normally remain withdrawn until the power range is reached, but are available at all times for rapid insertion in case of an accident. The withdrawal of the dynamic rods gives permission to withdraw the shim-scram rods.

The reactor operator will begin withdrawing shim-scram rods in sequence operation (mentioned previously) while observing nuclear startup instruments. Once the operator knows that the reactor is critical, he withdraws the shim-scram rods a limited distance beyond the critical position - just enough to place the reactor on the shortest period safe for startup. After the power level has reached 10^{-5} times full power, the control may be transferred to automatic operation of the shim-scram rods. After placing the transfer switch on automatic, the control system regulates the position of the shim-scram rods to bring the reactor from 10^{-5} full power to the power range at a safe rate corresponding to a period between 10 and 15 seconds. The 15-second period prevents withdrawal of the shim-scram rods, and the 10-second period calls for insertion of the shim-scram rods. Both signals are relay commands so an on-off servo operation regulates the power rate of change while operating on automatic in the period range. At 10^{-2} full power, the dynamic rods move into the neutral band and stop further shim-scram rod motion.

Shim-scram rods are always controlled in sequence when the automatic-to-manual transfer switch is placed in the automatic position. The transfer switch must be in the manual position below 10^{-5} full power before shim-scram rods can be withdrawn but may be in either position above this power level at the discretion of the operator. The manner in which the operator is capable of controlling a frame of rods is not restricted to sequence operation when the transfer is placed in the manual position. The operator, while in manual control, may select a desired frame of rods and operate that frame independently of those not selected. However, inasmuch as the dynamic rod servo cannot be placed on manual, the power demand servo always has automatic control of the flux in the power range. The frame selector switch is automatically bypassed when the shim-scram rod transfer switch is placed on automatic, ie, sequence operation is strictly enforced during automatic operation. The operator may override the automatic control system only by insertion of the shim-scram rods and never by withdrawing them. He may insert all rods simultaneously or in sequence at all times at his own discretion.

Reactor Control in the Power Range

Once the flux level is brought up to the power range, the dynamic rods provide continuous control. The present dynamic control system is expected to regulate the power level to within 1 per cent. The dynamic rods contain about 0.9 per cent $\Delta k/k$, and the servo control is rigid enough to compensate for all foreseeable internal fluctuations of reactivity. The servo operates two dynamic rods electrically synchronized although each rod has its own individual hydraulic actuator; if one should fail or lock into a fixed position, the other will continue to operate independently. The dynamic rods are normally maintained within a neutral position band by a servo error signal, which, upon exceeding a set limit, initiates shim-scram rod movement. Shim-scram rods always move in a direction to maintain the steady state position of the dynamic rods within the neutral band. When the

flux demand lever is set at any desired point above 10^{-2} times full power, the dynamic rod withdraws, thus calling for shim - scram rod withdrawal. When the desired power is reached, the dynamic rod will have returned to the neutral position.

4.25 REACTOR SCRAM AND SETBACK

The HTRE reactor control system provides three ways of reducing the power level when operating in unsafe regions or under undesirable conditions. Conditions which may take the reactor into unsafe regions are corrected short of scram. This corrective action calls for a setback in power levels by insertion of the dynamic rods until a predetermined lower power level is reached. When returning from a setback condition, the power rate of change is scheduled so that a sudden increase in power level is not possible.

Other conditions which are not of immediate concern (but which should be corrected before operation is continued) result in a reactor shutdown. The shim rods are all driven in simultaneously when these conditions occur. After the trouble has been discovered and corrected, a complete startup is necessary before operation may be continued.

When the reactor or engines are operating in unsafe regions which are considered to be potentially hazardous, the scram solenoid latches are released, and all spring-loaded shim-scram rods are driven in at the maximum rate. Each shim-scram rod is completely inserted within 200 milliseconds.

The safety channel operation is outlined below. A list of conditions which initiate the corrective measures mentioned above are included.

1. Definitions

Scram

Scram is a rapid simultaneous insertion of all shim-scram rods and dynamic rods. Spring-loaded shim-scram rods are tripped by release of a magnetic latch. Scram may be initiated both manually and automatically.

Setback

Setback is a percentage reduction in reactor power level when defined limits are exceeded. In this operation the action of dynamic rods plus the sequence operation of shim - scram rods is initiated automatically when approaching unsafe regions of operation. The level of setback is adjustable to 1 to 30 per cent immediate reduction in power level.

Shutdown

Dynamic rods are driven into the reactor. This in turn calls for insertion of all shim-scram rods by sequence operation. Selected shim-scram rods being used for experimental purposes are also inserted.

2. Followup System

Scram Followup

After a scram the shim drive actuators are all driven simultaneously to the fully inserted position in approximately three minutes.

Provisions are made for automatically latching the rods after the clutch mechanism has been driven to the engagement position.

Dynamic and shim - scram rod withdrawal is prevented until the demand potentiometer has been returned to its minimum position and the reset switch is turned on.

A reset is not possible until the scram trouble has been corrected. Annunciator lights are provided to locate the trouble and an annunciator reset switch is provided so the operator acknowledges the fault.

Setback Followup

Provisions are included to prevent the reactor power from returning to its original level until the cause has been corrected and the operator acknowledges by using the reset switch provided.

A rate limit on the return to original power level has been provided so no sudden stop increase in power level occurs when the reset switch is depressed.

Shutdown Followup

As in the scram followup system, dynamic and shim-scram rod withdrawal is prevented until the demand potentiometer has been returned to its minimum position and the reset switch depressed.

3. Summary of Conditions Causing Scram

The following is a list of scram conditions.

Reactor flux level above 1.10 N, where N is the rated full power flux level

Reactor period less than 5 seconds from the startup region to full power

Fuel element rupture

Fuel element temperature above 1900°F. Ten selected thermocouples are used to supply the necessary signals.

Air discharge temperature from the reactor above 1600°F. Four thermocouples are used.

Moderator temperature > 200°F

Moderator outlet flow - scrams on loss of flow

Sudden pressure change over a prolonged period. Loss of airflow

A 400-cycle power failure

Engine speed above 8200 rpm

Manual scram

4. Setback Conditions

Engine speed above 8050

Flux level above 1.05 N

Fuel element temperatures above 1850°F. Ten selected thermocouples are used to supply the necessary signals.

Reactor discharge temperature above 1500°F at four locations

Manual setback

5. Shutdown Conditions

Failure of any five control fuel element thermocouples

Standby diesel generators not operating

Loss of substation primary power. Can continue to operate five minutes longer on the standby power; but, if at the end of this period the substation power has not returned, the reactor is shut down.

Secondary coolant loss. Water is used to remove the heat generated in the reactor via a heat exchanger. If the water flow ceases on the secondary side, shutdown is enforced.

Excessive air activity at air discharge

Manual shutdown

4.3 HYDROLOGY AND GEOLOGY OF THE NRTS AREA

The National Reactor Testing Station area is located in the southeastern portion of Idaho, west of the Snake River. The eastern boundary is from 25 to 40 miles westerly and northwesterly from Idaho Falls. The elevation of the area ranges from 5000 feet at the southern end to approximately 4,800 feet at the northern end. Four streams drain into the area.

There is no agriculture within the area and very little surrounding the immediate boundaries.

The water table is at a depth of about 200 feet at the northern boundary of the IET site and about 550 feet at the southern boundary.

It is believed that at least 300 second feet constitutes the underflow beneath much of the NRTS area and that about 1500 second feet flows under part of eastern and southwestern portions. The rate of flow is estimated at an average velocity of one-half mile per year. It is believed that the nearest point of surface discharge is along the banks of the Snake River below the American Falls Reservoir, 75 miles from the site, where numerous springs issue from porous lava beds.

The entire area is underlaid by a series of Pleistocene lava flows, which are covered in places by soil or alluvium from a few inches to more than 100 feet in thickness. Logs of wells indicate that the successive flows occurred after considerable time intervals. The flows, which range in thickness from about 35 feet to 150 feet, are frequently separated by layers of sand, gravel, or clay.

The lava, wherever exposed, is very uniform in appearance and character and is very porous and vesicular in composition. Similar lava flows cover approximately 200,000 square miles in Idaho, eastern Washington and Oregon, and northern California. The lava is very fluid when hot and is thought, in general, to have issued from fissures rather than volcanoes. Its fluid character accounts for the large nearly flat level surfaces found in these areas. In addition to its vesicular character, which accounts for part of its porosity, lava flows frequently contain tunnels and cavities as the result of the top cooling and forming a stationary crust while the hot interior portion continues to flow, leaving a tunnel or cavity.

In places the surface of the lava is covered by gravel apparently deposited by Big Lost River or former streams. This gravel is one to two inches in size, and the pebbles are mainly fine grained limestone with some igneous stones. There is a gravel pit several hundred feet in diameter and about 20 feet deep near the site. The layers of gravel exposed in this pit average approximately six feet in thickness.

Near the sinks in the northern portion of the tract, the covering over the lava is fairly fine silt of unknown thickness. The log of the U.S.G.S. Well No. 7 in Section 27 T6N R31E, shows a depth of 126 feet before basalt was encountered. Most of this 126 feet is sand, silt, and clay.

The surface of the area is nearly flat, in general sloping gently to the north. Near the southeast corner and the northeastern edge are a few cinder buttes which rise two or three hundred feet, but otherwise the surface is very flat with elevations ranging from about 5,000 feet on the south to 4,800 feet at the north. The streams flowing into the area are Big Lost River, Little Lost River, Birch Creek, and Medicine Lodge Creek. These flow through shallow, meandering channels and disappear into the ground. No lakes or swamps have formed at these points.

Although many recorded earthquakes have been felt in Idaho, none were of sufficient intensity to cause more than minor damage to buildings. Of the 24 recorded earthquakes with epicenter within the State, seven had their epicenters within approximately 100 miles of the IET site, four to the southeast and three to the west. One of these, of unrecorded intensity was at Arco. The seismic map of the United States shows that most of Idaho, including the proposed site, is in zone 2, a zone where earthquakes of intensity to cause moderate damage may be expected.

Although the lava plain of the Snake River is geologically young, the surrounding mountains are mostly of great age. Some geologically recent faults appear to cross the plain beneath the lava beds, although their traces are not evident on the surface. None of these show indication of historically recent movement outside the lava plain. It may be expected that earthquake shocks will continue to be felt in the site area, but a prediction as to their intensity cannot be made with assurance.

It is believed that no serious damage is probable to structures soundly designed to resist shocks of moderate intensity. Movements may be sufficient to break underground pipe connections at faces of buildings since this damage has been of frequent occurrence in moderate intensity earthquakes. Some magnification of shocks may result in those portions of the site which are deeply covered with alluvium.

Surface drainage at NRTS is southerly toward a low area in which Big Lost River, Little Lost River, and Birch Creek formerly disappeared. Construction of dams at the headwaters of these streams and irrigation diversions have moved the disappearance points upstream. Although of very moderate slope over most of the area, the site has good drainage due to the limited rainfall and the permeability of most areas. Surface water is rapidly absorbed after rainfall. With the exception of Mud Lake, located northeast of the site, the land is well drained and devoid of swampy areas.

4.4 POPULATION DISTRIBUTION THE NRTS AREA

Within 30 miles of NRTS are approximately 1000 inhabitants at the present time. There are 7 communities or towns in this area each having a population of from 4 to 450. These towns are as listed.

Town	Population	Distance from Site (Miles)
Terreton	260	15
Howe	100	16
Monteview	43	15
Winsper	4	27
Hamer	90	28
Atomic City	450	29
Camas	30	30
Reactor Testing Station Central Facility	No Residents	20

In the area 30 to 50 miles from NRTS there are approximately 50,000 additional inhabitants.

The following are towns having a population of 300 or more in this outlying area.

Town	Population	Distance from Site (Miles)
Roberts	341	31
Arco	961	34
Lewisville	371	37
Dubois	430	37
Moore	300	37
Menan	432	38
Idaho Falls	19,218	42
Ucon	449	43
Rigby	1,826	43
Shelly	1,856	44
Iona	518	46
Blackfoot	5,180	47
Mackay	760	49
Rexburg	4,253	49
Sugar City	697	52
St. Anthony	2,695	55

The southeastern Idaho region, within 100 miles of the site, has a population of approximately 177,000. Pocatello is the only major city in the area.

The major population is located approximately 50 miles southeast of the site.

4.5 METEOROLOGICAL ASPECTS OF IET OPERATIONS*

The location of the ANPD site at the National Reactor Testing Station is shown in Figure 48. This area has the lowest elevation of the NRTS, and was at one time the site of end points, or sinks, of several rivers and creeks. The eastern bank of an ancient lake can be seen as a long arc of raised ground running generally north-south through the area. The surface is otherwise flat and level. The cover is mostly sagebrush and other desert plants.

The meteorological treatment in this report is based on two or more years of such data as temperature soundings, winds aloft soundings, tower wind and temperature data in the Central Facilities Area, and records from a recording weather station (designated as micro-net station "T") located about seven miles northeast of the ANPD site. Instrumentation and observational techniques are given in IDO-10020.†

Since the IET reactor will operate intermittently (the total number of hours per year not expected to exceed a few hundred), it is feasible to use meteorological advice to select periods favorable for its operation. It will be shown that 6 to 15 consecutive hours of suitable operating conditions are present almost every day in the year. It will also be possible to select suitable operating periods lasting as long as two consecutive days, if needed.

4.51 EFFECTIVE STACK HEIGHT

Because of the excessive temperature and velocity of the exhaust gases from this reactor, it is necessary to compute an "effective stack height," or height to which effluent

*Written by F. A. Humphrey and B. M. Wilkens of USWB in Idaho Falls.

†Humphrey, F. A. and B. M. Wilkens, Climatology of Stack Gas Diffusion at the National Reactor Testing Station, IDO-10020, March, 1952, U. S. Weather Bureau.

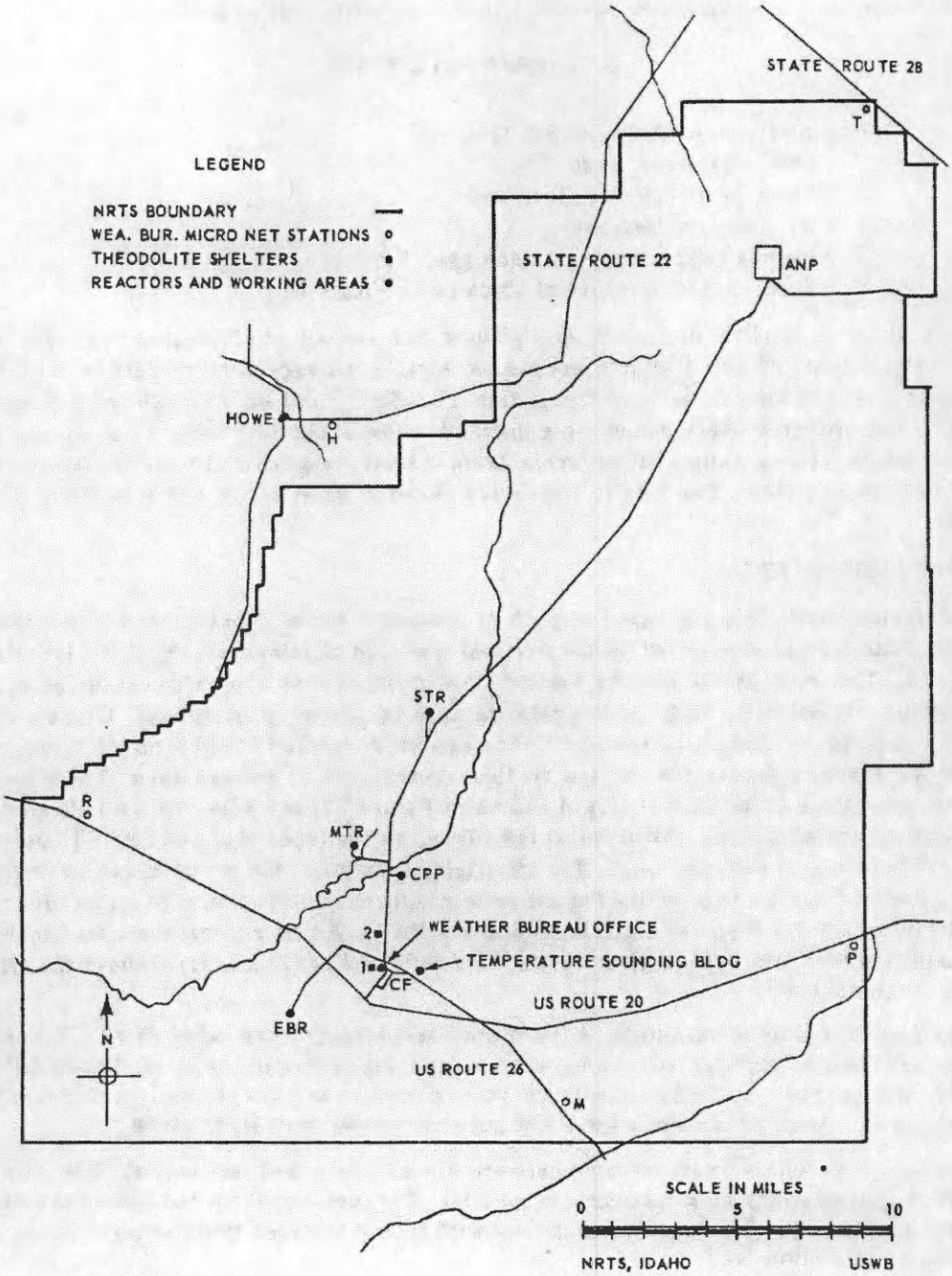

Fig. 48 - Location of reactors and main working areas

gases will rise above the 150-foot stack before leveling off. The empirical formula of Davidson-Bryant* seems best suited for this computation. It is written:

$$h = d\,(v/u)^{1.4}\,(1 + T/T_S)$$

h = increase in stack height, feet
d = stack diameter, feet
v = stack draft velocity, feet/sec
u = wind speed, feet/sec
T = excess temperature of stack gas, °F
T_S = absolute temperature of stack gas, °Rankine

For a stack of 20-foot diameter, 800 pounds per second of air heated to 1100°F will give a stack draft of 120 feet per second.† Assuming an excess temperature of 1050°F (using an average annual daytime temperature of 50°F) and an average wind speed of 15 mph, the effective stack height is computed to be about 500 feet. Wind speeds and ambient temperatures somewhat different from the values quoted will make little difference in the computation. The data to follow are based on an effective stack height of about 500 feet.

4.52 DIFFUSION TYPES

In diffusion principles the most important elements to be considered are winds and vertical stability (as measured by the vertical gradient of temperature) in the lower atmosphere. The wind speed largely controls the dilution rate of an effluent plume at the stack while air stability largely controls its rate of cross-wind spread. Given a wind direction and speed, the diffusion conditions can be described by five major types (see Figure 49) that are determined by the vertical distribution of temperature. The types of stability conditions (diagrams at left of stacks in Figure 49) are selected, as indicated by temperature sounding data collected at the NRTS, as the types that are likely to persist for periods of one to several hours. Though slight variations may occur in each category, these types will suffice to describe the diffusion conditions that occur in practice, and are verified by a number of smoke experiments at the NRTS. A description of smoke behavior to be expected with each type is given below. The daily and seasonal variations of the types will be treated later.

Type A occurs with superadiabatic (very unstable) temperature lapse rates. The stack effluent, if visible, appears to loop because of thermal eddies in the wind. Gases diffuse rapidly, but sparadic puffs having strong concentrations are occasionally brought to the ground near the base of the stack for a few seconds during very light winds.

Type B occurs with a gradient lying between dry adiabatic and isothermal. The effluent stream is shaped like a cone with axis horizontal. The distance from the stack that effluent first comes to the ground is greater than with type A because thermal turbulence, and hence vertical motion, is less.

Type C occurs with temperature inversion (stable flow) conditons. Laminar flow may also occur in a layer that is isothermal, depending on wind speed and roughness of terrain. The stack effluent diffuses practically not at all in the vertical. The effluent trail may re-

*Bryant, L. W., "The Effects of Velocity and Temperature of Discharge on the Shape of Smoke Plumes from a Funnel or Chimney. Experiments in a Wind Tunnel." National Physical Laboratory (Great Britain) Adm. 66, January, 1949.

Davidson, W. F., "The Dispersion and Spreading of Gases and Dusts from Chimneys." Transactions of Conference on Industrial Wastes, Fourteenth Annual Meeting, Industrial Hygiene Foundation of America, November 18, 1949, pp 38–55.

† The average barometric pressure for the NRTS, 25 inches of mercury, was used for this computation.

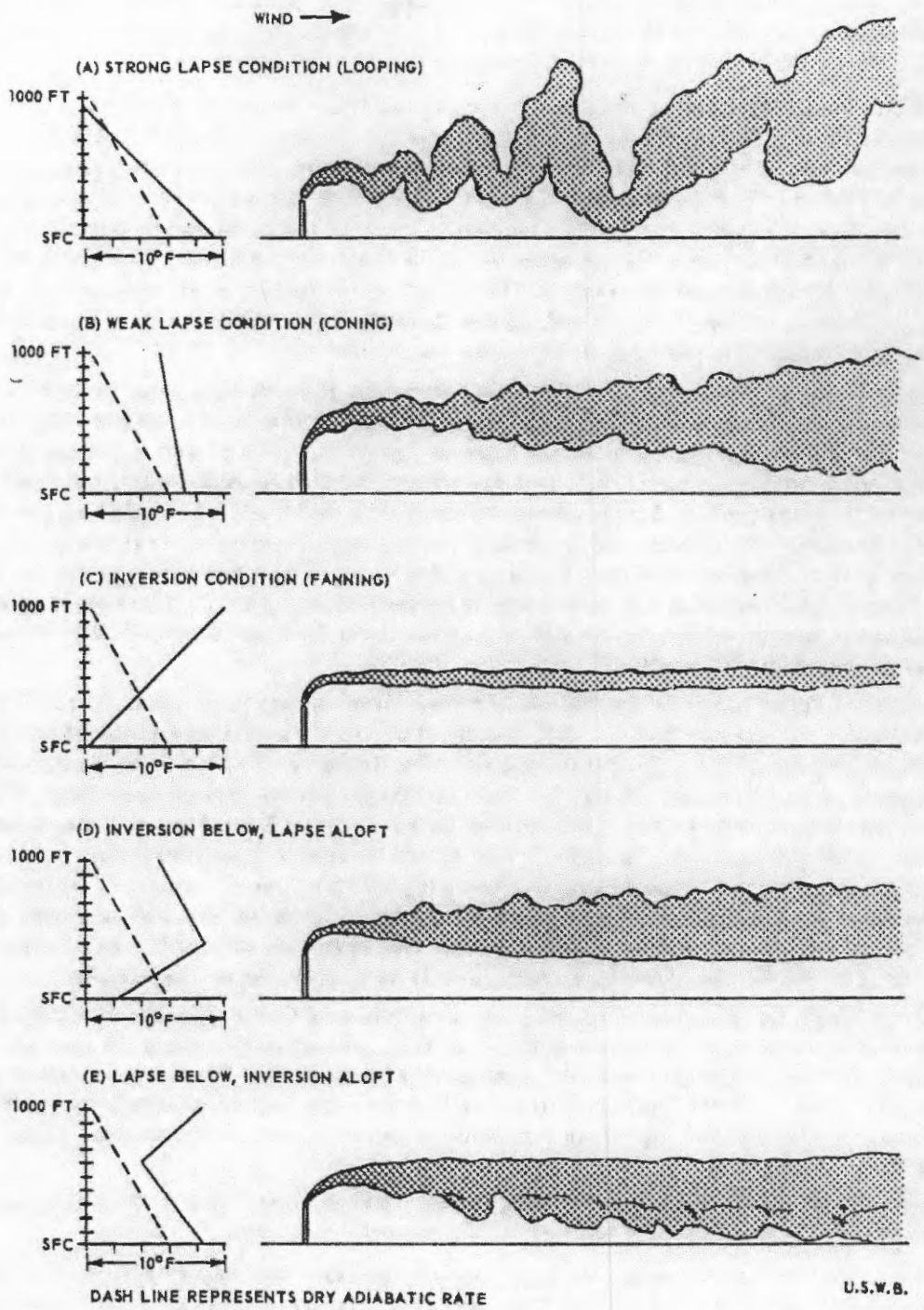

Fig. 49 - Schematic representation of stack gas behavior under various conditions of vertical stability

semble a meandering river, widening very gradually with distance from the stack. The concentration within the stream varies inversely with wind speed, but the distance that it travels within a time interval is directly proportional to wind speed.

Type D is usually associated with the transition from lapse to inversion, but may persist at times for several hours. Often the inversion does not build up to the 500-foot level during an entire night. The position of the zone of strong effluent concentration, as shown by shading in Figure 49D, will depend on the height of the inversion. It is caused by trapping by the inversion of effluent carried into the stable layer by turbulent eddies that penetrate the layer for a short distance. Except when the top of the inversion is very near the ground, this type may be considered the most favorable diffusion situation to be encountered. The inversion prevents effluent from reaching the ground; and at the same time the effluent may be rapidly diluted in the lapse layer above the inversion.

Type E occurs at the time that the nocturnal inversion is being dissipated by heat from the morning sun. The lapse layer begins at the ground and works its way upward rapidly in summer but slowly in winter. At some time the inversion is just above the top of the effective stack, and acting as a lid, forces the effluent stream to dilute within the shallow lapse layer near the ground. Large concentrations are brought to the ground along the entire effluent stream (that was formerly aloft during the type C condition) by thermal eddies in the lapse layer. The zone of strong concentration, shown by shading in Figure 49E is due to the trapping process that was mentioned in connection with type D. Sustained concentrations on the ground will be higher with this situation that with any other, but the average duration is only about 15 minutes.

The types of diffusion conditions described above can be classified as "ideal," "suitable," or "unsuitable" for operation of the IET reactor. It readily is seen that type D diffusion is the "ideal" condition. Using the Sutton equation* for diffusion of gases from a continuous point source, it can be shown that ground concentrations during normal operations of the reactor will not exceed tolerable limits during type A and type B conditions. These conditions have been designated as "suitable." The type E condition, commonly referred to as the fumigation type, will be designated as "unsuitable." The type C condition, while good from the standpoint of protecting the immediate surroundings of the reactor, is a mechanism by which highly concentrated effluent plumes may travel far beyond the boundaries of the NRTS. For the purpose here this condition will be considered as "unsuitable."

Table 10 gives the per cent frequency of occurrence of the various types of diffusion conditions seasonally, and at various times of day. Occasionally it was not possible to make temperature soundings because of strong or gusty winds. These unsuccessful attemps were added into the statistics in order to avoid bias toward nonwindy days. It is appropriate to assume that type A or B conditions existed during such periods. Table 10 affords the following conclusions.

1. Considering all seasons and sounding times, "suitable" or "ideal" operating conditions (item 7) were present with about 78 per cent frequency.

2. During all but winter months the frequency of "suitable" or "ideal" operating conditions between the hours 1100 and 1830 MST is so high as practically to eliminate the necessity for forecasting for these periods (except for infrequent precipitation).

3. "Suitable" or "ideal" conditions were present during the majority of all soundings except at 0200 and 0500 MST in summer and 0715 MST in autumn. This indicates that the highest frequency of "unsuitable" conditions would be found two to three hours before and after sunrise in summer and fall.

*Sutton, O. G., "The Theoretical Distribution of Air-borne Pollution from Factory Chimneys." Quarterly Journal of the Royal Meteorological Society, vol. 73, pp. 426–436, 1947.

TABLE 10

SEASONAL SUMMARY OF TEMPERATURE SOUNDINGS
NRTS, IDAHO, CENTRAL FACILITIES
(Two Year Period: September, 1950 through August, 1952)

Time of sounding (MST):	0200				0500				0715				0900				1100				1500				1630				2000				2130				All Soundings
	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	WINTER	SPRING	SUMMER	FALL	
Total Soundings made	64	68	71	68	68	60	71	72	68	67	73	70	62	65	72	71	59	65	70	65	58	57	63	61	56	54	67	61	59	60	67	62	59	58	68	47	2306
Total not taken due to strong winds	9	7	1	6	4	6	3	2	5	5	2	3	8	12	2	2	12	12	5	1	15	20	11	4	11	23	9	4	9	15	9	4	9	13	5	2	270
Total attempts	73	75	72	74	72	66	74	74	73	72	75	73	70	77	74	73	71	77	75	66	73	77	74	65	67	77	76	65	68	75	76	66	68	71	73	49	2576
Percent of Soundings																																					
1. Type (A)	8	1	0	0	10	3	0	1	7	8	28	6	11	64	89	63	39	73	89	89	52	69	78	92	15	20	61	3	12	1	1	2	10	3	0	0	28%
2. Type (B)	10	9	6	10	7	9	4	8	6	17	15	7	10	52	7	6	4	5	4	4	8	4	68	2	18	25	17	15	10	12	9	4	13	8	6	10	9%
3. Type (C)	23	39	53	36	35	47	72	43	42	40	35	56	36	65	0	19	22	3	0	4	7	0	0	0	9	4	16	3	19	12	9	11	26	18	16	20	21%
4. Type (D)	45	41	40	36	43	30	20	45	38	26	9	27	30	21	1	8	17	3	0	0	10	1	0	0	44	22	8	72	46	55	68	76	37	52	71	65	30%
5. Type (E)	1	0	0	0	0	2	0	0	0	1	11	0	1	1	0	1	0	1	0	0	3	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1%
6. Percent Types (A), (B), and windy	30	20	7	18	22	21	8	12	19	32	46	16	33	84	99	71	61	94	100	95	81	99	100	100	48	74	90	25	35	34	22	12	37	30	12	14	48%
7. Percent Types (A), (B), (D), and windy	75	61	47	54	65	53	28	57	56	58	55	44	63	92	100	79	77	96	100	95	90	100	100	100	91	98	97	97	81	81	91	88	74	82	84	80	78%

4. "Ideal" conditions (Item 4) existed more than half of the time as early as 2000 and 2130 in all seasons except winter, and as early as 1830 MST in autumn. Since the average time of beginning of the nocturnal inversion, and hence type D conditions, is about sunset, it is indicated that "ideal" conditions could be selected by forecasts for most days between sunset and 2130 MST. This would mean that most days would provide about two to four hours of ideal operating conditions, provided that the hours following sunset could be utilized.

The remarks above are not applicable except for normal operating conditions. In particular, operations that might result in a release of radioactive effluent near the ground, such as an explosion, should not be conducted except during type A or B conditions. Type A is the most frequent daytime condition. In the event that the effluent temperatures or exhaust rates are altered so as to provide a lower effective stack height, the frequency of "ideal" operating conditions will be reduced.

The regime of diffusion types on a typical day is shown in Figure 50. Note that "suitable" conditions were present at 1100 and 1500 MST, "ideal" conditions at 1830, 2000, and 0200 MST. This day would have afforded at least 15 consecutive operating hours, seven hours of which would have been "ideal."

The frequencies of the stated good operating conditions will be altered only slightly by such phenomena as precipitation, or prolonged periods of stagnant fog conditions that sometimes occur in colder months. Three years of record at the NRTS indicate that precipitation falls only about 6 per cent of the time. The stagnant conditions may persist for three to five days, but this occurs usually not more than two or three times during a winter. These frequencies need not be altered appreciably by unfavorable winds, provided that stack and working areas are not aligned with the prevailing winds. Calms are very infrequent at the 500-foot level.

4.53 WIND FREQUENCIES

The ANPD site is located in a region where winds are channeled by mountain ranges on the northwest and the southeast. Drainage of air down these steeper slopes does not seem to affect the NRTS, but drainage down the more gradual slope of the plain, which is to the southwest, is a common phenomenon. There is a strong tendency for southwesterly (upslope) winds in the daytime, and northeasterly (downslope) winds at night. A study of 18 months of continuous wind recordings at the 250-foot level indicates that the lag in changing from upslope to downslope flow (and vice versa) is such that the northeasterly flow usually does not begin until near midnight nor end until almost noon. The same is indicated for the 500-foot level by a study of two years of wind-aloft soundings made at the hours 0100, 0400, 0700, 1000, 1300, 1600, 1900, and 2200 MST. The diurnal effect on winds in the lower few hundred feet is so pronounced that seasonal influences are almost negligible, except that the time of change of wind direction is most erratic in winter and least erratic in summer. Other than the daily upslope effect, the frequency of southwesterly winds near the ground is augmented by the prevailing westerlies aloft. The frequency of northeasterly winds is augmented by cold air spilling over the Continental Divide to the north and northeast. During times conducive to downslope flow, and when the northeasterly winds over the plain are very light, there is sometimes a very light northwesterly drainage wind over the ANPD site from the Birch Creek Valley. This flow is presumably very shallow, although it might possibly affect the 500-foot level. It has an annual frequency of less than 5 per cent, according to 20-foot level wind records at the "T" station. Apparently a return flow up the Birch Creek Valley does not occur since southeasterly winds are practically nonexistent at this site. The annual wind rose for the "T" station is shown in Figure 51.

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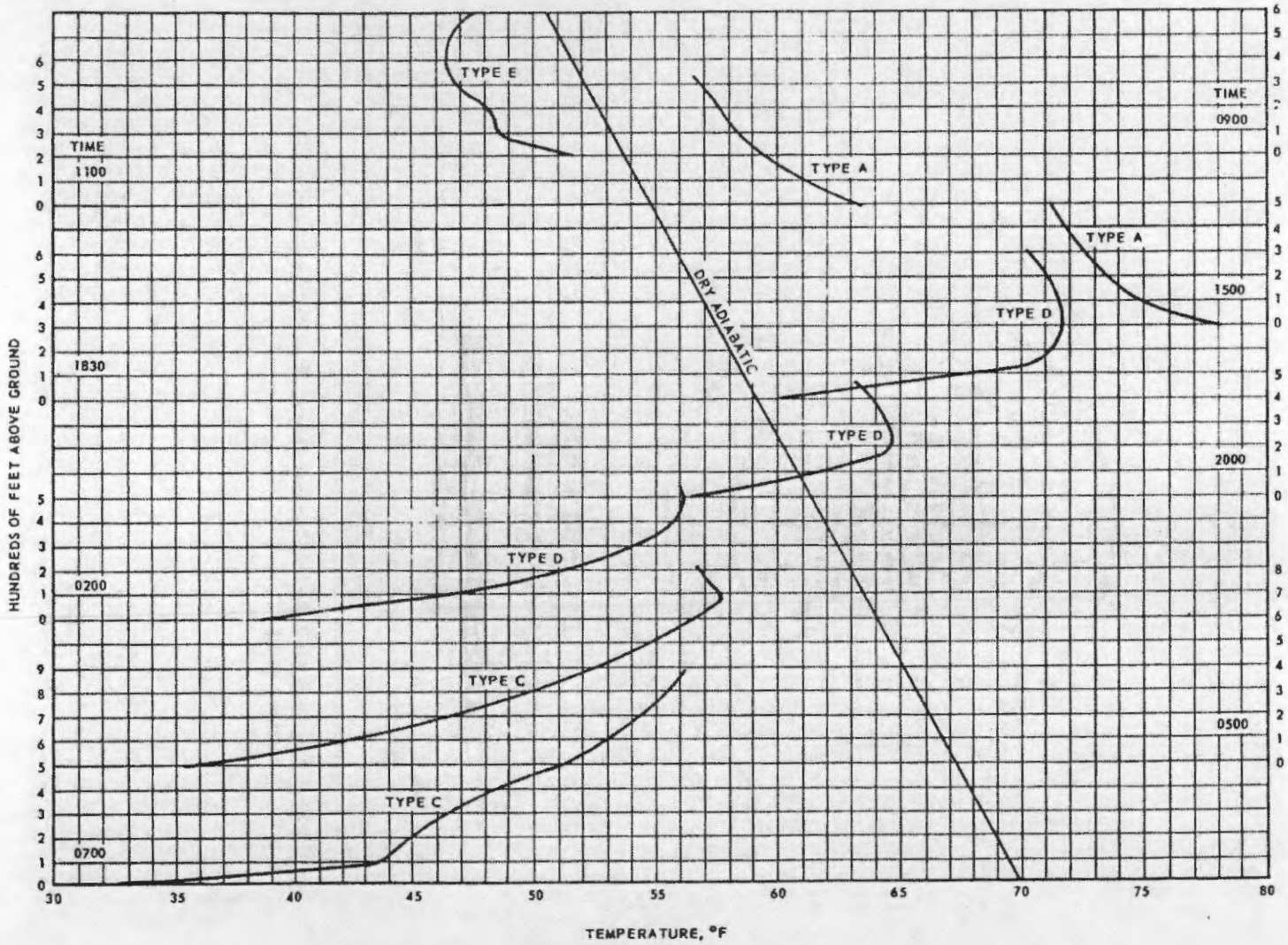

Fig. 50 - Temperature soundings on a day with clear skies and right winds

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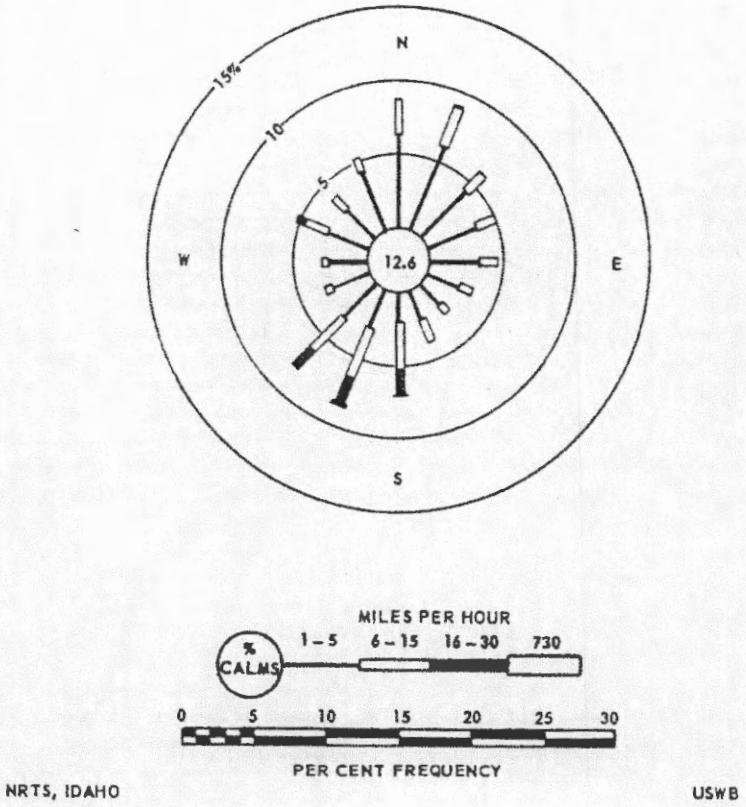

Fig. 51 - Annual wind rose for two years, June 1950 through May 1952

The most important features of the wind flow are the frequency distributions of directions and speeds at the 500-foot level (since this is the computed effective stack height) during "ideal" and "suitable" diffusion conditions. These were constructed from two years of wind-aloft soundings (pilot balloon) made near the times of the temperature soundings, and are presented in Figure 52. Although these soundings were make in the Central Facilities area, it is felt that they are representative of the ANPD Site.

These wind roses show, as mentioned previously, that stack and building arrangements can be achieved so that the frequency of acceptable operating conditions will not be lowered appreciably by unsuitable wind directions and speeds. The reasons are that calms are of negligible frequency and that winds from the southeast and northwest quardrants are very infrequent. This would assume that northeasterly and southwesterly winds are suitable. At such distances as working area or communities lie in these directions, there will be sufficient dilution of the effluent to permit the reactor operations that are planned. This is dealt with in the health physics section dealing with hazards.

4.54 ATMOSPHERIC DUST

The objective of the dust program at the NRTS is to determine for expected meteorological conditions the concentrations of dust by weight per unit volume of air, the particle size distributions, the chemical nature, the abrasiveness of particles, and the variations of dustiness with respect to location on the NRTS and with respect to height of air intake. Observations so far have been confined mostly to the ANPD area. The sampling began July 22, 1952. Concentration and particle size analyses are performed by the Weather Bureau Office, Idaho Falls, Idaho, and spectrographic analyses are performed by the Public Health Service, Cincinnati, Ohio. High volume air samplers with Mine Safety Appliance fluted filters are used for concentration measurements and to obtain dust samples for spectrographic analysis. A Millipore* filter and rotary pump is used to obtain samples for particle size analysis. The most pertinent results of this work follow.

Concentrations

Dust concentrations measured in the ANPD area thus far have varied from a low of 0.0369 mg/m^3 on a summer day with light winds to a high of 0.1513 mg/m^3 during a period when dust devils were present in the vicinity of the sampling station. The average concentration over 1759 sampling hours (most of which were during the windiest parts of the days) was 0.0726 mg/m^3. During July and August the concentrations ran between 0.04 and 0.05 mg/m^3, but with the beginning of road construction and increased vehicular traffic, they rose to 0.05 - 0.13 mg/m^3 in November.

Dust sampling at Central Facilities gave a concentration of 0.7720 mg/m^3 at the same time that the high concentration of 0.1513 mg/m^3 was measured at the ANPD site. This also is indicative of the increased dustiness resulting from human activity, and points out that the ANPD site can be expected to have higher dust concentrations as construction develops.

Particle Size Distributions

Particle sizings from four samplings during a variety of wind and dustiness conditions in August and November gave similar size distributions. Median sizes ranged from 0.330 to 0.385 microns, and standard deviations ranged from 1.94 to 2.75. In all samples, less than 1 per cent of the particles were greater than 10 microns, and only about 15 per cent on the average were greater than one micron. A few of the particles collected were as large as 80 microns.

*Manufactured by Lovell Chemical Co.

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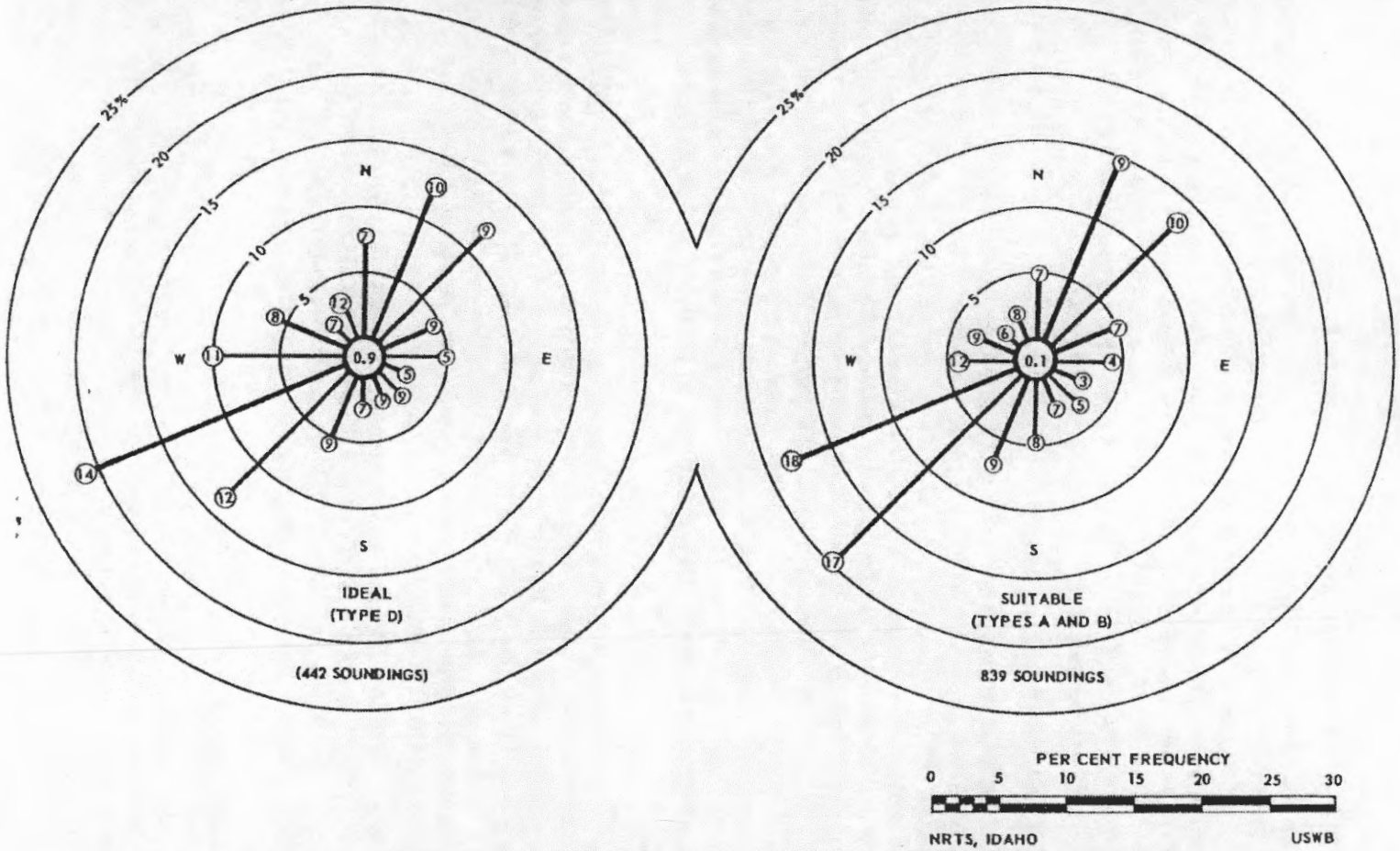

Fig. 52 - Wind roses during ideal and suitable diffusion conditions - 500 foot level

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Chemical Composition

The results of spectrographic analysis of five fluted filters are given in Table 11. Each of the filters had about 0.04 milligrams of dust per cubic meter of air pulled through them. All were exposed during the windiest part of summer afternoons, and dust devils were present during the sampling period for all but filter No. 1-0. Spectrometric tests were made for each element listed in Table 11, and the concentrations present in a control filter (which was not used in sampling) were subtracted out of the concentrations found in the sampling filters. Calcium and silicon are the major constituents on the average. Comparatively large concentrations of aluminum and iron were present when filter No. 5-0 was exposed.

An analysis of surface soil in the ANPD area gives an idea of the composition of the dust that may be raised locally when the crusted surface is pulverized by increased human activity. For this purpose four representative samples of topsoil were selected for spectrographic analysis, and the results are given in milligrams per gram of soil in Table 12. The concentrations in the four samples were averaged, since they differed only slightly in their chemical contents.

TABLE 11

CONCENTRATIONS OF VARIOUS CHEMICAL CONSTITUENTS OF FILTERED DUST IN THE ANPD Area

(Given in Milligrams per Cubic Meter of Air Filtered)

Element	Filter 1-0	Filter 5-0	Filter 7-0	Filter 13-0	Filter 15-0	Average
Ca	1.11×10^{-4}	7.84×10^{-4}	6.50×10^{-4}	0.82×10^{-4}	0.83×10^{-4}	3.42×10^{-4} mg/m^3
Mg	0.17	0.33	0.17	0.11	0.16	0.19
Ni	0.04	0.11	0.06	0.03	0.04	0.06
Cu	0.11	0.33	0.26	0.11	0.16	0.19
Al	0.34	2.04	0.77	0.56	0.67	0.88
Zn	----	----	----	----	----	----
Mo	----	trace	trace	0.006	trace	trace
Mn	----	0.06	0.03	0.02	0.02	0.03
Cr	0.03	0.15	0.15	0.02	0.07	0.08
Fe	----	1.39	----	0.48	0.36	0.45
Sb	----	----	----	----	----	----
As	----	----	----	----	----	----
Ba	0.02	0.04	0.03	0.02	0.02	0.03
Co	----	----	----	----	----	----
Pb	0.02	0.02	0.08	----	0.04	0.03
Si	0.59	>3.00	1.03	>1.13	0.39	>1.23
Sn	0.04	0.06	0.06	0.02	0.04	0.04
Ti	trace	0.11	0.08	0.06	0.04	0.06
Hg	----	----	----	----	----	----
Bi	----	----	----	----	----	----
Cd			Insufficient Sample			
Be			Insufficient Sample			
W	----	----	----	----	----	----
V	----	0.006	trace	0.002	trace	0.002
U	----	----	----	----	----	----
Na	----	trace	----	trace	----	----
Sr	----	----	----	present	----	----

TABLE 12

AVERAGE CONCENTRATIONS OF VARIOUS CHEMICAL CONSTITUENTS OF SURFACE SOIL IN THE ANPD Area

(Given In Milligrams Per Gram Of Soil)

Element	Concentration	Element	Concentration	Element	Concentration
Ca	65.6	Sb	----	Cd	----
Mg	12.0	As	----	Be	----
Ni	0.18	Ba	> 0.9	W	> 1.0
Cu	0.31	Co	0.05	V	0.23
Al	22.7	Pb	----	U	?
Zn	0.32	Si	major	Te	----
Mo	----	Sn	----	Na	present
Mn	1.38	Ti	8.1	K	present
Cr	0.62	Hg	----	Sr	present
Fe	31.2	Bi	----		

Silicon was the major constituent, but strontium, sodium, and potassium were also present. Uranium possibly was present in two of the samples. Calcium, iron, aluminum, and titanium were present in appreciable quantities.

Abrasiveness

Petrographic examination of samples of airborne dust at the ANPD site was performed by the Harvard University School of Public Health. The examination indicated that approximately half of the particles were crystalline minerals, and the rest oxides or organic matter. The crystalline minerals were principally silicates, but some quartz also was present, indicating that the dust is moderately abrasive.

Seasonal and Diurnal Variations

The maximum dustiness can be expected during the warmer months. During colder months the presence of snow cover and frozen or moist ground will lower the frequency of dusty conditions. Observations of the state of the ground (recorded twice daily at the NRTS) show that the ground is in a condition favoring dustiness a little less than half of the time during the year.

It has been found that with wind speeds averaging 16 mph or more at the NRTS there will be gusts of 20 mph or more, and visible dustiness often results. Dust-favoring winds occur about 10 per cent of the time during the year for an average of six hours of 13 windy days per month. The frequency of dusty conditions is then about 5 per cent, since the state of the ground favors dustiness only about half of the time. In general, the afternoons of the warmer months provide most of the dusty conditions that occur. Dust devils are often seen over the area in summer, and these raise dust locally when wind speeds are too light to raise dust on a large scale.

4.6 THE APPLICATION OF SUTTON'S DIFFUSION EQUATIONS TO RADIATION HAZARDS FROM RADIOACTIVE CLOUDS

Sutton* has developed a theory of atmospheric diffusion which is of considerable aid in the calculation of hazards due to the emission of radioactive materials into the atmosphere. According to this theory the concentration of material in the air at any point (x, y, z) can be determined for some special cases by the following formulas.

4.61 FORMULAS FOR DETERMINING CONCENTRATION OF RADIOACTIVE MATERIAL IN AIR

Instantaneous Emission From An Elevated Point Source

$$X(x,y,z,t)=\frac{B}{\pi^{3/2}\,c^3(ut)^{\frac{3(2-n)}{2}}}\left\{\exp\left[-\frac{(x-ut)^2+y^2+(z-h)^2}{c^2(ut)^{2-n}}\right]+\exp\left[-\frac{(x-ut)^2+y^2+(z+h)^2}{c^2(ut)^{2-n}}\right]\right\}$$

where the origin of coordinates is on the ground directly beneath the point of emission and,

$X(x,y,z,t)$ = concentration in units/m^3 at x,y,z as a function of time
x = down wind distance in m
y = cross wind distance in m
z = height above ground in m
h = height of emission in m
B = total amount emitted
u = velocity of wind in m/sec
t = time at which concentration is given
c = virtual diffusion coefficient in m$^{n/2}$
n = dimensionless stability parameter.

The two exponential terms are required to cover the reflection of that part of the cloud which reaches the earth.

Continuous Emission From An Elevated Point Source

$$X(x,y,z)=\frac{Q\exp\left(-\frac{y2}{c^2x^{2-n}}\right)}{\pi c^2x^{2-n}}\left\{\exp\left[-\frac{(z-h)^2}{c^2x^{2-n}}\right]+\exp\left[\frac{(z+h)^2}{c^2x^{2-n}}\right]\right\}$$

where Q = emission rate of material in units/sec and other symbols have the same meaning as before.

For cases where the concentration to be determined is on the ground then z = o and the equations assume the following simplified forms

$$X(x,y,0,t)=\frac{2B}{\pi^{3/2}a^3}\exp\left[-\frac{(x-ut)^2+y^2+h^2}{a^2}\right]$$

$$X(x,y,0)=\frac{2Q}{\pi a^2}\exp\left(-\frac{y^2+h^2}{a^2}\right)$$

where $a=cx^{1-\frac{n}{2}}$ or $c(ut)^{1-\frac{n}{2}}$

*Sutton, O. G., "The Theoretical Distribution of Air-borne Pollution from Factory Chimneys." Quarterly Journal of the Royal Meteorological Society, vol. 73, pp. 426–436, 1947.

4.62 RADIATION HAZARDS DUE TO RADIOACTIVE CLOUDS

If a person is exposed to a radioactive cloud containing gamma and beta emitters both in particulate and gaseous form, he is subject to several distinct hazards. First he breathes the radioactive material into his lungs where the lung itself becomes irradiated; and if the material is soluble, other organs may be exposed also. In addition, he is exposed to the external radiations during the passage of the cloud. Finally, he is subject to exposure to radiations from the fallout and rainout products on the ground after passage of the cloud.

Inhalation

The simplest problem is that of inhalation. If R is the rate of air intake while breathing, the total amount inhaled into the lung during passage of an instantaneously emitted cloud is

$$A = R\int_0^\infty \chi(x,y,0,t)\,dt = \frac{2RB}{\pi^{3/2}}\int_0^\infty \frac{\exp\left[-\frac{(x-ut)^2+y^2+h^2}{a^2}\right]}{a^3}\,dt$$

This integration can be simplified by assuming that the cloud size does not change during its passage over (x,y) that is, by holding a constant at its value at x. Then if the substitution $ut-x=f$ and $dt=\frac{df}{u}$ is made

$$A = \frac{2RB\exp\left(-\frac{y^2+h^2}{a^2}\right)}{\pi^{3/2}a^3u}\int_{-x}^\infty \exp\left(-\frac{f^2}{a^2}\right)df$$

which very nearly is

$$A = \frac{4RB\exp\left(-\frac{y^2+h^2}{a^2}\right)}{\pi^{3/2}a^3u}\int_0^\infty \exp\left(-\frac{f^2}{a^2}\right)df$$

so that

$$A = \frac{2RB\exp\left(-\frac{y^2+h^2}{a^2}\right)}{\pi u a^2}$$

This is precisely the same equation that would be obtained by using the formula for a continuous point source, where emission is carried on for a time t and the substitution $B=Qt$ is made. However, for continuous emission over appreciable periods of time, it is likely that the wind direction will change, so it is necessary to calculate an average to approximate actual conditions.

Consider the case in which material is released at the rate of Q per second into a sector of angle θ. At a distance x in the plane of the emitter the concentration has the average value $\overline{\chi}$ and the variation in concentration with altitude is as $e^{-\frac{z^2}{a^2}}$.

The amount of the emitted material contained in a strip 1 meter thick and $x\theta$ long is

$$\overline{\left(\frac{1}{u}\right)}\,Q = 2\overline{\chi}\,x\theta\int_0^\infty e^{-\frac{z^2}{a^2}}\,dz$$

from which

$$\overline{\chi} = \overline{\left(\frac{1}{u}\right)}\frac{Q}{\pi^{1/2}\,a\,x\,\theta}$$

and the amount breathed at ground level is

$$A = \overline{\left(\frac{1}{u}\right)} \frac{2QtRe^{-\frac{h^2}{a^2}}}{\pi^{1/2} a x \theta}$$

External Dose From Cloud

The rate of energy absorption in a gram of air at the distance, r, from a radioactive source which radiates B units of energy per second is

$$E = \frac{\mu_a' B \left[1 + \frac{\mu' - \mu_a'}{\mu_a'} (\mu r)\right] e^{-\mu r}}{1293 \times 4\pi r^2}$$

where

μ_a' = energy absorption coefficient in m^{-1}
μ' = total absorption coefficient in m^{-1}
μ = total absorption coefficient in m^{-1} corrected for temperature and pressure of the air

The dose rate in rad/sec to tissue is

$$D_R = G \mu_a' B (1 + K\mu r) e^{-\mu r}$$

where

$$G = \frac{10^7 \times 1.11}{1293 \times 4\pi \times 100} = 6.83 \text{ for } B \text{ in watts*}$$

$$K = \frac{\mu' - \mu_a'}{\mu_a'}$$

This expression with a scattering buildup factor linear in μr was chosen because it gives the correct value of the energy absorption in an infinite homogeneous radioactive medium where the energy absorbed must equal the energy emitted.† Its use here tends to overemphasize the scatter contributions to the dose from the shorter distances more than higher order representations would, and since the greatest portion of the dose comes from the nearby portions, this is a conservative approach.§

Consider the dose rate to a point on the ground at $(x, y, 0)$ due to an element of volume of an instantaneously emitted radioactive cloud moving with a velocity u whose center is at the point $(ut, 0, h)$ as indicated in Figure 53.

The dose rate to $(x, y, 0)$ from that part of the cloud which is reflected from the ground is the same as if the cloud had passed through the ground plane if the albedo of the ground

*The factor 1.11 is used to convert from G for air to G for tissue; it is the ratio of the electron densities of tissue and air.

†See discussion in Chap. 2.7 pp. 817–818 of the Reactor Handbook Vol. I, based on a proposal by H. Goldstein.

§Somewhat similar treatments without the buildup factor are (1) "Cloud Dosage Calculations," R. L. Waterfield, (2) "The Theoretical Ground Level Dose Rate from the Radio-Argon Emitted by the Brookhaven Reactor Stack," P. H. Lowry, BNL 81(T-19), 1950. A later treatment using a buildup factor is "A Comparison of Computed and Measured Ground Level Dose Rates from Radio-Argon Emitted by the Brookhaven Reactor Stack," I. A. Singer, BNL 292(T-49), 1954.

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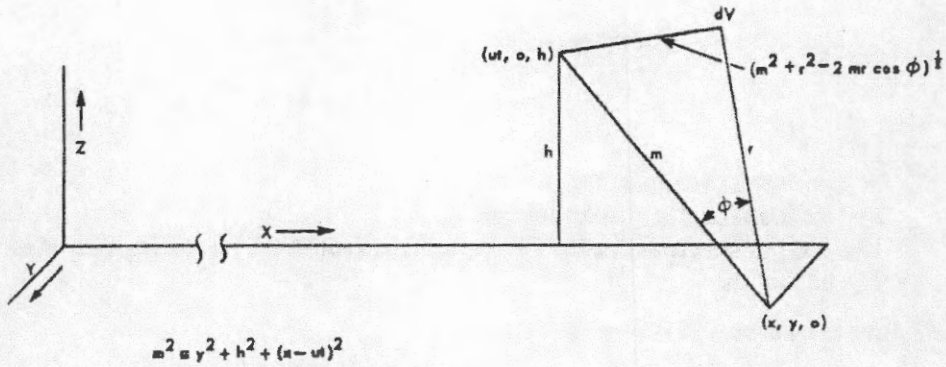

Fig. 53 - Sketch of coordinate system for cloud

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is considered to be unity. Then since the cloud is symmetric with respect to the line from $(x, y, 0)$ to $(ut, 0, h)$, the dose rate due to the whole cloud is

$$D_R = \frac{BG\mu_a'}{\pi^{3/2} a^3} \int_0^\infty \int_0^\pi \frac{(1+K\mu r)\exp(-\mu r)\exp\left(-\frac{m^2+r^2-2mr\cos\phi}{a^2}\right)}{r^2} 2\pi r^2 \sin\phi \, d\phi \, dr$$

$$= \frac{2BG\mu_a'}{\pi^{1/2} a} \int_0^\infty \frac{(1+K\mu r)\exp(-\mu r)\left\{\exp\left[-\left(\frac{m-r}{a}\right)^2\right] - \exp\left[-\left(\frac{m+r}{a}\right)^2\right]\right\}}{mr} dr$$

The total dose to the point $(x, y, 0)$ during the time in which the cloud passes is then

$$D = \frac{2BG\mu_a'}{\pi^{1/2}} \int_0^\infty \frac{1}{a} \int_0^\infty \frac{(1+K\mu r)\exp(-\mu r)\left\{\exp\left[-\left(\frac{m-r}{a}\right)^2\right] - \exp\left[-\left(\frac{m+r}{a}\right)^2\right]\right\}}{mr} dr \, dt$$

This double integral can be simplified somewhat by maintaining the value of a constant at its value when the cloud is a distance x from the emitting point, so that

$$D = \frac{2BG\mu_a'}{\pi^{1/2} a} \int_0^\infty \int_0^\infty \frac{(1+K\mu r)\exp(-\mu r)\left\{\exp\left[-\left(\frac{m-r}{a}\right)^2\right] - \exp\left[-\left(\frac{m+r}{a}\right)^2\right]\right\}}{mr} dr \, dt$$

Values for the dose were obtained by graphical and numerical integrations, and the dose is given for a large range of the possible values of the parameters h and μ which will hold for any meteorological condition which can be described with suitable values of c and n in Sutton's equation. The integration actually performed assumes that the cloud came from minus infinity, which means that for small distances from the stack the result may be too high by as much as a factor of two. At the point of maximum dose the error is negligible.

The results are best given as the sum of two separate terms where

$$D = \frac{4BG\mu_a'\mu}{u} [I_1 + K I_2]$$

The values of I_1 and I_2 are given in Figures 54 and 55 as a function of μa for several different values of μh. These values are for the cloud passing over a point $(x, 0)$ on the ground. For a point (x, y) data should be taken substituting $(y^2 + h^2)^{1/2}$ for the h indicated. It should be remembered that B may be a function of time and hence a function of distance also.

This method of determining the dose is applicable to both gamma and beta radiation. In determining the beta dose, it is necessary to assume some effective value of the absorption coefficient, and of course the value of K is zero for betas.

For cases where μa is large, ie, greater than 10, the values of the two integrals can be given quite accurately by the approximation:

$$I_1 = I_2 = \frac{\exp\left[-\frac{h^2+y^2}{a^2}\right]}{\mu^2 a^2}$$

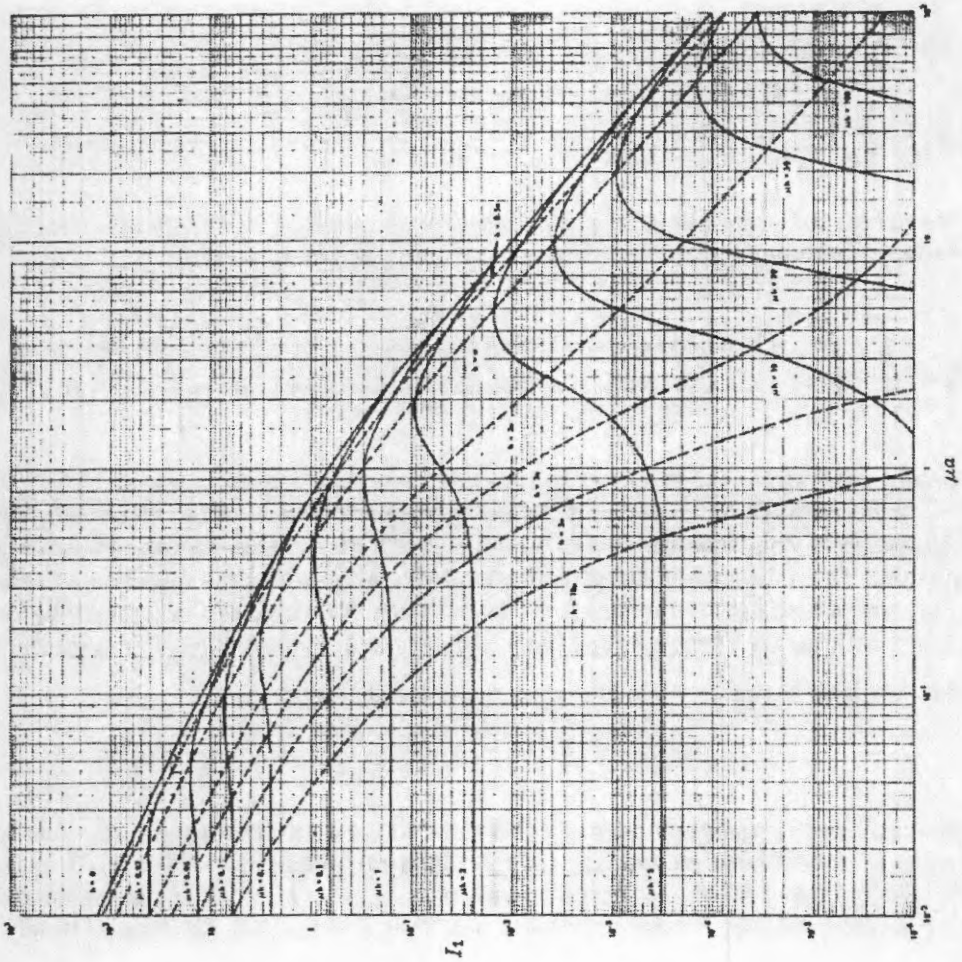

Fig. 54 - I_1 versus μa for cloud dose

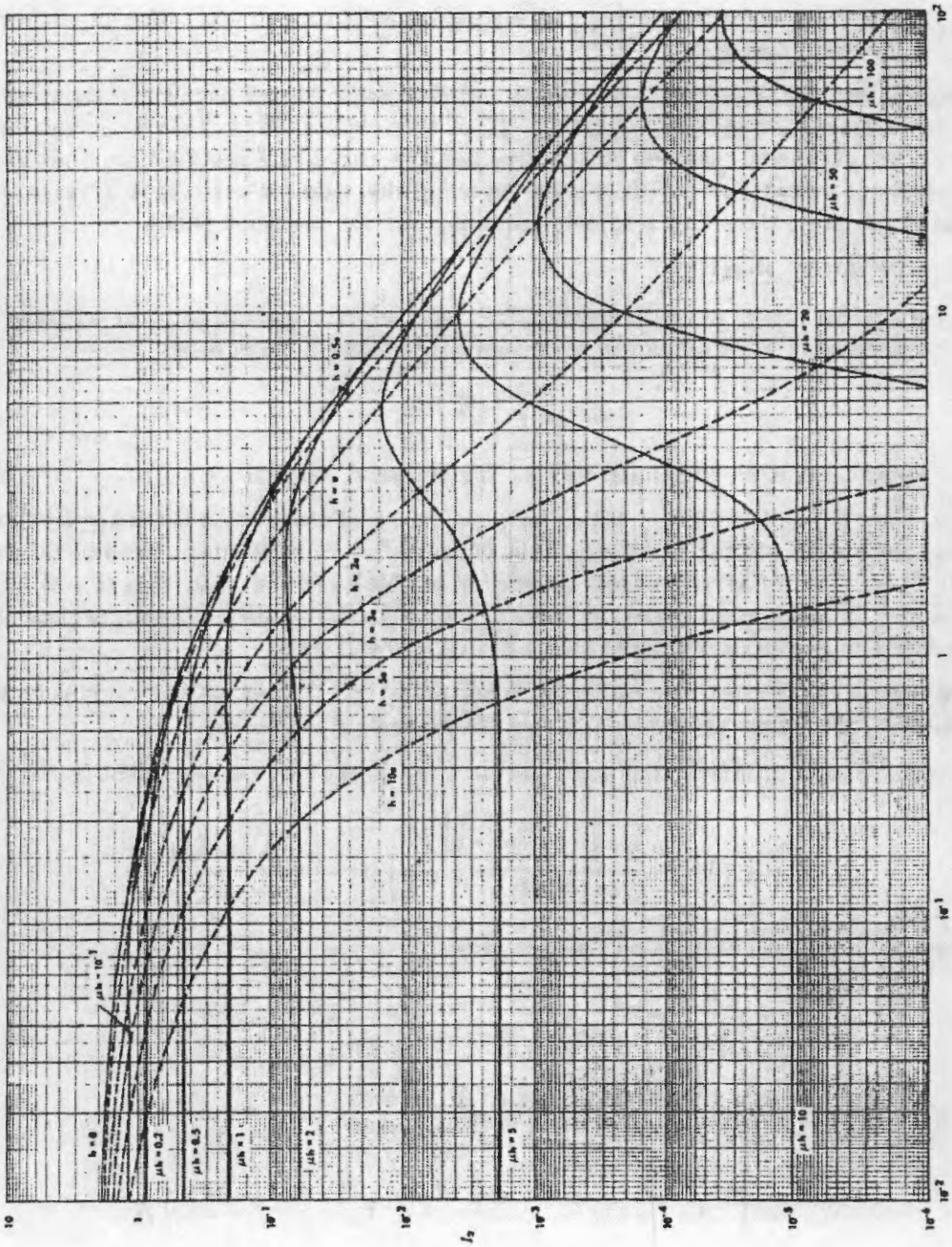

Fig. 55 - I_2 versus μa for cloud dose

and the dose would then be

$$D = \frac{4BG \exp\left[-\frac{h^2+y^2}{a^2}\right]}{u\sigma a^2}$$

where $\sigma = \frac{\mu}{\mu'}$ and the actual values of μ and μ_a' need not be known. This is most useful for cases involving beta radiations where it would not be necessary to determine an effective value of μ for the radiation.

Included in Figures 54 and 55 are additional dotted lines which are useful in constructing curves for values of μh not given directly. To do this, pick a value of $\mu a = \mu h$, and then the peak of the curve will be at the point where the $a=h$ curve crosses this line. Then pick other points accordingly; at $\mu a = 2\mu h$ go to the point where the $a=2h$ curve crosses the $\mu a = 2\mu h$ line, etc.; then draw a smooth curve through the resulting points.

Dose Due To Rainout Material

If a radioactive cloud is emitted during or just before a rainstorm, the amount of radioactive material in the cloud will be reduced according to the equation

$$Q = Q_0 e^{-\nu\left(\frac{x}{u} - \tau\right)}$$

where τ is the time at which rainout starts. The emission takes place at $t=0$.

The number ν expresses the fraction of the volume of the contaminated air which is swept out per second. For an ordinary rain of about 0.1 inch per hour the value of ν is about 10^{-3}; for a very heavy downpour amounting to 1 inch per hour the value of ν is only about 4×10^{-3}. It is assumed here that every bit of radioactive material which comes into contact with a falling drop is captured and carried to the ground.

To determine the ground concentration at any point (x, y), assume that the cloud size and content do not change appreciably during the passage of the cloud.

The concentration of material at any point (x, y, z) in the cloud at the time t is

$$X(x,y,z,t) = \frac{Q_0 \exp\left[-\nu\left(\frac{x}{u} - \tau\right)\right]}{\pi^{3/2} a^3} \exp\left[-\frac{(x-ut)^2+y^2+z^2}{a^2}\right]$$

The rate of buildup of activity on the ground is

$$R(x,y,t) = \nu \int_{-\infty}^{\infty} X(x,y,z,t)\, dz = \frac{\nu Q}{\pi a^2} \exp\left[-\frac{(x-ut)^2+y^2}{a^2}\right]$$

The surface concentration after passage of the cloud is

$$S(x,y) = \int_{\tau}^{\infty} R(x,y,t)\, dt = \frac{\nu Q \exp(-y^2/a^2)}{\pi a^3} \int_{\tau}^{\infty} \exp\left[-\frac{(x-ut)^2}{a^2}\right] dt$$

$$= \frac{\nu Q \exp(-y^2/a^2)}{\pi a^2 u} \int_{u\tau - x}^{\infty} \exp(-f^2/a^2)\, df$$

If $u\tau$ is small with respect to x then

$$S(x,y) = \frac{\nu Q e^{-\frac{y^2}{a^2}}}{\pi a^2 u} \cdot 2\int_0^\infty e^{-\frac{f^2}{a^2}}\, df = \frac{\nu Q e^{-\frac{y^2}{a^2}}}{\pi^{1/2} a u}$$

The dose at some particular point $(x_1, 0)$ at a height b above the ground is

$$D = \frac{\nu Q G \mu_a'}{\pi^{1/2} a u} \int_{-\infty}^{\infty}\int_0^\infty \frac{\left\{1+\frac{K}{2}\mu\left[(x-x_1)^2+y^2+b^2\right]^{1/2}\right\} \exp\left\{-\mu\left[(x-x_1)^2+y^2+b^2\right]^{1/2}\right\} \exp\left(-\frac{y^2}{a^2}\right)}{(x-x_1)^2+y^2+b^2}\, dx\, dy$$

where $K/2$ is used to allow for loss of scattered radiation from that part of the primary radiation which enters the ground. This can be written

$$D = \frac{2\pi^{1/2}\nu Q G \mu_a' \mu}{u}\left(I_D + \frac{K}{2} I_S\right)$$

where the factor 2π is added as a normalizing factor, and

$$I_D = \frac{1}{2\pi\mu a}\int_{-\infty}^{\infty}\int_0^\infty \frac{\exp\left[-\mu(r^2+b^2)^{1/2}\right]\exp\left(-\frac{y^2}{a^2}\right)}{r^2+b^2}\, dx\, dy$$

$$I_S = \frac{1}{2\pi\mu a}\int_{-\infty}^{\infty}\int_0^\infty \frac{\exp\left[-\mu(r^2+b^2)^{1/2}\right]\exp\left(-\frac{y^2}{a^2}\right)}{(r^2+b^2)^{1/2}}\, dx\, dy$$

For the case where the quantity μa is large, that is greater than 10, $\exp\left(-\frac{y^2}{a^2}\right)$ may be taken equal to unity for all significant values of y, and the values of I_D and I_S become*

$$I_D = \frac{1}{\mu a}\int_{\mu b}^{\infty} \frac{e^{-z}}{z}\, dz$$

$$I_S = \frac{1}{\mu a}\int_{\mu b}^{\infty} e^{-z}\, dz = \frac{e^{-\mu b}}{\mu a}$$

These values of I_D and I_S serve as upper limits of the integrals for μa large. For other values of μa, graphical integrations were performed, and the results are given as functions of μa in Figures 56 and 57. Also included are dotted lines for various values of a in terms of b, which are useful in constructing other curves for special values of μb as required.

Dose Due to Fallout Material

The same method of calculation used for rainout can be used to cover the fallout case if a suitable method of expressing the rate of removal from the cloud can be found.

*Values of the exponential integral $\int_{\mu b}^{\infty} \frac{e^{-z}}{z}\, dz$ are available in "Tables of Functions" by Jahnke and Emde, Dover Publication, 1945.

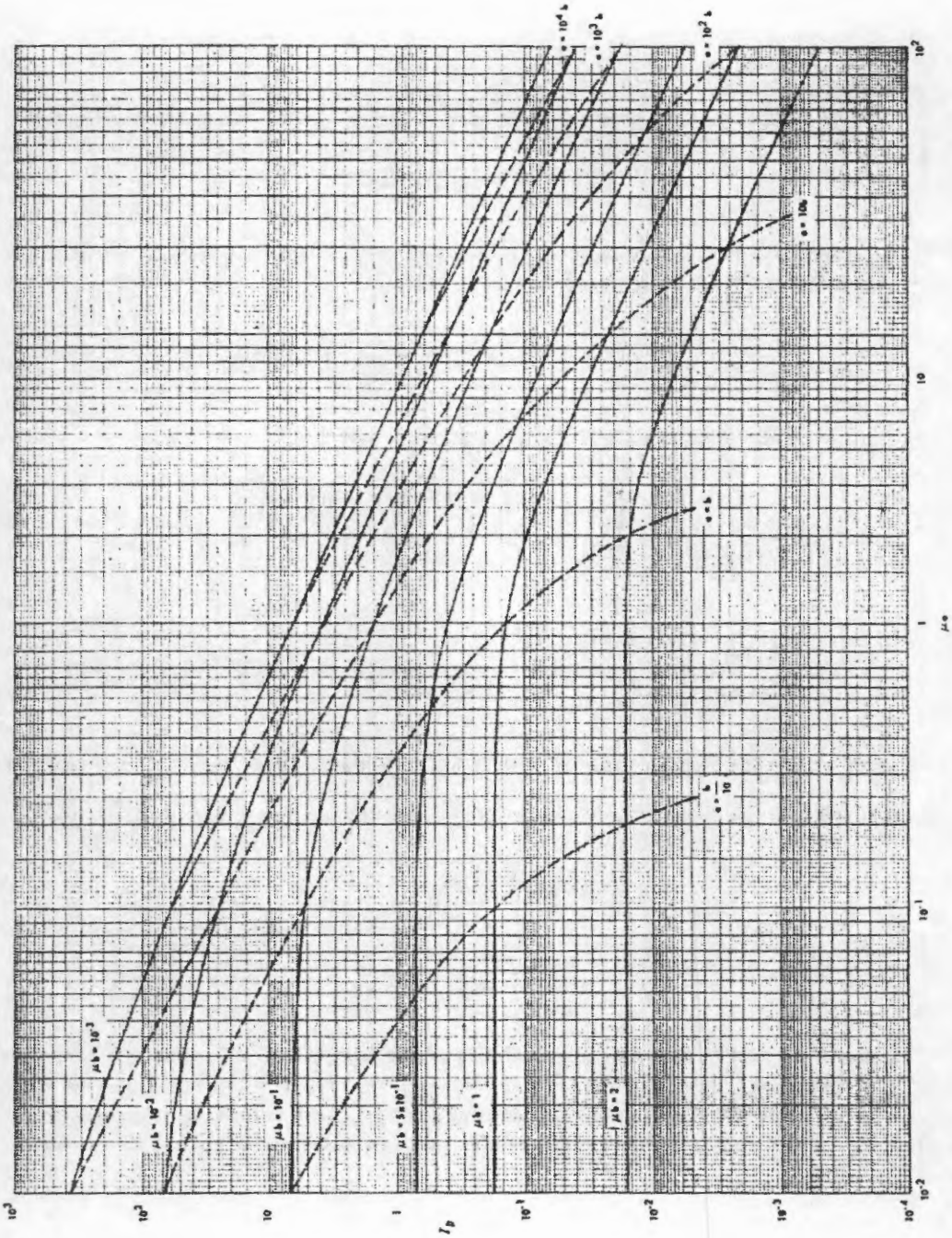

Fig. 56 - I_D versus μ a for rainout dose

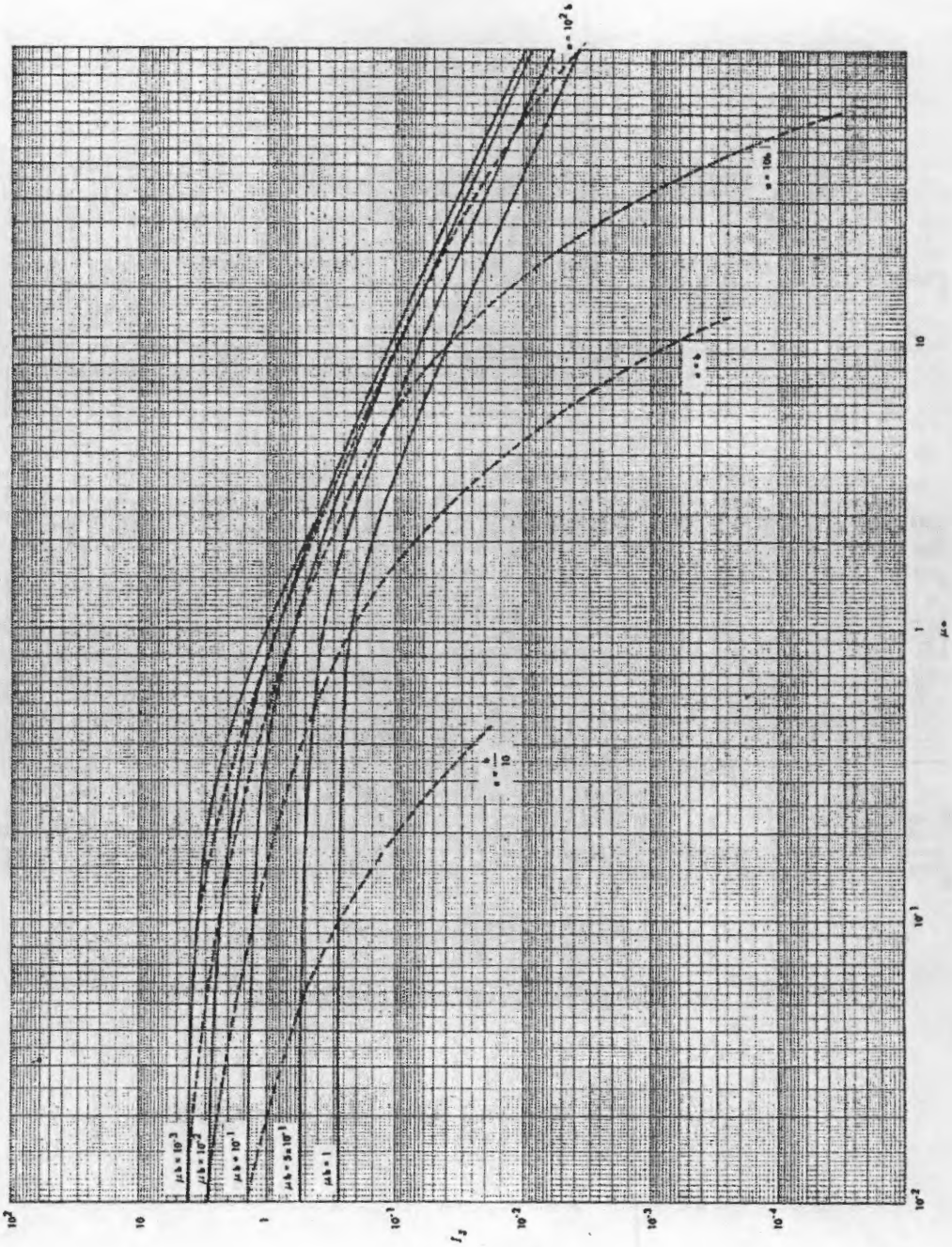

Fig. 57 - I_S versus μ a for rainout dose

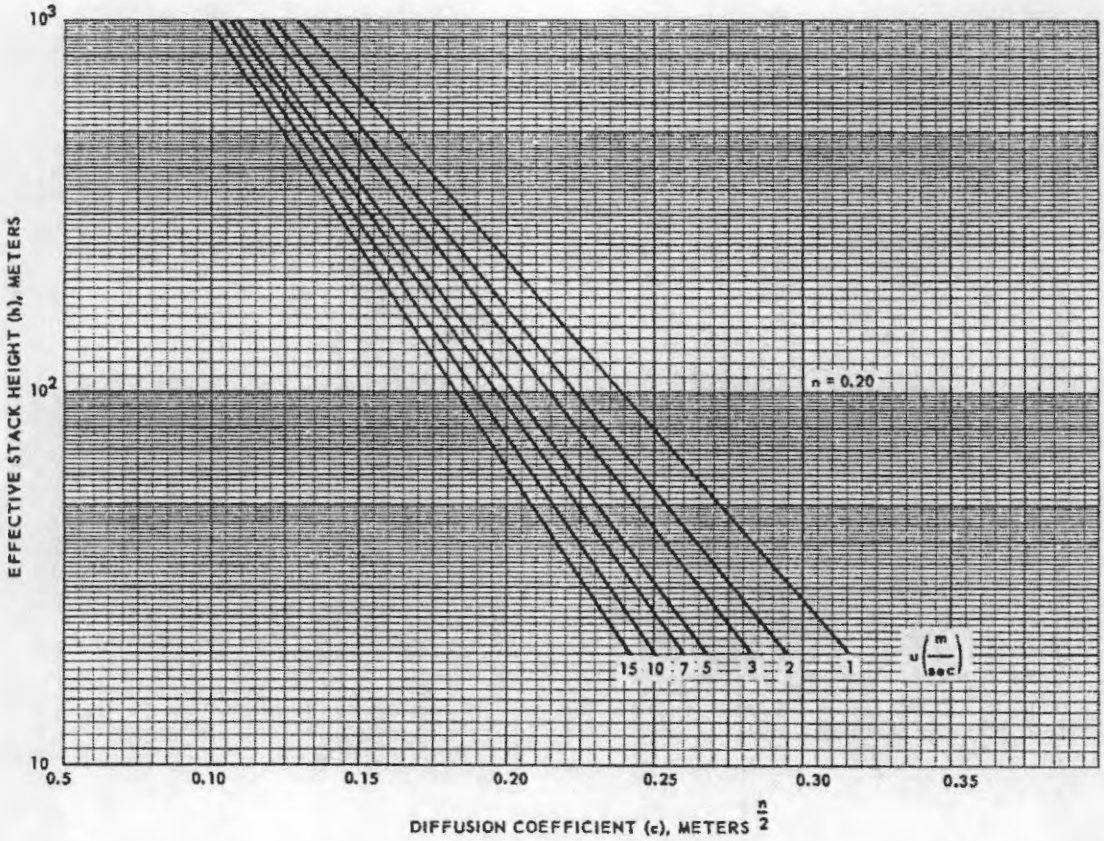

Fig. 58 - Stack height versus diffusion coefficient for n = 0.20

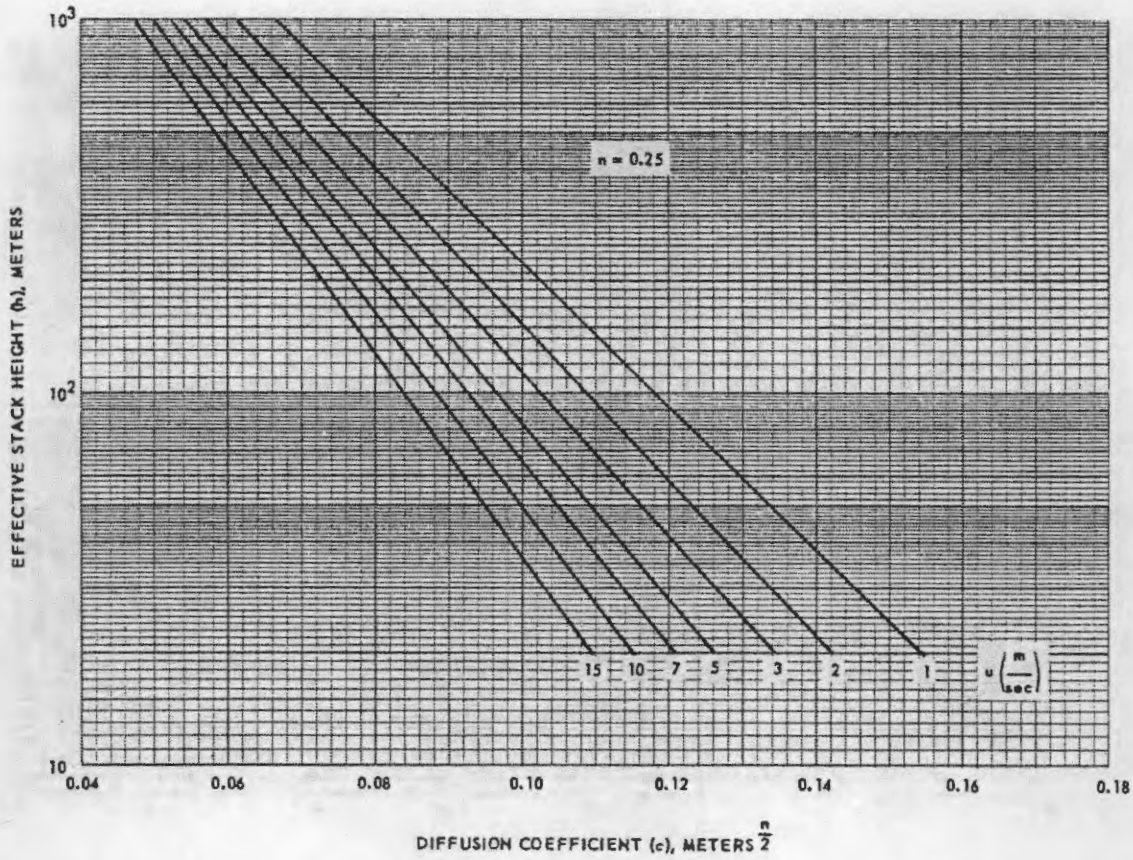

Fig. 59 - Stack height versus diffusion coefficient for n = 0.25

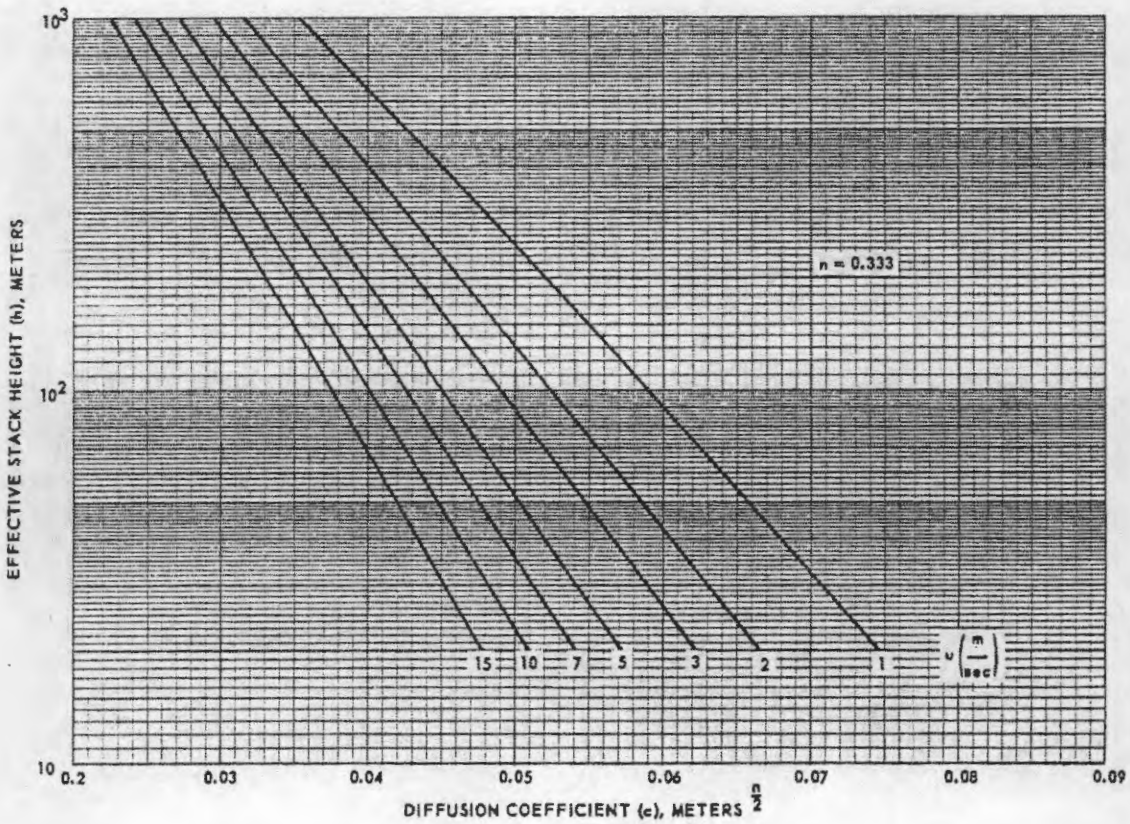

Fig. 60 - Stack height versus diffusion coefficient for n = 0.333

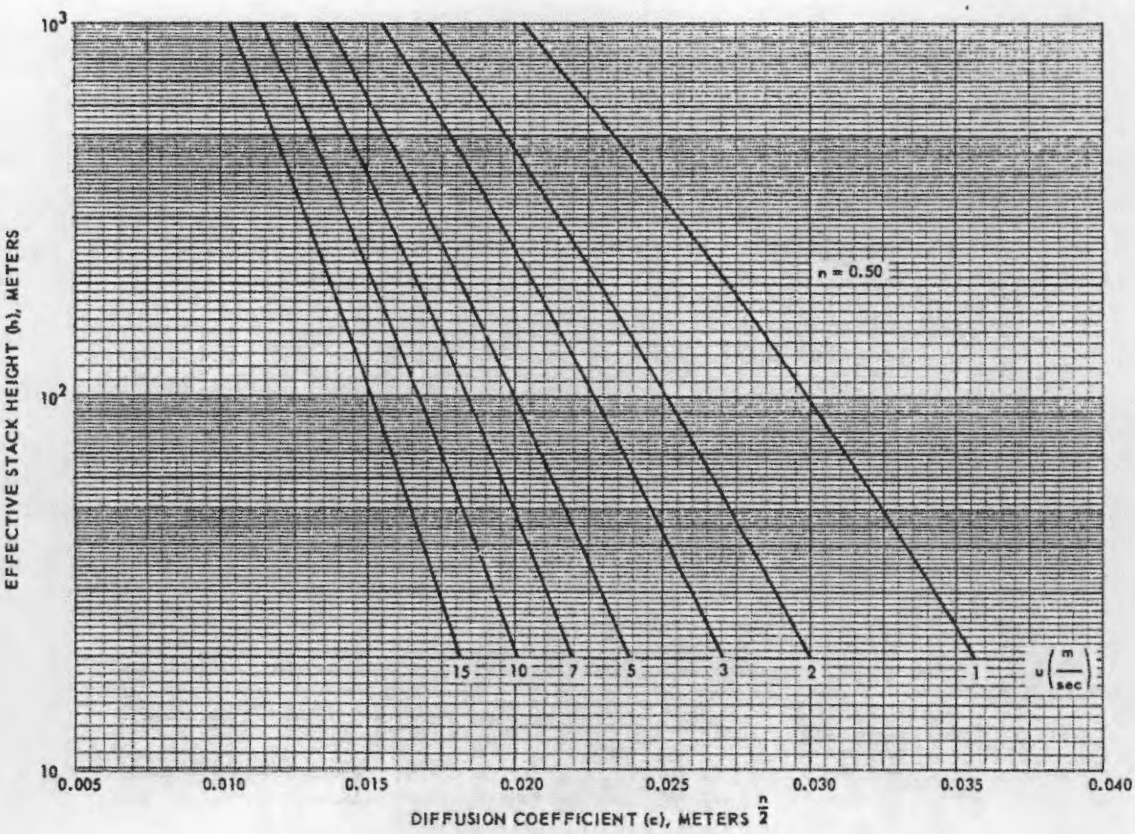

Fig. 61 - Stack height versus diffusion coefficient for n = 0.50

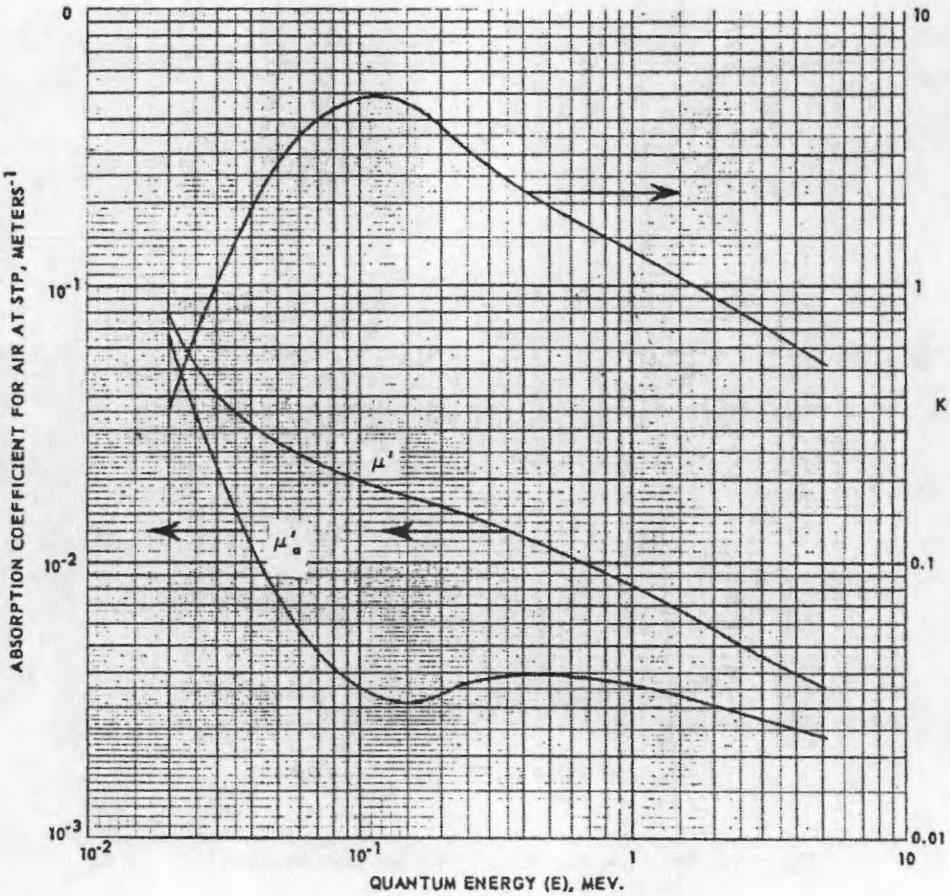

Fig. 62 - μ', μ'_a and K versus quantum energy

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An upper limit to the expected dose and dose rates can be obtained by determining the value of ν which will maximize the expression

$$\nu \exp\left[-\nu\left(\frac{x}{u}-\tau\right)\right]$$

where τ would represent the time after emission at which the largest particles would reach the ground.

$$\frac{d\left\{\nu \exp\left[-\nu\left(\frac{x}{u}-\tau\right)\right]\right\}}{d\nu} = \exp\left[-\nu\left(\frac{x}{u}-\tau\right)\right] - \nu\left(\frac{x}{u}-\tau\right)\exp\left[-\nu\left(\frac{x}{u}-\tau\right)\right] = 0$$

from which

$$\nu = \frac{u}{x-\tau u}$$

and

$$\nu Q = \frac{Q_0 u}{(x-\tau u)e}$$

so that the maximum possible dose due to fallout is

$$D = \frac{2\pi^{1/2} Q_0 G \mu_a' \mu}{(x-\tau u)e}\left[I_D + \frac{K}{2} I_S\right]$$

4.63 VALUES OF PARAMETERS FOR THE DOSE EQUATIONS

Sutton's original work indicated certain diffusion coefficients to be used for particular wind velocities and stability conditions. Hilst and Barad* developed, theoretically, expressions to give the values of the diffusion coefficients for other values of wind speed and turbulence. Wanta† has corrected original values for these constants which were incorrectly translated from measurements based on centimeters to values measured in meters. Values for c as a function of height of the emitting stack for several values of the wind velocity have been calculated and are given in Figures 58, 59, 60, and 61 for the stability parameter values of $n = 0.2$, 0.25, 0.333, and 0.5.

The values of μ', μ_a', and K are given for air at STP conditions in Figure 62. These are based on calculated values which agree well with experiment.§

*Hilst and Barad – HW-21415 plus supplement plus addendum.
†Wanta – Private communication from E. M. Wilkins, USWB at Idaho Falls.
§Based on calculations in Heitler, "Quantum Theory of Radiation."

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