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Kinglet Safety Analysis

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CONTENTS

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ABSTRACT

The Kinglet critical assembly, with circulating enriched-uranium solution, is to provide design information for the proposed KING high-flux reactor. The assembly, at the Pajarito Site, is complete except for introduction of the solution. It is demonstrated that safety features of the critical-assembly facility and of Kinglet, and the restrictions of Pajarito Operating Limits will effectively protect personnel and the public.

INTRODUCTION

The Kinglet critical assembly simulates certain significant characteristics of the proposed KING high-flux reactor. As in the reactor, an enriched-uranium solution is circulated at moderate velocity through a region where criticality is attainable. Unlike the reactor, Kinglet has neither heat exchanger nor special shielding, because it is intended for critical experimentation instead of reactor-type operation. Consistent with this use, Kinglet is subject to the fission-product limitation and other restrictions that have been adopted for the operation of critical assemblies at the Los Alamos Scientific Laboratory.

Broadly, the objective of Kinglet critical experiments is to contribute to the design of the KING reactor. One important question to be answered relates to conditions under which dynamic instabilities can be avoided. If flow through the critical region tends to be unstable, special damping features may be necessary to eliminate reactivity oscillations. Another somewhat related question has to do with the formation of radiolytic-gas bubbles under various operating conditions, and resultant reactivity effects. In general, Kinglet will provide check-points for KING design calculations that involve complex hydraulic and neutronic interactions.

The active part of Kinglet is shown in Fig. 1. Uranyl-sulfate solution pumped up the zirconium tube can become

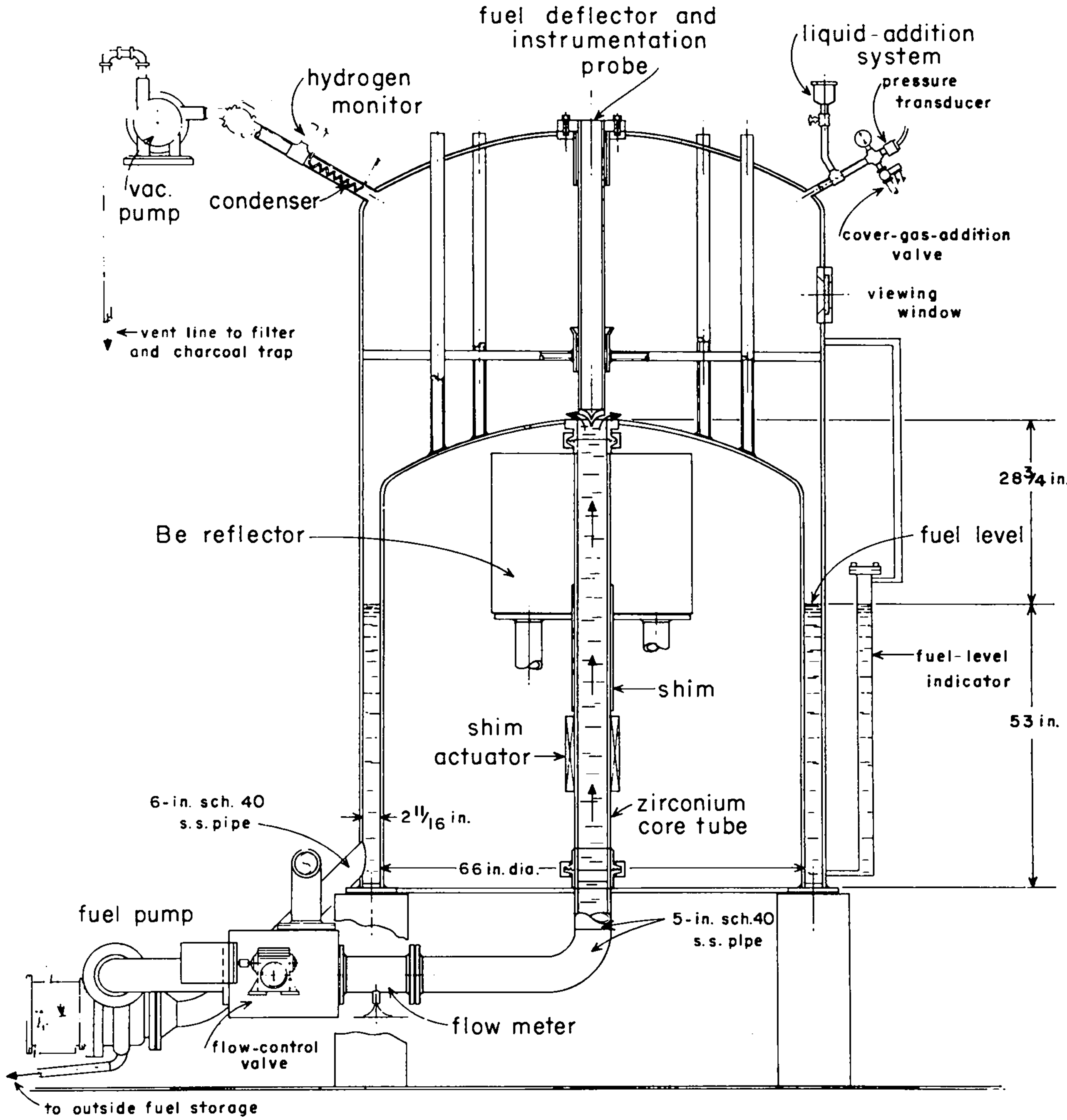


Fig. 1. Kinglet circulating system.

critical as it passes through the beryllium reflector. Upon leaving the core, the solution enters a tank, is deflected outward, and drains into an annular reservoir that feeds the large constant-speed fuel pump. A special valve controls flow by sending part of the solution through a bypass line. A cadmium coated sleeve (the shim) controls reactivity during normal operation, and provides rapid shutdown capability as part of the safety system.

The principal features of Kinglet are summarized in Table 1. Included are quantities related to the fission-product limitation that characterizes LASL critical assemblies. This limitation translates to the listed maximum value of 1.3×10^{18} fissions for any operation. As shown later, the most severe reactivity-insertion accident that is possible with Kinglet would yield only one-tenth of this maximum allowable number of fissions.

Table 1

Characteristics of Kinglet

Fuel, $U(93.2)\,O_2SO_4$ solution:	
^{235}U concentration, target value	86 g/ℓ
volume	~600 ℓ
Core, Zircaloy-2 tube:	
inside diameter	5.000 in.
outside diameter	5.375 in.
fuel velocity, maximum	22.5 ft/sec
excess reactivity, maximum	~6$
Reflector, Brush S-200-C Be:	
inside diameter	5.575 in.
average thickness	11.5 in.
height	28.0 in.
Control-safety sleeve 0.030-in. Cd on 0.046-in. steel:	
maximum withdrawal rate (2 in./sec)	~2.0$/sec
insertion rate (also max. possible withdrawal rate)	~4.0$/sec
shutdown	> 10$
Cover gas, 90 v/o He - 10 v/o O_2:	
pressure, maximum	< 10 psig
volume	~ 3000 ℓ
radiolytic gas volume (STP), maximum per run	~ 210 ℓ
Fission-product limitation:	
fissions per run, maximum	1.3×10^{18}
fuel ΔT in core, maximum	~ 20°C
maximum fuel temperature	< 100°C

ADMINISTRATIVE FRAMEWORK

The operating group. Critical experiments at Los Alamos have been conducted since 1947 by a group initially designated W-2 and renamed Group N-2 in 1955. This group is also concerned with computational programs that parallel critical experiments, with radiation effects and shielding studies that are primarily computational, with the development of specialized instrumentation, and with neutron physics research that does not involve criticality. Consequently, only 20 of the 32 members of Group N-2 actually perform critical experiments, so would be available for Kinglet operation. Of these, only two have been with the group less than ten years (one five years, the other three years). Backgrounds are summarized briefly in Table 2. As shown there, 15 group members are qualified as "crew chiefs", to be in charge of critical experiments, and 5 others serve simply as "crew members".

Operating procedures. Old "Pajarito Operating Regulations" have evolved into the LASL document LA-4037-SOP (April 1969), entitled "Operating Procedures for the Pajarito Site Critical Assembly Facility". These general procedures are supplemented by an Experimental Plan that includes procedures specific to a given experiment. There is a requirement that each critical or near-critical operation be covered by such an Experimental Plan.

Table 2

Backgrounds of Critical Experimenters

Joined the Group	Education	Specialties
Crew Chiefs		
1943*	AB, mathematics	assembly operation
1946*	BA, mechanical engineering	assembly design, operation
1946*	PhD, physics	administration, all aspects
1950	MA, physics	reactivity, cross-section studies
1950	PhD, chemistry	reactor physics, theory, administration
1951	PhD, physics	Rover, criticality safety
1953	PhD, physics	reactor kinetics, dynamics
1953	PhD, physics	fission detection, cross-section studies
1953	BS, electrical engineering	neutron spectral studies
1955	PhD, physics	reactor physics, theory
1956	BS, mechanical engineering	weapon-directed tests
1957	MA, physics	specialized instrumentation
1959	BS, electrical engineering	Rover studies
1961	MA, physics	criticality safety
1966	MA, nuclear engineering	nuclear physics, theory
Crew Members		
1951	---	control engineering
1958	some university work	assembly design, maintenance
1960	AB, business	material records, inventory
1961	some university work	instrument maintenance
1968	graduate student	neutron spectral studies

*With the predecessor of Group W-2

A most important function of the operating procedures, of course, is to establish conditions for the protection of people handling fissile material. For this purpose there is emphasis upon a "hand-stacking limit" that corresponds to a value of 10 for idealized neutron multiplication (or three-quarters of a critical mass, where that has more significance). Storage, handling, and transfer practices are in accordance with the ANSI Standard N16.1-1969, Revision of N6.1-1964, "Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors," and are designed to be far below the quoted hand-stacking limit.

Next in importance are provisions for backing up protective features built into the facility, that is, to maintain effectiveness of the isolation area during remote operation. These provisions include survey of that area before operation, interlocks to prevent operation with the gate to that area open, captive-key actuation of the switch that controls power for the machine and the same key required to open the gate, alarms to signal imminent operation, and flashing lights at the gate during operation.

Another category of procedures has the purpose of averting accidental excursions during remote operation or to limit consequences if such excursions should occur. Minimum scram capability and fail-safe scram actuation, with duplicate sets of radiation monitors and with multiple scram mechanisms for critical operation, are called for. Interlocks serve (1) to prevent startup unless the vernier control is at minimum reactivity and two scram monitors are active, (2) to establish the sequence of events during startup, and (3) to prevent operation of the vernier control before fissile components are in position (or Kinglet solution is in the core). Also specified are two channels of startup instrumentation and one for automatically recording the neutron flux during critical operation, as well as appropriate selector switches, position indicators (solution level and valve position indicators for Kinglet), and indicator lights at the control console. Finally, there are limits on rates of reactivity addition.

Certain departures from the general operating procedures are permitted provided they are specified in the governing experimental plan. The most usual deviation is relaxation of limits on reactivity-addition rate provided they are required for kinetic or dynamic measurements and provided they can be justified by reproducibility of the system. It is expected that greater-than-normal reactivity-addition rates will be used for Kinglet dynamic tests if justified by operation under standard conditions.

As stated in the Operating Procedures, the LASL Reactor Safety Committee is responsible for general review of operations within the critical facility. Matters of technical execution, as well as policy, are included.

There is also an N-2 Nuclear Safety Committee that advises the Group Leader about the implementation of procedures or of modifications that should be initiated.

Operating Limits. The Operating Procedures and content of Experimental Plans are constrained by overall limitations that appear in the document, "Operating Limits for the Los Alamos Critical-Assembly Facility". This document, as revised in 1968, has AEC approval, and no departures from its restrictions are permitted without concurrence of the Operational Safety Division in the Albuquerque Operations Office. No such departure is contemplated for Kinglet operations. The restrictions that appear in Operating Limits may be paraphrased as follows.

> Controlling documents. The ANS standard, ANS-STD. 1-1967, "A Code of Good Practices for the Performance of Critical Experiments" (Appendix I), the "Pajarito Plan for Radiation Emergency" (Appendix II), and the following supplementary operating limits will be observed, unless an exception is approved specifically by the ALO Operational Safety Division.
>
> Fission-product limitation. The fission-product power generation in any assembly, when averaged over the first hour after shutdown shall not exceed 600 watts. This limit is the first-hour

average that would follow a burst of 10^{18} fissions. Figure 2 relates fission power at various times after shutdown to fission energy and duration of operation.

Administrative requirements. 1.) Pajarito operations shall fall under the general surveillance of the LASL Reactor Safety Committee which represents the Laboratory Director. This committee shall review and approve Operating Procedures (LA-4037-SOP, "Operating Procedures for the Pajarito Site Critical Assembly Facility") and any proposed changes of Operating Limits.

2.) Each critical or near-critical experiment shall be covered by a written Experimental Plan (distinct from Operating Procedures and Operating Limits) which shall be approved by the Chairman of the N-2 Nuclear Safety Committee, the N-2 Group Leader, and the N-Division Leader. An Experimental Plan shall be valid for no more than two years after the date of issue unless reinstated.

3.) Each operating crew that performs experiments shall be appointed by the N-2 Group Leader, and shall consist of a crew chief who is experienced in Pajarito methods of operation, and

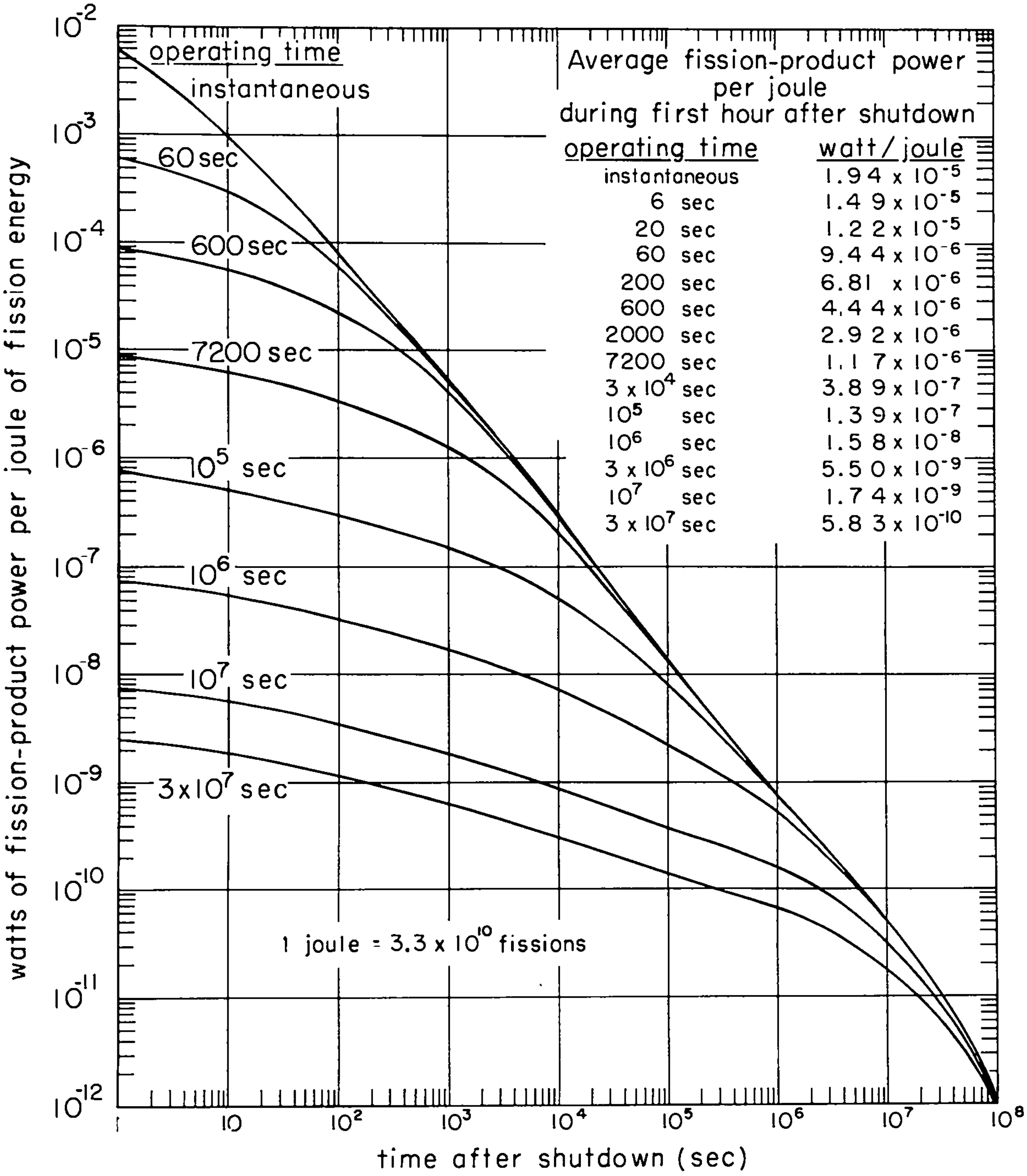


Fig. 2. Fission-product power.

at least one other competent person. The chief shall be responsible for all aspects of the crew's operation and shall consider personnel safety of paramount importance.

Operational requirements. 1.) Two independent disassembly (scram) devices and a vernier control device are required for critical operation. An assembly that does not satisfy this requirement shall be maintained subcritical by a margin stated in the Experimental Plan.

2.) The excess reactivity of an assembly shall not exceed the worth of remote controls.

3.) For an assembly in which the effectiveness of an inherent prompt shutdown mechanism is doubtful, the excess reactivity shall not exceed the value corresponding to a positive period of 5 sec.

4.) For an assembly in which the effectiveness of an inherent prompt shutdown mechanism is clear, the reactivity margin below prompt criticality shall be at least three times the reproducibility demonstrated by a series of disassembly and reassembly operations, unless further requirements for super-prompt-critical operation are satisfied.

5.) The further requirements for super-prompt-critical operation are that the fissile material shall be limited to enriched uranium, and that the demonstrated reproducibility (adjusted to constant temperature) shall be within ± 0.2 cent for a solid assembly or ± 2.0 cents for a solution assembly. Above prompt criticality, an increase of reactivity beyond a value previously attained shall not exceed 1.0 cent for a solid assembly or 10 cents for a solution assembly.

Safety Analysis Report. The SAR that governs LASL critical experiments is report LA-4273, "Safety Analysis for the Los Alamos Critical-Assembly Facility", by W. U. Geer, P. G. Koontz, J. D. Orndoff, and H. C. Paxton (Nov. 1969). This report updates LAMS-2698, "Hazards Evaluation for the Los Alamos Critical Assembly Facility", by the same authors (April 1962). The ALO Operational Safety Division judged that Kinglet differed enough from other LASL critical assemblies to require a supplement to the existing SAR. The Director of LASL was so notified in the OSD report "Nuclear Safety Survey of the LASL Critical Assembly Facility at Pajarito", forwarded May 25, 1970:

"It is recommended that a safety evaluation be prepared for the Kinglet facility and submitted to ALO for approval prior to fueled testing."

The first response to this recommendation, "Kinglet Safety Evaluation Report", by T. F. Wimett and R. H. White was submitted to ALO-OSD on March 31, 1971, and a supplement responding to ALO comments forwarded on Sept. 3 was submitted on Sept. 20. The present SAR consolidates and expands these documents, as requested by J. R. Roeder, Director of OSD, in a letter of Sept. 21.

THE FACILITY

The Site. The Los Alamos Critical Facility is located at Pajarito Site, off the road between White Rock and the Los Alamos residential area (Fig. 3). The site is at the junction of Pajarito Canyon and its southern fork named Three Mile Canyon. The Facility consists of three outlying buildings (called "Kivas") in which critical assemblies are operated remotely from three separate but grouped control rooms (Fig. 4). The main laboratory building within which the control rooms are located is about one-quarter mile from Kivas 1 and 2 and somewhat less distant from Kiva 3. The fenced Kiva areas, indicated in Fig. 4, are closed by separate gates during periods of remote operation.

Critical assemblies now operational within the three Kivas are described briefly in Table 3. Hydro, an assembly that had been located outside Kiva 2, was retired early in 1971 (the portable assembly, Jezebel, is still operated outside of Kiva 2 when effects of Kiva walls are to be avoided). As shown in Figs. 4 and 5, Kinglet is located in its own building immediately to the south of Kiva 1. It is two and one-half miles from the nearest residences, 1500 ft from the road to White Rock, and 1000 ft from the gate at the entrance to the Kiva 1 area.

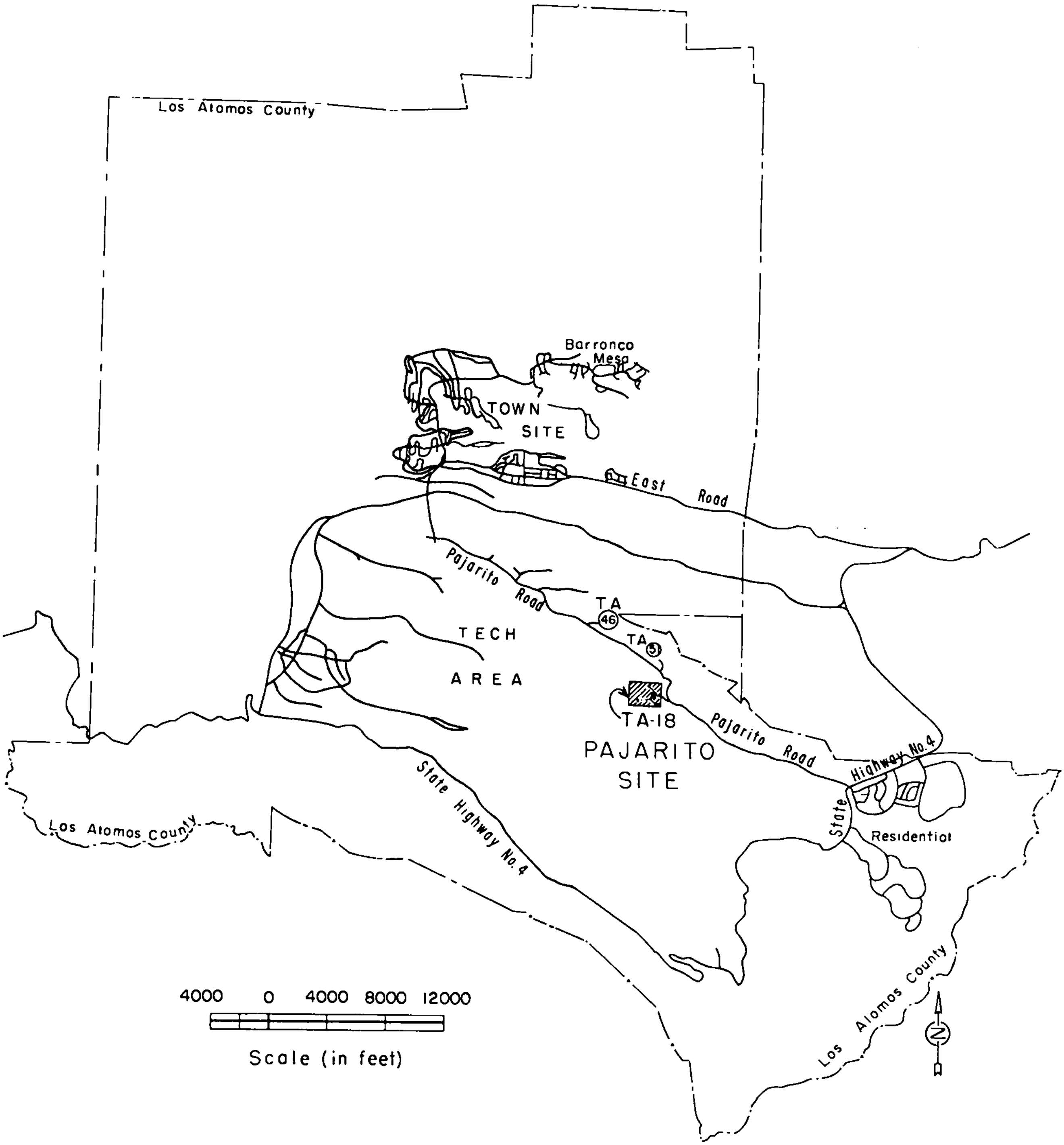


Fig. 3. Environs of Pajarito Site.

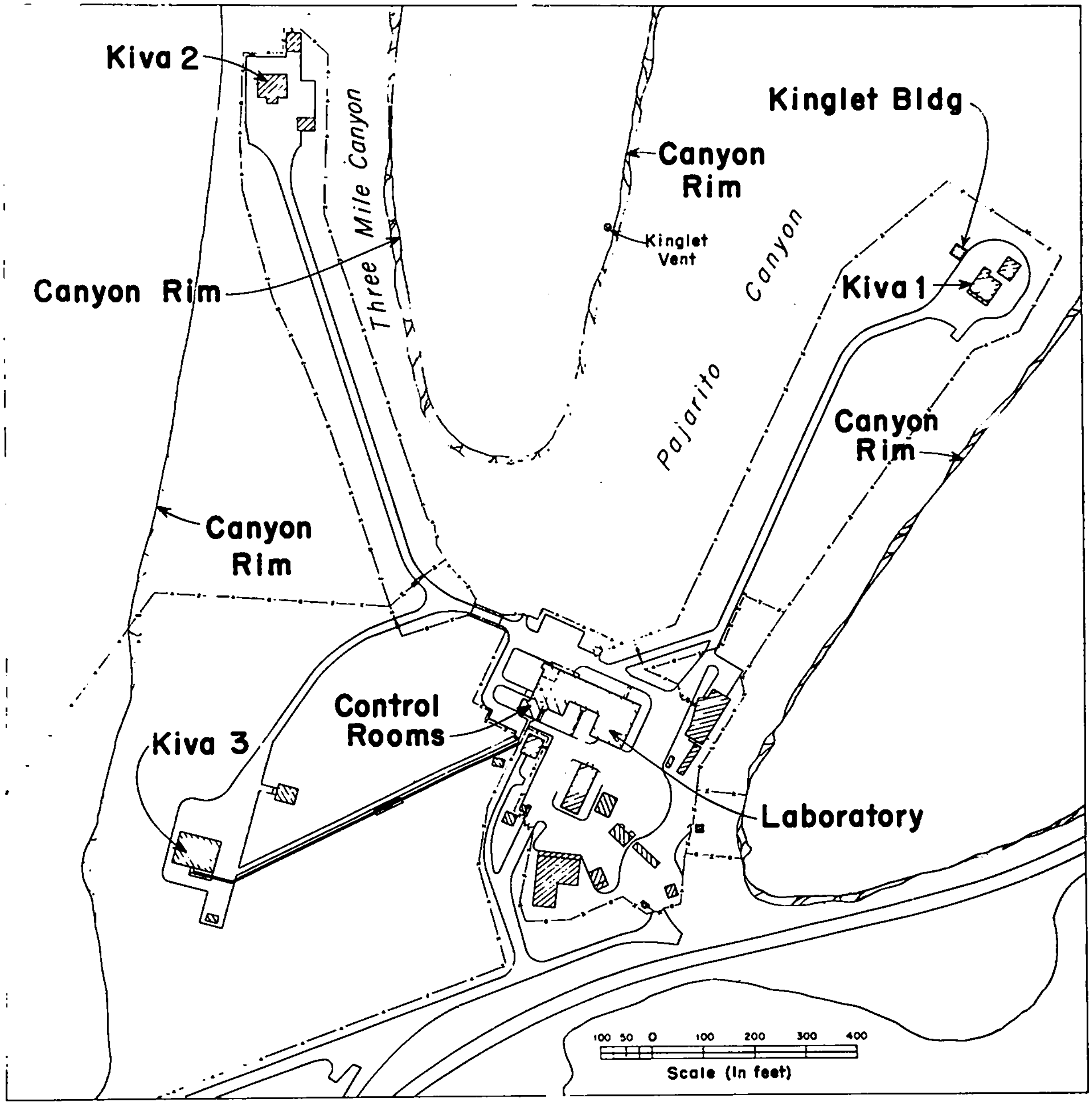


Fig. 4. Pajarito Site and terrain.

Table 3

Critical Assemblies within the Kivas

Name	Description	Function
Kiva 1		
Pewee Zepo	Rover fuel, some ZrH_2, Be reflector	mock-up Pewee reactors
Nuclear Furnace Zepo*	Rover fuel, water moderation Be reflector	mock-up Nuclear Furnace reactor
Honeycomb	unreflected 4-ft cube of graphite-U(93) at $C/^{235}U = 180$	reactor-physics measurements
Kiva 2		
Jezebel	unreflected, near-spherical δ-phase Pu	computational bench-mark, low-level activation
Flattop	spherical U(93), Pu, or ^{233}U core, 19-in.o.d.U(normal) reflector	computational bench-marks, sample activation
Big Ten	cylindrical U(10) core, 6-in.-thick U(depleted) reflector	computational bench-mark, reactor-physics measurements
Comet	hydraulic lift with variety of super-structures	weapon tests, other criticality safety tests
Kiva 3		
Parka	Rover fuel in Be reflector (Phoebus 1 components)	mock-up Phoebus 1 reactors
Godiva IV	unreflected cylinder of U(93) -1½% Mo, center-of-shock mounted	fast-burst experiments

*Will be moved to Kiva 3.

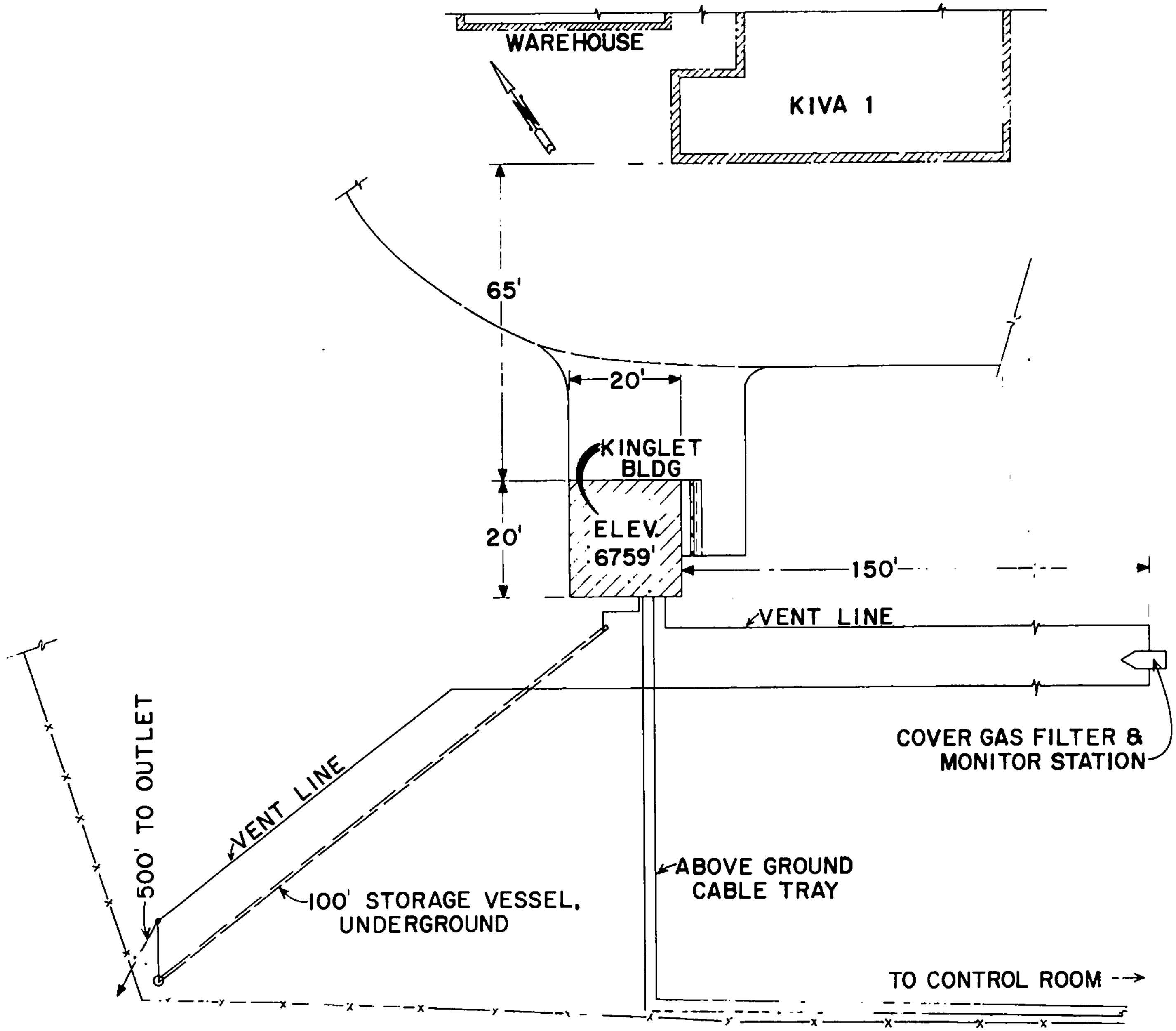


Fig. 5. Kinglet Building and auxiliaries.

Kinglet building. The building that houses Kinglet is of all-metal double-wall construction with rigid frames anchored to a concrete pad (Fig. 6). It is designed to withstand a snow load of 30 lb per horizontal ft^2, and a wind load of 25 lb per ft^2. The base is 20-ft by 20-ft (outside) and the height at the eaves is 14 ft (about 17½ ft at the peak). All walls and ceiling are insulated by Fiberglas. Heat is electrical and a gravity ventilator is on the roof.

Only Kinglet and its auxiliaries are to be housed in the building--there is not even provision for incidental storage (Kiva 1 ante-rooms and warehouse are to be used for that purpose). In particular, flammable materials will be avoided except for the essential electrical insulation and about 20 gal hydraulic fluid in the control-rod-drive system. Because of low combustible loading and the wish to avoid flooding, there is no automatic fire protection. A fire-alarm box has been installed at the northwest corner of the building.

Certain appendages of Kinglet outside the building are indicated in Fig. 5. An underground storage pipe for solution extends southeastward, and there is an above-ground tray for cables to the control room. A cover-gas vent line goes through a continuous monitor to the east, then southward to a discharge point above the rise between canyon branches (Fig. 4). These features are described later.

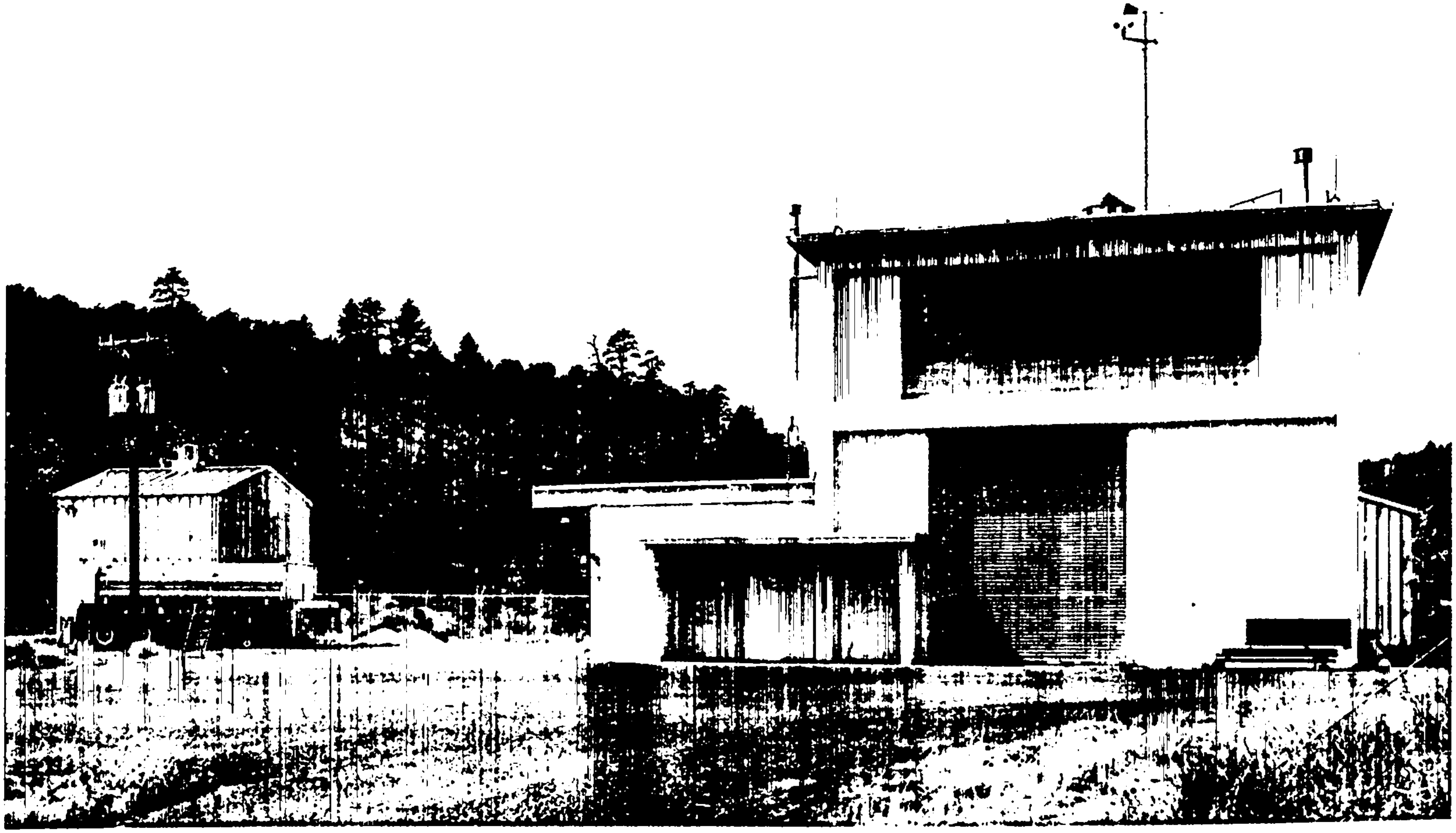


Fig. 6. Kinglet building at left, and Kiva 1. The off-gas vent is on plateau in background.

Meteorological conditions. Pajarito Site is semi-arid, but at its elevation of 6760 ft gets some winter snow, and is subject to summer thunderstorms that are characteristic of the general region. Runoff from storms has not been severe in Pajarito Canyon, for at no time during the 25-year history of the site has flood water reached the floor elevation of the Kinglet building.

Winds in Pajarito Canyon are not as severe as on the plateau above, because of the moderating effect of canyon walls and the Jemez mountains to the west. The canyon is not aligned with the prevailing winds from the southwest. An anemometer on the roof of Kiva 1, with indicator in the control room, has been in service for 24 years. The highest observed wind velocity during this period is 60-65 mph, in the form of a gust. The 25 lb/ft^2 wind loading capacity of the Kinglet building corresponds to a wind velocity of 95-100 mph, which is considered generous for Pajarito Site.

Seismic considerations. A review of the earthquake potential of Los Alamos, by T. E. Kelley and F. C. Koopman of the U.S. Geological Survey (Sept. 1970), is reproduced as Appendix III. According to that report and a supplement of April 1971 by T. E. Kelley, only three earthquakes in the vicinity of Los Alamos have been recorded. One tremor, of magnitude 5, occurred at 3:45 am on Aug. 17, 1952, and caused only minor damage at Los Alamos. Another, of magnitude 7, occurred at 1:56 am on Jan. 23, 1966 near Dulce, but was not felt at Los Alamos. The third, recorded at 4:28 am on Feb. 18, 1971, was felt at Los Alamos though its magnitude was only 3. Reports from Los Alamos suggest that no shock has exceeded intensity V (MM). It is estimated that Kinglet, under operating conditions, would withstand a shock of intensity VII without damage, and at intensity VIII might develop a leak but would not be upset. Because of a catch pan (described later), a leak would have no serious consequence.

THE KINGLET ASSEMBLY

General. The features of Kinglet that are illustrated by Fig. 1 and the principal characteristics listed in Table 1 are consistent with a design value of 1.3×10^{17} fissions/sec for the maximum fission rate in the core region, and with the need to avoid criticality elsewhere. The design fission rate was selected to give the maximum allowable number of fissions per run (established by Pajarito Operating Limits) in 10 sec, about the shortest duration that is practical. Except for the Zircaloy core tube, the only material that the fuel contacts is stainless steel (Type 316), selected for compatibility with the uranyl-sulfate solution. (The chemical stability of Zircaloy-2 with this solution is discussed in Appendix IV.)

The layout of Fig. 4, with provision for operation from Control Room 1, about 1200 ft from the Kinglet building, is intended to take full advantage of protective features that characterize the Pajarito Facility. Controls, electrical interlocks, and instrumentation are designed to satisfy requirements of the general Pajarito Operating Procedures, and to facilitate meaningful experimentation. Accordingly, instrumentation will provide accurate and continuous monitoring of pertinent conditions such as solution levels, flow rate, and temperatures, neutron flux values, and radiolytic-gas concentration.

The underground storage pipe that appears in Fig. 5 is for containing the fuel solution when the system is not in operation. With the solution thus removed from Kinglet proper, personnel will not receive significant exposures while inspecting components, installing experimental apparatus, or adjusting instruments. The storage vessel, piping, and main tank form a closed system that will contain radiolytic gases and fission products, with such large volume that the pressure rise during any operation will be negligible.

Fuel solution. The fuel composition planned for the dynamic test program is described as follows. The uranium enrichment will be 93.2%, with the solution content being 86 grams ^{235}U/liter in the form of UO_2SO_4. The solution will also contain 0.500 $\underline{M}$ excess H_2SO_4 + 0.05 $\underline{M}$ $Fe_2(SO_4)_3$ +0.01 $\underline{M}$ Cu SO_4. The additives are for the purpose of inhibiting the precipitation of UO_4. Observations about the chemical stability of uranyl-sulfate solution appear in Appendix IV.

Important physical properties of the fuel are the freezing point, normal boiling point, and the volumetric expansion coefficient, all of which are close to those of pure water, i.e., 0^oC, 100^oC, and $2.1 \times 10^{-4}/^oC$, respectively. The solution density will be 1.13 to 1.15 g/cm^3.

Fuel pump. The pump and motor assembly (see Figs. 7 and 8) is a two-speed Buffalo Forge No. 5 x 6 HCCM, with a rated capacity of 1150/550 gpm. The pump unit is close coupled to a three-phase, 30 hp, 1750/875 rpm motor, and is capable of developing a total head of 58 ft of fuel solution at 1150 gpm.

The pump is a totally enclosed unit with a 6-in.-diam horizontal suction port and a 5-in. bottom horizontal discharge. All parts wetted by the fuel solution are of 316 stainless steel construction. The motor is a hermetic canned-rotor type. The rotor and stator liners are of 316 stainless steel, with the stator liner designed for 150 psi working pressure. All electrical insulation used in motor windings, leads, etc., and all seals are capable of operating with a fuel solution temperature of 75°C. Specifications call for insulating materials which will operate in a field of nuclear radiation to an exposure of 1×10^9 R, and maintain electrical properties.

The measured total solution inventory for the pump and motor is 14.1 liters. Since this volume is slightly larger than that specified to the vendor, safety precautions required a criticality test to confirm a predicted low neutron multiplication in the pump and its fittings. The test and results are described later.

Fuel piping and flow-control system. The main fuel piping system is designed to provide controlled circulation

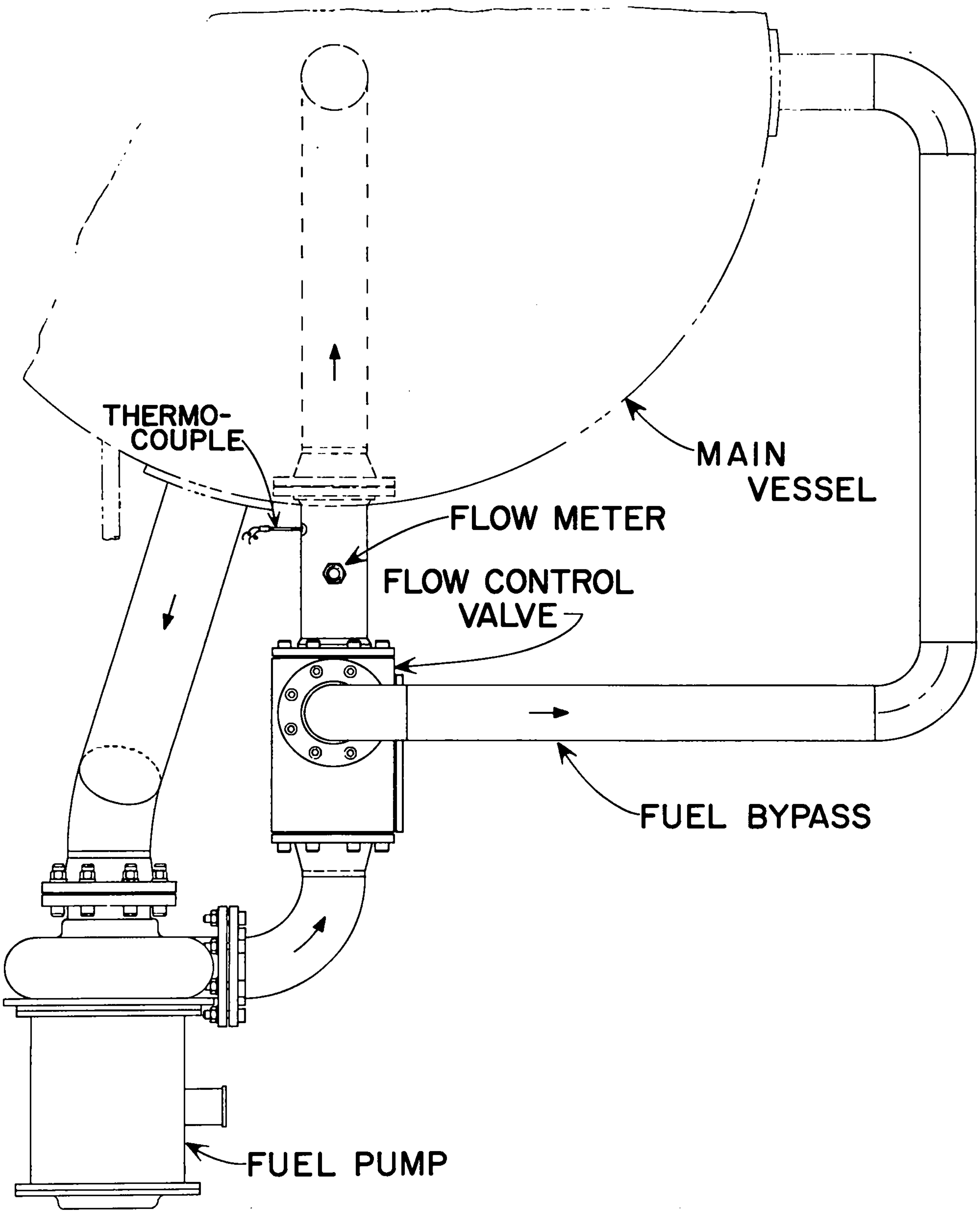


Fig. 7. Solution circulating system.

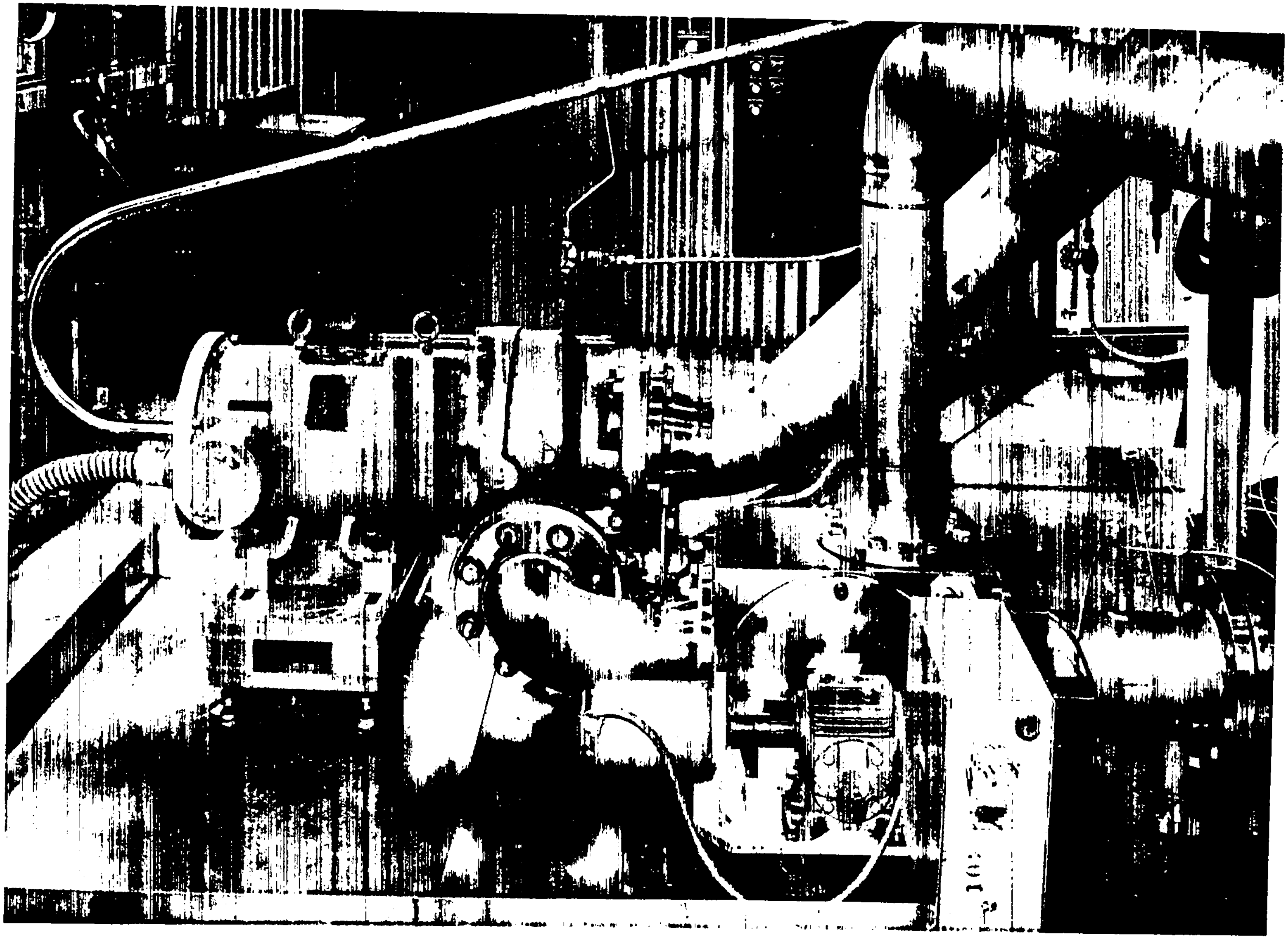


Fig. 8. Fuel pump, flow-control valve and flow-rate meter.

of the fuel solution between the main tank and the pump, as shown in Figs. 7 and 8. The solution is delivered by the pump through the flow-control valve which, by remote control, regulates the flow to the Zircaloy core tube by diverting all or part of the stream to the tank annulus through a by-pass pipe. A turbine flow meter, which is installed in the core-tube delivery line, provides fuel-velocity indication at the control room. The lengths of connecting pipe and the number of bends have been minimized for optimum flow characteristics. All pipe and flanges are of stainless steel, Type 316. Flanged joints are sealed by gold-plated stainless-steel gaskets, backed up by O-rings.

A secondary fuel piping system will be used to transfer the fuel solution between the main tank and the underground storage reservoir. This line is connected to the bottom of the fuel pump housing (the lowest point in the circulation system) and the low end of the storage reservoir. A normally closed solenoid valve in the line prevents the fuel solution from draining back to the reservoir during test runs.

The flow control valve directs fuel flow between the core tube and the core-tube by-pass. The valve body and spool are fabricated from 316 ELC stainless steel. Remote operation of the valve spool is accomplished by means of a Slo-Syn stepping motor driving through a 50-to-

1 gear reducer. A digital readout in the control room displays the total number of pulses sent to the motor for open or close spool direction. A calibration of pulse counts vs flow rate through the core tube was made during the distilled-water checkout that is described later. The valve is equipped with limit switches to indicate the limits of rotation of the spool, and to provide a remote-control interlock which will ensure by-pass flow during startup.

Except for the flow control valve, all manual and remote operated valves in the fuel and cover gas systems are commercially available stainless steel items. These valves were furnished with O-ring and seal materials that are compatible with the fuel solution.

The total radiation received by O-rings in flanges and valves will be logged so that the rings may be replaced before damage accrues. Data on p. 10.146 of Nuclear Engineering Handbook (Harold Etherington, Ed), suggest that O-rings should be changed at an accumulated dose of about 10^7 rad. Readings of thermoluminescent detectors that monitor doses will be maintained.

Main solution tank. The 6.0-ft -o.d. by 10.5-ft -high main tank (Fig. 9) is constructed entirely of Type 316 stainless steel with Class II, penetrant-inspected welds. The 2.7-in.-thick by 67.8-in.-high annular section is designed to hold the fuel solution

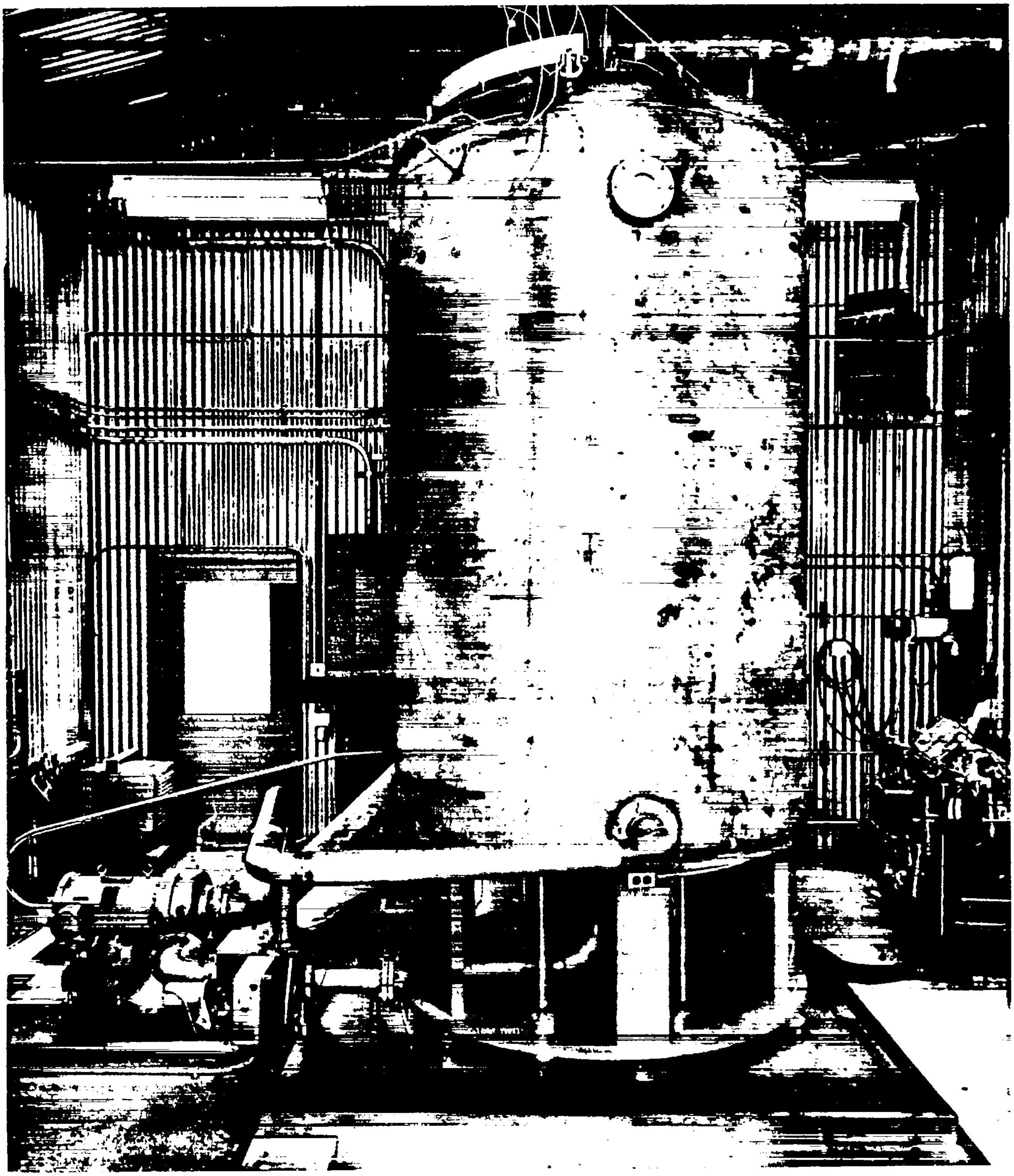


Fig. 9. Main tank and circulating system, with catch-pan below.

in a subcritical geometry. A 110-cu -ft gas volume between the two domes is sufficiently large to contain all radiolytic gases produced during a maximum allowable run, with a pressure rise of less than 1 psig. Access is provided through the top of the tank on the vertical axis for a fuel deflector which is secured just above the core-tube exit. A small port at the end of the deflector permits location of a thermocouple in the reactive portion of the fuel stream.

A liquid-level pressure transducer in the main tank and a probe in a vertical length of tubing outside the tank monitor the level of solution in the annular section.

Three 4-in.-diam viewing ports are located near the top of the tank for the purposes of tank inspection and observation of performance of the fuel deflector during preliminary system operation with water. Before operation with the fuel solution, the glass ports will be replaced with 1/2-in. thick stainless steel plates and O-ring seals. The steel ports are designed to withstand a pressure (approx. 800 psig) many times that of a safety rupture disc in the vent line (20 psig).

The tank is designed to withstand both a full vacuum and an internal operating pressure of 10 psig. A pressure test of 20 psig was performed by the vendor, as was a helium leak check. The leak check specified an overall leak rate not to exceed 1 x 10^{-7} standard cc/sec of helium, in accordance with Section 6 of Mil. Std. -271D. Both the pressure and leak tests were witnessed and accepted by LASL personnel.

Zircaloy core tube. The core tube (Fig. 1) is 5-in. i.d. by 5-3/8-in. o.d., 73-in. long, and is flanged at both ends for Conoseal joints. It was fabricated from a solid bar of Zircaloy-2 metal (hafnium free), a zirconium alloy containing approximately 1.0% Sn, 0.1% Fe, 0.05% Ni, and 0.1% Cr. This alloy was chosen for the core tube because of small neutron-capture cross section, and suitable corrosion resistance in the presence of fissioning uranyl-sulfate solution at relatively low temperature (< 100°C).

The tube was accepted following a helium leak test by LASL personnel. It satisfied specifications that the leak rate be no greater than 1 x 10^{-7} standard cc/sec of helium, in accordance with Sec. 6 of Mil. Std. -271D.

Be reflector. Existing machined beryllium blocks have been used to construct the reflector assembly (Fig. 1). All material is Brush Beryllium Co. grade S-200-C. The central section, which surrounds the upper part of the Zircaloy core tube, has been fabricated from blocks secured together with aluminum screws, then bored for the core tube and control shim.

In order to maintain the Be-to-Zircaloy clearance for the control shim the central Be unit is located by a recess machined in the reflector support platform. The entire reflector has been assembled on the support platform, and secured as a unit with metal banding.

Shim actuator and control. The shim actuator assembly consists of a hydraulic cylinder, a servo valve, metering and scram valves, and one potentiometer for position control and readout. This entire unit is mounted adjacent to the Zircaloy core tube, with the shim carrier secured to the cylinder rod through a flexible coupling. Ball bearings on the shim carrier run directly on the outside surface of the core tube, thus minimizing alignment problems.

The actuator hydraulic system, Fig. 10, is designed to provide operational characteristics which will satisfy requirements for reactivity control and for nuclear safety (the scram mode). Shim travel rate and direction are controlled by the servo valve. The withdrawal rate (reactivity increase) will be adjustable, by means of a manual metering valve, from zero to about 2 in./sec. The insertion rate (scram) is established at 4 in./sec. All other valves in the system are of the direct-acting solenoid type. In the scram mode, the solenoid valves are de-energized, allowing oil from the accumulators to pass directly to the cylinder for insertion of the shim.

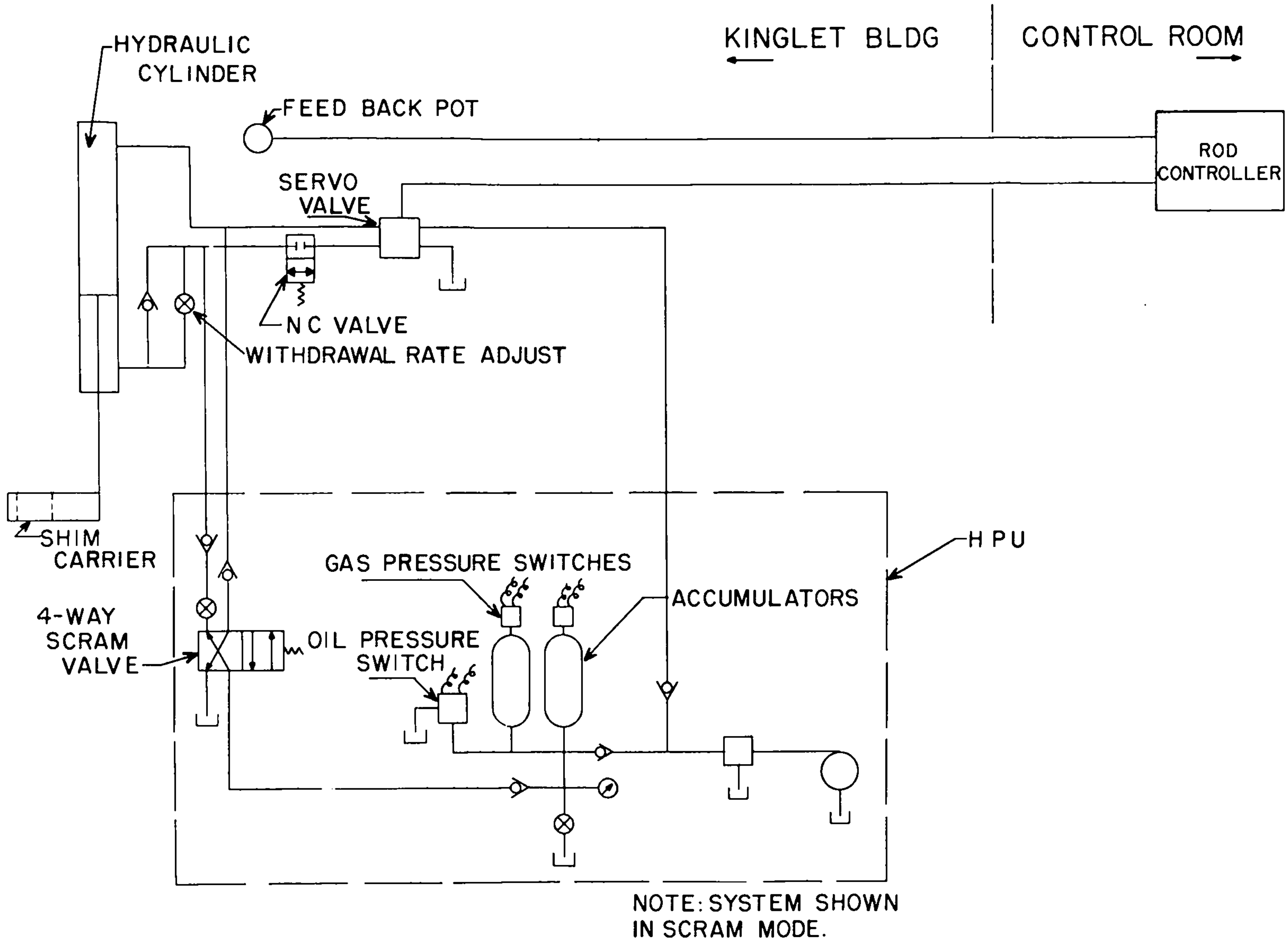


Fig. 10. Hydraulic system for driving the shim.

A pressure switch on the gas side of the accumulators is interlocked with the control circuit to ensure accumulator nitrogen precharge pressure before the actuator system can be operated. The up (full shim insertion) limit switch on the actuator is also interlocked to prevent startup of the reactor with the shim off this limit. The actuator is operated from the control room by the shim controller, which is designed to position the shim to 0.01 in. The controller is also equipped with special circuitry to permit:

1.) manual control of shim position
2.) presetting of shim position
3.) predetermined reactivity ramp increases
4.) calibration of controller functions
5.) immediate detection of electronic malfunction.

Operation of the shim controller is described in detail in "Kinglet Rod Control System", a memo from W. R. Tucker (N-4-2921).

The shim controller was designed to accommodate the necessarily fast reactivity adjustment to initiate a ten-second power run. Any such rapid insertion will be accomplished by a precalibrated ramp terminated at a preselected excess reactivity. Capability for two consecutive ramps was included to attain the ultimate power without overshoot.

Loss of hydraulic pressure due to breaking of supply lines would cause the shim to stop its motion in either direction. A scram would then be initiated manually by the operator or automatically by signal from the wall-mounted monitors, causing the fuel pump to stop. Under these conditions the downward drift of the shim would be limited to approximately 1/2 in./min due to friction in the hydraulic cylinder (determined by direct observation), allowing time for the scram.

Loss of pressure due to electrical failure of the hydraulic pump motor would deenergize a scram valve causing immediate insertion of the shim by stored accumulator pressure.

Fuel storage pipe. The 100-ft underground fuel storage tank, shown in Figs. 5 and 11, was fabricated at the site from 6-in. schedule-40 stainless steel pipe, Type 316. The size of pipe used was determined by criticality analysis based on complete water immersion.* Before installation, the vessel was helium leak checked and found to be within specifications. The leak rate was less than the 1 x 10^{-7} standard cc/sec of helium specified as a limit in Section 6 of Mil. Std. -271D.

Both the horizontal and vertical portions of the pipe are wrapped with two heating tapes, each controlled

*Ref. Fig. 10 of TID-7028, "Critical Dimensions of Systems Containing U^{235}, Pu^{239}, and U^{233}."

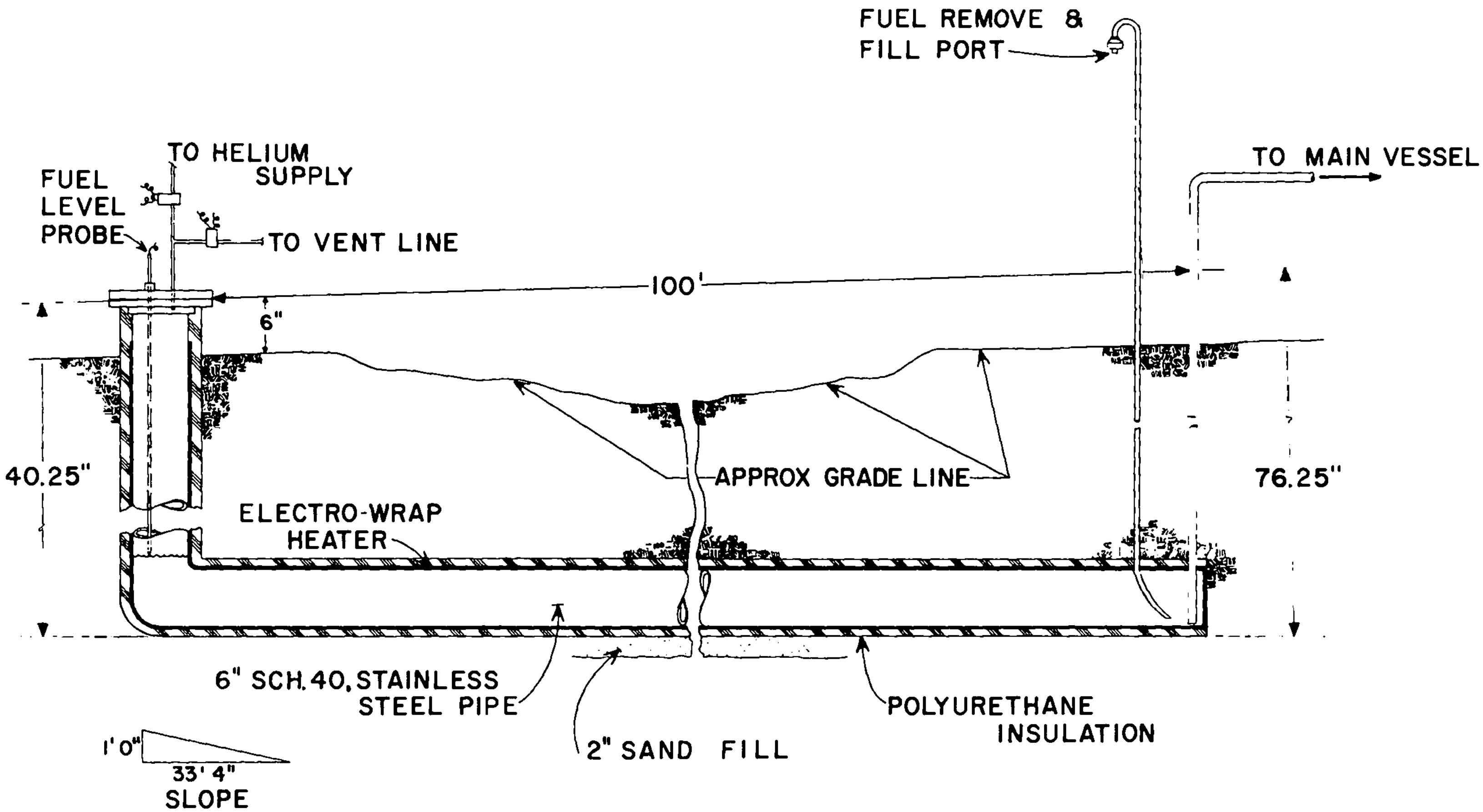


Fig. 11. Underground solution-storage tank.

by its own thermostat. Electrical service to the tapes is coupled to the SCAM area monitoring system. Additional protection will be provided by an underground temperature monitor located near the inlet end of the container. This monitor will also be coupled to the SCAM area system. The storage pipe and fuel transfer lines are insulated with 1-in.-thick closed-cell polyurethane.

The vessel will be filled with fuel solution to a level a few inches into the vertical section. This level will be checked each time the solution is returned to storage by means of a sensitive liquid level probe which will detect a 50 cc change in solution inventory. The probe is electrically interlocked with the fuel transfer valve, such that the valve will be shut off automatically when all but a few liters of fuel have been transferred to the storage pipe. This will prevent the 10-psig helium in the main tank from escaping into the pipe and producing a large bubble which might force a few cc of fuel into the filtered vent line.

Cover-gas system. The cover-gas system will provide a means of handling and monitoring fission products and radiolytic gases resulting from a test run. A purpose is to indicate when the cover gas should be vented or flushed. Special attention is given to the accumulation of hydrogen which is formed by the dissociation of water in the fuel solution.

Major components of the system (Fig. 1) are the enclosing tank, and an exhaust line with the following features successively. There is a vapor condenser, hydrogen monitor, shutoff and flow-control valve, vacuum pump, filter with charcoal trap, radiation monitoring equipment, and finally the vent. Another line, from the underground tank to the vent, has a valve, separate filter unit, and sampler (Fig. 11).

The filters are Flanders CY Stock No. A235669, with a rated capacity of 80 cfm at 1-in.-water gage pressure. A dry filter to remove particulates is combined with activated charcoal for iodine removal. The filters operate satisfactorily at 100% relative humidity and can stand moderate wetting; separators are of Al foil, and the adhesive withstands 350°F. The efficiency is 99.97% in DOP test, and 99.9% in iodine test conducted by LASL Group H-5. After each significant run, the on-line monitor record will be checked for indication of filter deterioration. The radiation detector through which cover gas from the principal vessel will be routed is a Tracerlab on-line gas and particulate monitor (Model MAP.1B-MGP.1A). Fission product analyses of samples from the vessel after low-power operations will provide a means of predicting activities after high-power runs. Storage tank gas samples (from W-41 paper on a charcoal filter in a 2 cfm sampler behind the filter-charcoal trap) will be analyzed periodically for fission-product activity.

Before starting a test run, with fuel in the tank, the cover gas space in the main vessel will be evacuated. This is followed by back-filling, to a pressure less than 10 psig, with a gas mixture consisting of 90 v/o helium and 10 v/o oxygen. The addition of oxygen is necessary for proper operation of the hydrogen monitor. The helium eliminates concern about radiation-induced chemically active compounds such as nitrogen oxides. During a test run, both the cover gas pressure and the hydrogen level are continuously monitored in the control room.

For runs generating numbers of fissions near the allowable limit, the radiolytic gases and fission products will be contained in the main vessel for approximately 24 hours, or longer if dictated by prior results. Fission products will not be released from Kinglet until the activity is such that air concentrations averaged over a 24-hr period would not exceed the values in Annex A, Table 1, column 1 of AEC Manual Chapter 0524, "Standards for Radiation Protection." Ultimately, the gas will be discharged at a predetermined rate through a remotely operated flow-control valve. The vent line is an above-ground 1-1/2 in. plastic pipe running to an outlet located 500 ft to the southwest of Kinglet and elevated 250 ft above the building floor level.

CONTROLS, SAFETY SYSTEM, AND INSTRUMENTATION

Control functions and constraints. The Kinglet building is considered an extension of Kiva 1 in all matters pertaining to assembly operation. Remote controls are on panels in Control Room 1 (see Fig. 12), and built-in circuits for radiation-level scram, neutron counting, and recording fission power, apply to Kinglet operations in exactly the same manner as for assemblies within Kiva 1.

The electrical control system has been designed with features that automatically prevent most unsafe operational procedures. The system will not function unless the gate to the Kiva 1 area is closed, safety circuits responding to radiation, hydrogen concentration, hydraulic pressure, and manual scram, are operational, the control shim is fully inserted, and the flow-control valve is set to bypass the core completely. Electrical interlocks impose these restrictions.

Other interlocks establish a definite sequence of operations, primarily for safety purposes, but also for the protection of equipment. A proper head of solution must exist before the pump can be started, and the pump must be at low speed immediately before operation at high speed. The requirements that the shim be inserted and the flow be fully bypassed before pump startup imply a delay before criticality can be attained. Operational

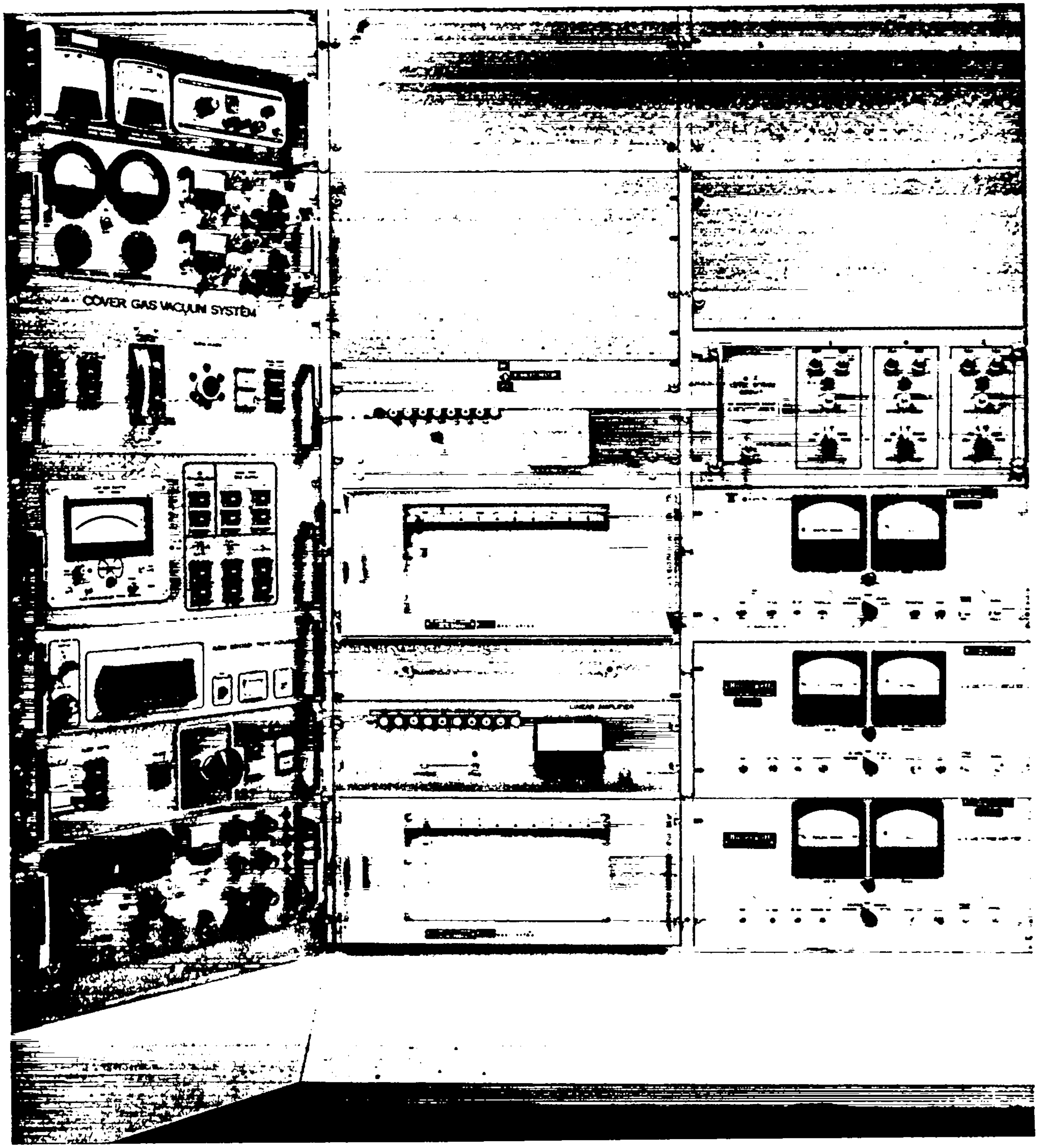


Fig. 12. Kinglet control console, showing operating controls at left, power recorders, and scram monitors.

steps and the conditions imposed upon them by interlocks are summarized in Table 4.

Safety circuits. The primary function of safety circuits, as defined here, is to signal the automatic shutdown of Kinglet (a scram) if preset values of certain process parameters are attained. Scram actions are pump shutdown and rapid shim insertion. The various signals that can initiate a scram arise from power-level monitors (high power), the indicator of hydrogen concentration in the cover gas (high concentration), a hydraulic-pressure switch on the shim drive (low pressure), or manual switches,"scram buttons", on the control panel and in Kiva 1.

In addition to shutdown capability, the safety system prevents certain actions except during the scram mode. These actions that cannot be performed while fuel is circulating are additions of cover gas to the main tank and transfer of fuel from one tank to the other.

Figure 13 represents functions of the entire system composed of safety circuits and interlocks. Starting at the upper left, the figure shows the sequence of events that is required for "reset" before an experimental run can begin:

1) The operating plan switch is positioned for remote operation (Plan 3), automatically closing the Kiva 1 area exclusion gate and applying

Table 4

Operations and Constraining Interlocks

Transfer fuel between storage tank and main vessel.	System in scram condition. Area exclusion gate down.
Establish control system ready condition (Reset).	Exclusion gate down. Power-level scram monitors reset. Control shim at UP limit. Flow control valve at zero flow position. Cover gas hydrogen concentration below high limit. Hydraulic system pressure switch closed.
Start fuel pump, slow speed.	Flow control valve at zero core flow position. Control shim at UP limit. Fuel in main tank.
Operate fuel pump, fast speed.	Slow speed relay closed.
Operate control shim.	Scram chain in ready condition.
Operate cover gas system.	Control power on scram mode.

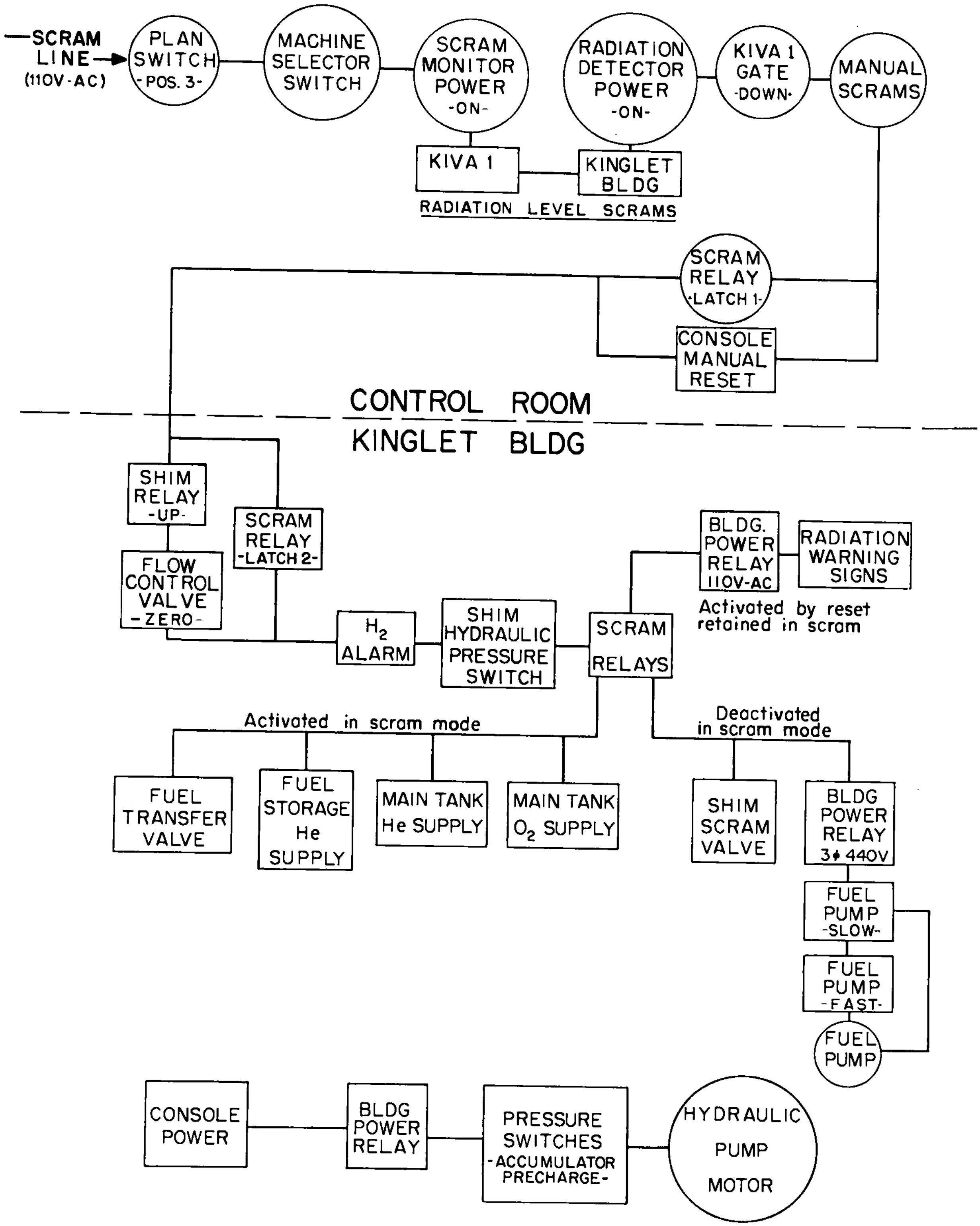


Fig. 13. Scram chain and interlocks.

power to the scram monitors and the linear level recorders.

2) The machine selector switch is positioned to "Kinglet", applying power to the Kinglet control console and allowing power to be routed to the Kinglet building.

3) Manual scram switches are in the "reset" mode.

4) The shim actuator is in the UP position (full insertion).

5) The flow-control actuator is positioned at ZERO (valve in full bypass condition).

6) The alarm relay contacts for hydrogen in the main tank are closed (concentration less than 5%).

7) The hydraulic-pressure switch on the shim actuator is closed (the system is at operating pressure).

8) The console MANUAL RESET switch is depressed, closing scram relay contacts and permitting operation.

The lower right-hand chain in the figure represents the shutdown actions that occur when the scram relay contacts are opened. The lower left-hand chain refers to other actions that may occur only when the relays are in the scram mode. In addition, power supplied to radiation warning signs and beacons when scram relays are reset is not interrupted when the relay contacts open (a manual shut-off switch is provided). The hydraulic system for shim operation (bottom of the figure) is not influenced by the scram chain because hydraulic pressure is always desired. Interlocks within that system require closure of gas-precharge pressure switches on the two accumulators before the hydraulic-pump motor can be started.

The power-level scram detectors in the Kinglet building and in Kiva 1 are Westinghouse type WL 6937 BF_3 ion chambers. These are connected by independent lines to logarithmic amplifiers and meters in the control room. The value of signal to actuate a scram is normally adjusted to about twice the maximum planned during operation.

The Kinglet control and safety systems appear to conform with the portions of Standard IEEE 279 that are applicable. The items of the standard concerning "Channel Bypass" do not apply because, unlike power reactor systems, the Kinglet safety controls prevent system operation if any channel is removed or causes "protective action" as a result of channel malfunction. The use of separate scram monitors and cables associated with Kiva 1 and the Kinglet building reduces the likelihood of common-mode failure of the protective system.

Process instrumentation. Several instruments in the Kinglet building and Kiva 1, with recorders in the control room, will measure radiation during experimental runs. In the course of approaches to criticality, neutron levels will be monitored by two moderated BF_3 proportional counters. These chambers, which drive scalers in the control room, are suitable for the low-level neutron counting that is required for evaluating subcritical reactivity changes.

Power during critical operation, up to about 10 kW, will be monitored by two BF_3 ion chambers like those used for scram monitors. The wall-mounted chambers are connected to a linear amplifier, which in turn drives a strip chart recorder in the control room. For power above 10 kW, similar chambers located inside Kiva 1 (75 ft away) will be used. The Kiva 1 detectors not only extend the power range to higher values but also provide an independent monitoring system. From experience with the Hydro assembly in Kiva 2 area, it is estimated that the two sets of monitors will overlap in power by more than three decades.

All nuclear instrumentation will be calibrated according to normal Pajarito procedures, viz., by operating at steady low power for a measured time interval and analyzing the accumulated fissions by radiochemistry. Any drift from calibration would be indicated by a change of correlation with fuel flow rate and temperature rise. The temperature rise at low flow rate will provide adequate preliminary power monitoring.

Other instrumentation that registers on strip-chart recorders in the control room is for the following purposes:

1) Temperatures of fuel below the core and in the deflector at the top of the core are measured by two chromel-alumel thermocouples encased in stainless steel.

2) The flow rate of fuel through the core tube is monitored by a turbine flow meter with a panel indicator as well as strip chart. The turbine is inserted between the flow-control valve and the core. The instrument, which is factory calibrated, may be read with an uncertainty of ~ 2%.

3) Solution level in the main tank is measured with an uncertainty less than 0.5 in. (~ 4ℓ) by a differential pressure transducer. In addition, an electrical probe, when contacting the solution, actuates a visual indicator and interlocks the control of the fuel pump. The purpose is to prevent pump operation without an adequate head of solution.

4) Cover-gas pressure is monitored by a pressure

transducer near the top of the main tank. The pressure reading is accurate to 0.5 psi.

Oxygen concentration is recorded independently.

Instruments for monitoring radioactivity in the Kinglet building and in vented gas, and for indicating solution height in the storage tank, indicate locally instead of in the control room.

PRELIMINARY TESTS

Static criticals. Before assembly of the complete Kinglet system, several critical experiments were performed with a subassembly consisting of the Zircaloy core tube, beryllium reflector, and control shim. The purpose was to supplement criticality calculations by observations of shim effectiveness, temperature and void coefficients, Rossi alpha, and the dependence of critical conditions upon ^{235}U concentration of the solution.

The first series of tests made use of the Comet assembly machine in Kiva 2, as shown in Fig. 14. Although the shim entered the core from above, the geometry of the critical region was essentially the same as for Kinglet. Three sets of measurements were conducted with the core tube containing solutions at ^{235}U concentrations of 70, 75, and ~ 78 g/ℓ. After partial assembly of Kinglet, there were further static critical tests with core, reflector, and shim in place within the main tank. The core tube was closed at the base so as to contain solution, which was at a ^{235}U concentration of 84.4 g/ℓ.

The resulting criticality data were used to estimate the solution concentration required to attain the design maximum power of 1.3×10^{17} fissions per second. At this concentration, 86 g $^{235}U/\ell$, the maximum excess reactivity is expected to be 5.5-6\$ (assuming $\beta_{eff} = .008$). The data

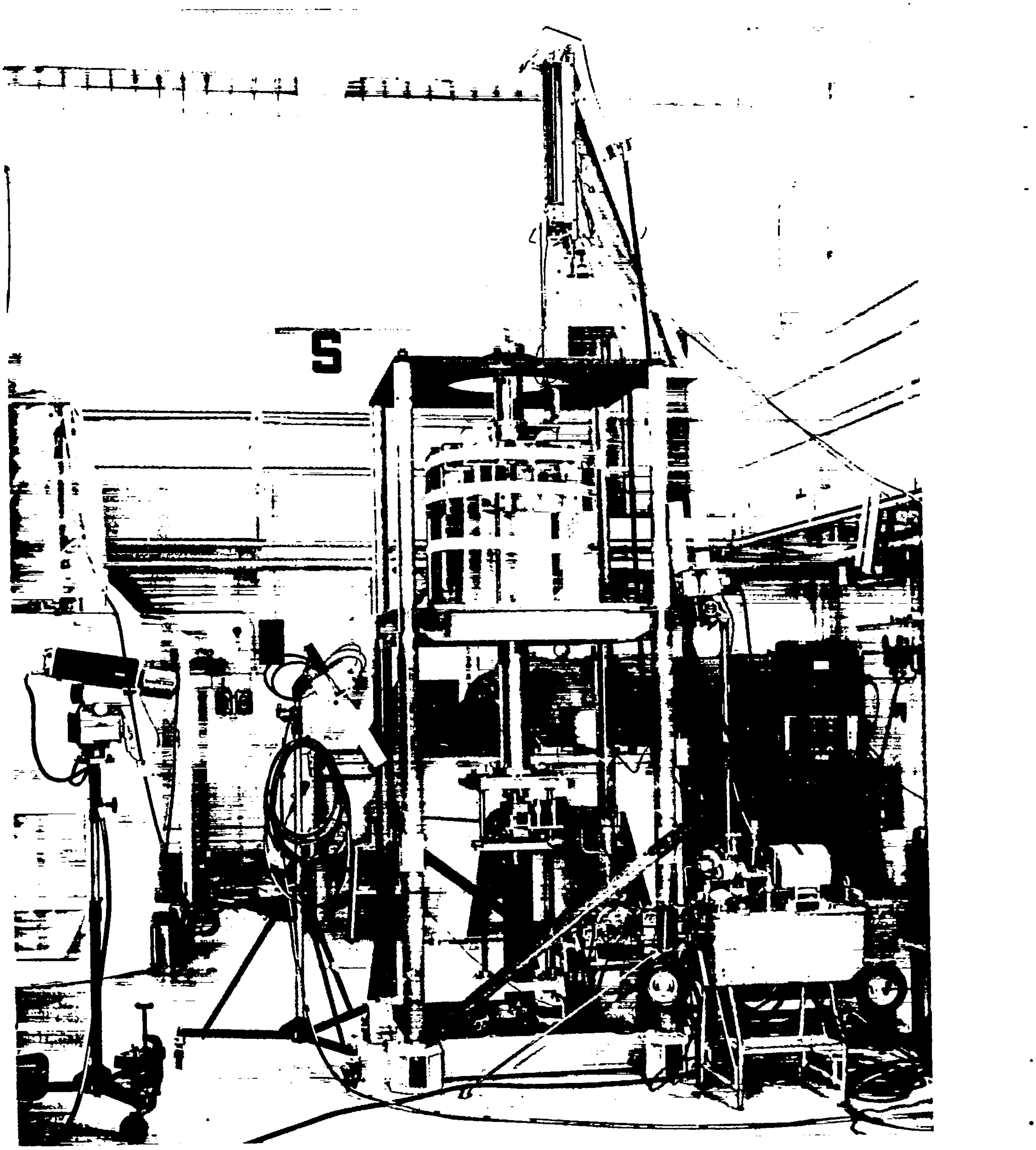


Fig. 14. Setup for static test in Kiva 2.

on Rossi alpha, void reactivity coefficient, and shim control effectiveness were extrapolated to the design solution concentration. Predicted values at that concentration are 56.3 per second for Rossi alpha and 1.2¢/cc central void. The estimated differential worth of the shim as a function of insertion distance into the reflector appears in Fig. 15.

An additional test confirmed the safety of the solution-filled pump with significant inlet and outlet pipes attached. The setup, Fig. 16, was on the Supercomet assembly machine in Kiva 3 (Supercomet has since been put in storage). Measured neutron source multiplication was only ~ 2 with 25 liters solution at 84.4 g/ℓ concentration. Accordingly, this part of the system should be highly subcritical with the design solution.

Flow tests. The complete fuel-pumping and storage system was tested with distilled water in place of solution. Liquid-level detectors were checked for reproducibility, modified, and calibrated. In the case of the differential pressure transducer which measures liquid level at the main tank, a density factor will modify the final calibration of the sulfate solution level. Stability of solution flow through the core was examined visually and photographically through ports in the main tank, in addition to flowmeter readings. Except for low-level readout fluctuations characteristic of the

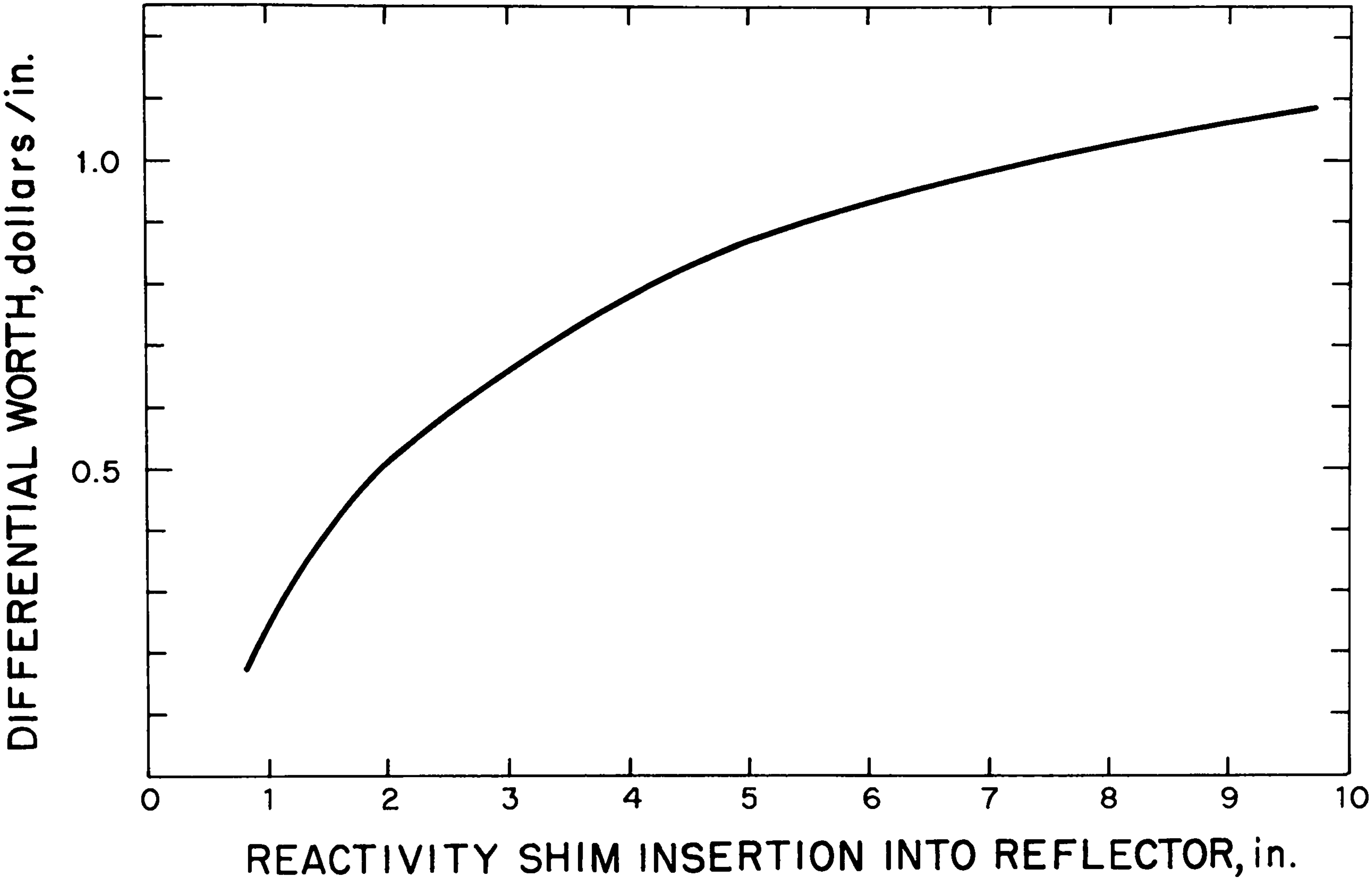


Fig. 15. Preliminary control-shim calibration.

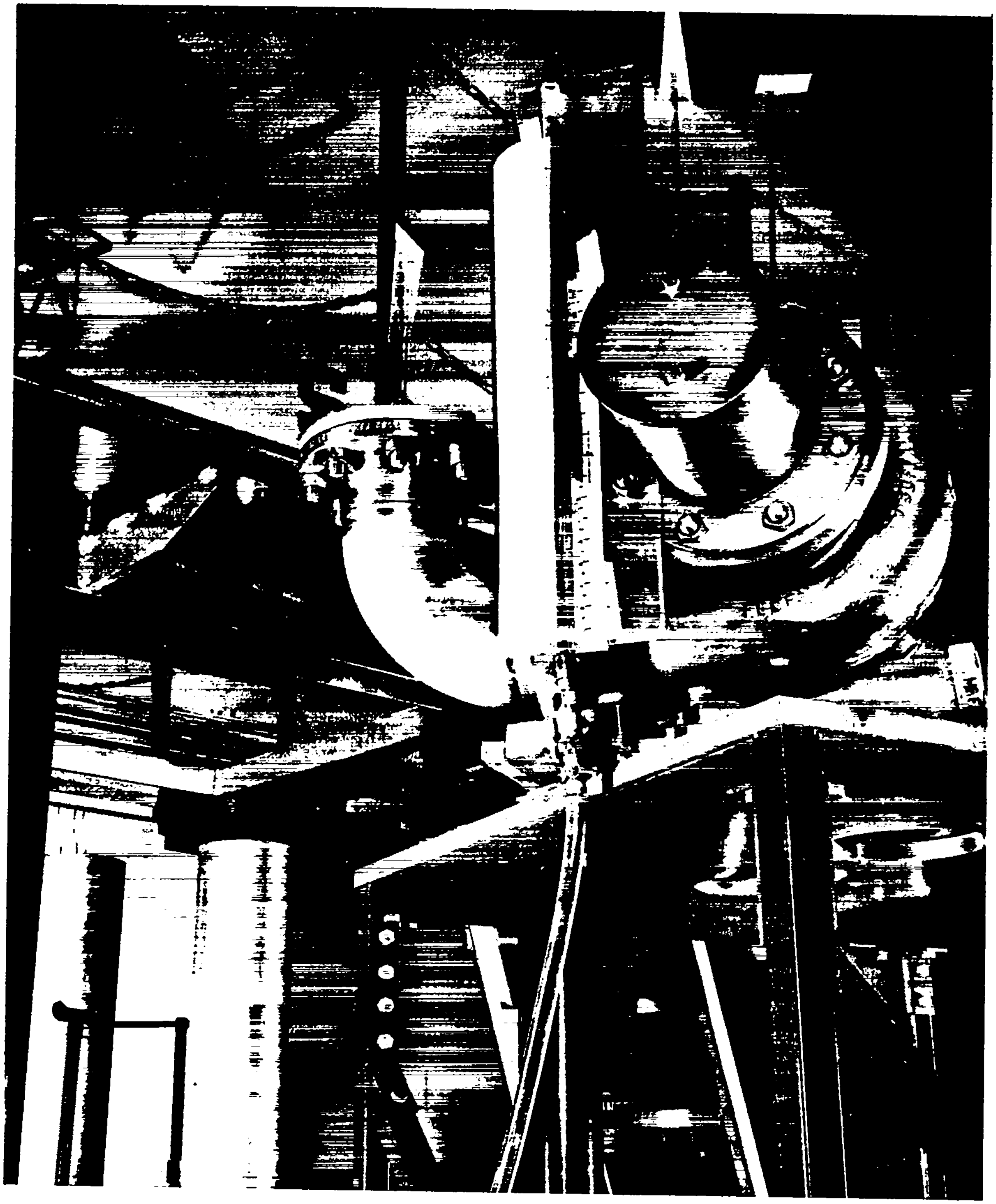
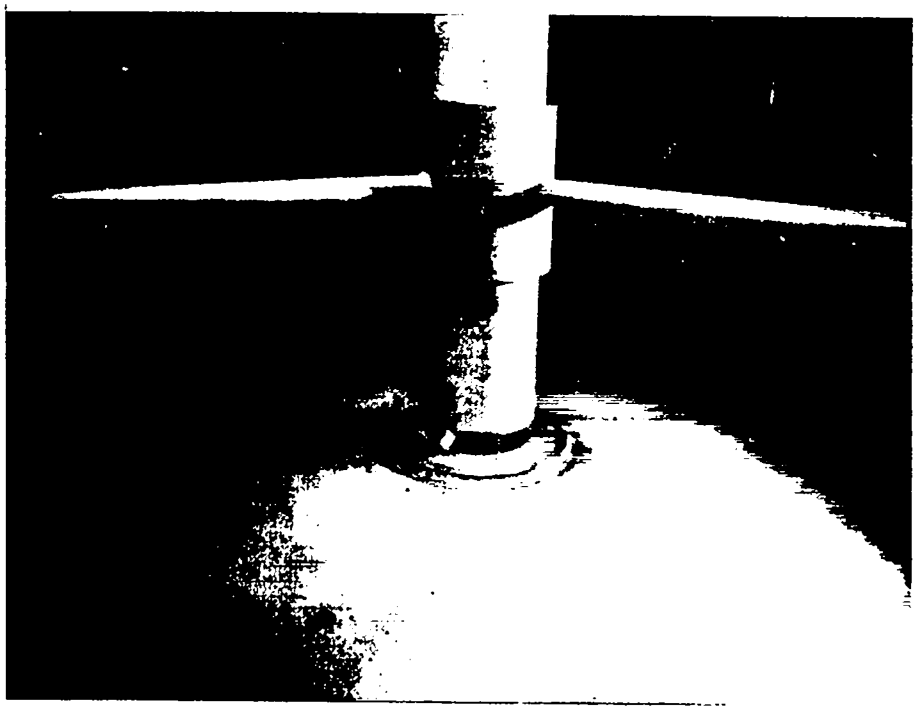


Fig. 16. Setup for pump safety test in Kiva 3.

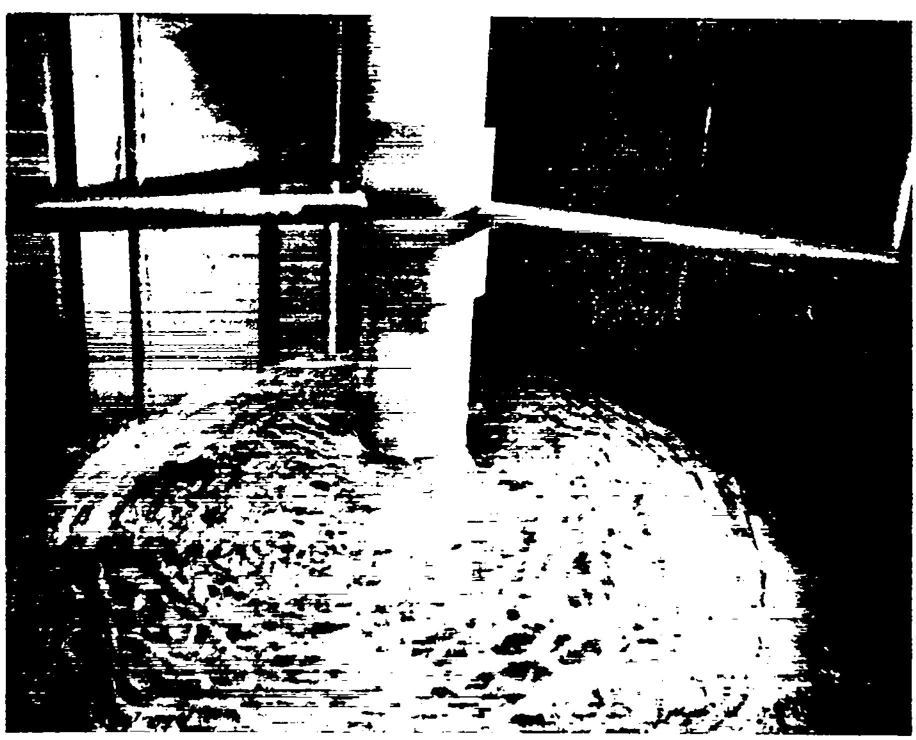
flowmeter, observations confirmed adequately uniform flow for the purpose of the experiment. Water flow past the fuel deflector, at a rate of ~ 250 gal/min, is illustrated by the bottom photograph of Fig. 17.

Along with the hydraulic tests, all non-nuclear instrumentation was checked out including temperature recorders, gas pressure indicators, hydraulic oil pressure interlocks, etc. Finally, shim-control operation was thoroughly tested to gain experience and to confirm reliability.

Neutron multiplication tests during storage-tank filling and initial main-tank transfer will complete the static critical experiments.



a.



b.

Fig. 17. Core exit, a) no flow, b) 250 gal water/min.

ADAPTATION OF PROCEDURES

General procedures. As stated earlier, Kinglet operations will be planned to satisfy the requirements of "Operating Limits for the Los Alamos Critical-Assembly Facility". It follows that there will be no departure from the Standard ANS-STD.1-1967, "A Code of Good Practices for the Performance of Critical Experiments" (Appendix I), because of its incorporation in the Operating Limits. On the other hand, certain deviations from the general practices of "Operating Procedures for the Pajarito Site Critical Assembly Facility", LA-4037-SOP, are permitted if spelled out in the required Experimental Plan.

The scram-chain characteristics and sequential limitations that are called for in LA-4037-SOP are more than satisfied by the functions of the safety and interlock system represented in Fig. 13. Extra features, for example, are introduced to protect the fuel pump and to inhibit solution deterioration. Components specified for so-called "Class II" assemblies are at least two "major disassembly devices" (for scram) and one vernier control. The shim serves both as the vernier control and as one of the scram devices. Like a control rod, it is positioned at minimum reactivity for startup, rather than at maximum reactivity as is usual for "safety 'rods', where provided,...". For the second scram action, solution is dropped out of the core by stopping the fuel pump. Even with the flow-control valve at full bypass, the fluid would fall about 0.5 in./sec. This implies positive shutdown, though not as rapid as by shim action.

The only other deviations from the general operating procedures will be ultimate departure from the 5¢/sec limit on shim withdrawal rate and the 5-sec positive-period limit that are specified for Class II machines. Initial tests, which will adhere to these limits, will provide information for the start of a series of steps toward an expected reactivity insertion rate of 2$/sec and fractional-second positive periods. Actual limits attained will depend upon the progressive series of observations specified in Operating Limits when an inherent prompt shutdown mechanism is certain. As demonstrated by KEWB experiments,* the shutdown mechanism that will be effective in Kinglet is a combination of thermal expansion and formation of radiolytic-gas bubbles. The considerable reactivity-insertion rate and the short periods will be required for meaningful stability tests at high fission rates.

*M. S. Dunenfeld and R. K. Stitt, "Summary Review of the Kinetic Experiments on Water Boilers", US AEC report NAA-SR-7087, Atomics International (Feb. 1963).

Special characteristics. The circulation of fuel leads to certain aspects of Kinglet behavior that differ from static observations. As flow rate increases, delayed-neutron precursors are swept out of the core region more and more effectively. If returning precursors are ignored, the effect would be to increase the apparent reactivity (as calibrated statically) at which delayed criticality (constant fission rate) occurs, shifting it toward the unchanged condition for prompt criticality. The zero-flow inhour relation of Fig. 18 shifts toward the dashed curve that applies to the maximum-attainable flow rate if there are no returning precursors.

At the maximum flow of ~ 90 ℓ/sec (Table 1) only 7 sec are required for solution to make the complete circuit and return delayed-neutron precursors to the core. During this interval, only a small fraction of the precursors would decay so that the inhour relation would shift back from the extreme dashed curve of Fig. 18 so as to approach the zero-flow curve. If this were the only change, the control shim would have to be inserted somewhat to maintain constant fission rate.

Another effect, however, tends to reduce the reactivity with time. This is the increased rate of production of radiolytic gas bubbles as the solution becomes saturated with the radiolytic hydrogen. The downward drift of density leads to decreasing reactivity unless there is compensation

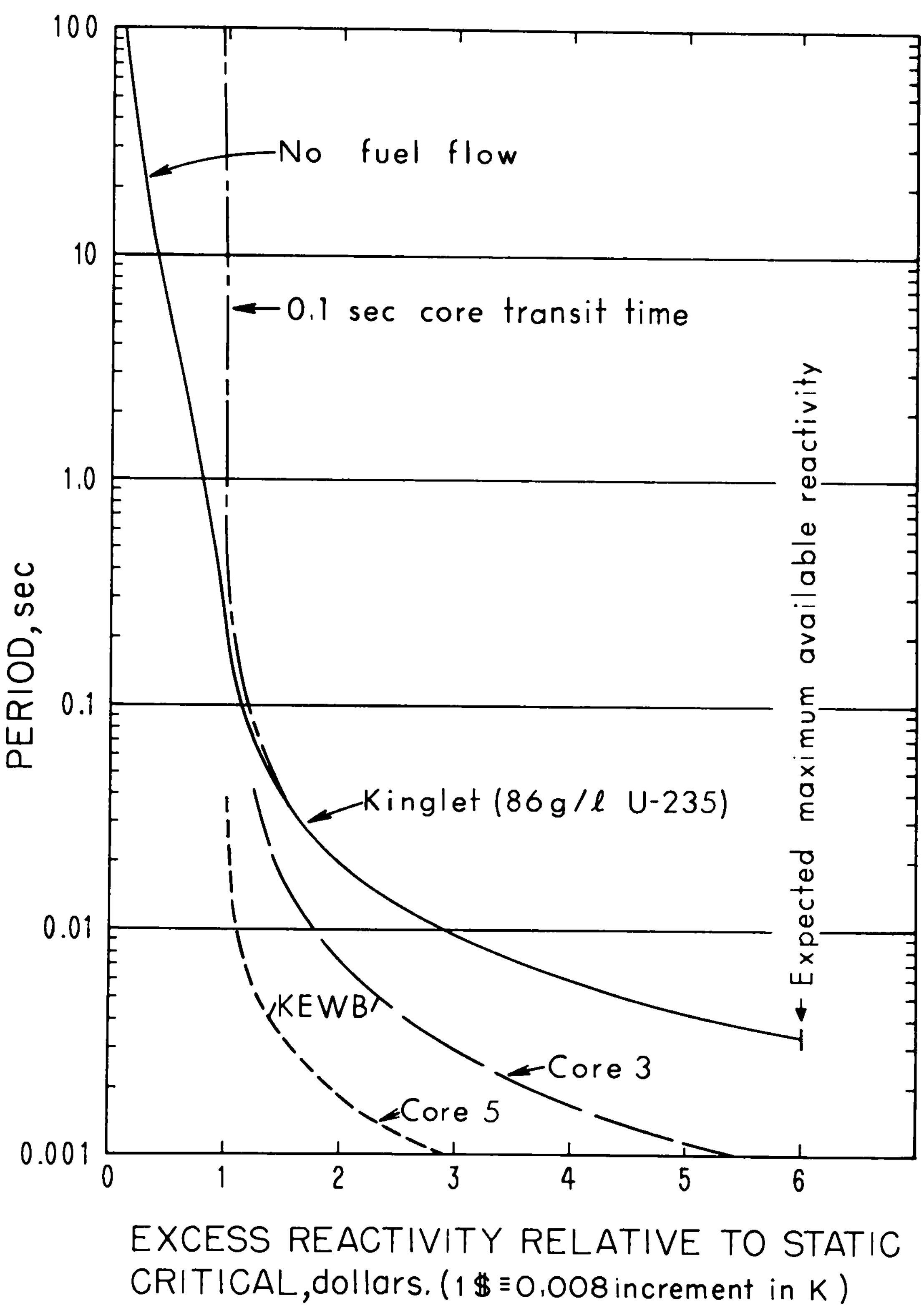


Fig. 18. Period-reactivity relations under static conditions and at maximum flow rate; also for KEWB.

by withdrawal of the control shim. After a brief transient, this effect will be greater than that due to the circulation of delayed-neutron precursors. In general, therefore, it is expected that continuous adjustment of the shim will be required to maintain constant fission rate.

More rapid shim adjustments would be needed near the beginning of short, relatively high-power runs. At the design fission rate of 1.3×10^{17} fissions/sec (if it can actually be attained), only 10-sec operation would be permitted by the fission-product limitation of Operating Limits. Because this duration must be reduced in proportion to fissions accumulated during the rise to power, it would be desirable to attain power and level off within a few seconds. On the assumption that such rapid action will ultimately be required, there is provision for programming withdrawal of the shim at any chosen ramp rate, followed by reduction to another rate. With such flexibility, only slight manual adjustment, if any, would be needed for brief operations at high power. The feasibility of operation at these extreme conditions will be judged by results of a series of more modest runs in which there are stepwise increases of fission rate. The series would be terminated if necessary to maintain a margin to prompt criticality that is three times the magnitude of fluctuations whenever that magnitude is $\pm$ 2.0¢ or greater (requirements of Operating Limits).

Supplementary procedures. A series of Experimental Plans (or one with addenda) will implement Pajarito Operating Procedures and Operating Limits. They will allow for the special features of Kinglet that are discussed above, spelling out the departures from the general Operating Procedures, and will provide additional guidance for the orderly conduct of experiments.

There will be a discussion of neutron-multiplication measurements for monitoring the initial loading of the storage tank and the initial introduction of fuel into the circulating system. It will establish neutron source and detector locations, and conditions for unmultiplied counts, and will tell whether there should be any special interpretation of results.

Procedures for dynamic operation will define source location (required for any run under new conditions), identify required detectors, and specify an initial limit for speed of control shim withdrawal and conditions for increasing that limit. Although established by interlocks, the shim, flow-value, solution-level, and cover-gas conditions required for fuel-pump startup will be reiterated.

Instrument readings to be preserved for the guidance of further operations and for analyses will be listed. Finally, there will appear a means of limiting the magnitude of steps in fission rate from one run to the next.

ACCIDENT CONSEQUENCES

Predictions of Kinglet dynamic behavior used in this report rely strongly on experience drawn from similar systems which have operated for several years. The fuel solution is similar to that of the LASL "Water Boiler," the five cores used in the power excursion experiments at Atomics International (KEWB), and a series of reactivity-ramp experiments in France referred to as "Consequences Radiologiques d'un Accident de Criticite" (CRAC) as reported in a series of French Atomic Energy Commission reports, SEEC No. 70 to 98, the latest dated March 1971.* The latter series employs uranyl nitrate instead of uranyl sulfate as in KEWB and early "Water Boiler" experiments. Results of the KEWB experiments demonstrated the inherent safety of power excursions in uranyl sulfate reactors both with and without thick graphite reflectors. In those experiments power excursions were generated safely at $\sim 2.5 \times 10^{17}$ fissions/excursion by "step" reactivity increase (~ 300$/sec). The CRAC experiments demonstrated the safety of operating with slower (~ 1$/sec) reactivity ramps but larger available excess reactivity (~ 10$) producing multiple bursts of

*L. D. P. King, "Design and Description of Water Boiler Reactors", Proc. U.N. Int. Conf. Peaceful Uses Atomic Energy, 2, 372-391 (1956); M. S. Dunenfeld and R. K. Stitt, op cit; P. R. Lecorche, "CRAC - Experimental Study of Criticality Accidents", Trans. ANS 14, No. 1, 33-34 (June 1971).

lower individual yields ($\sim 3 \times 10^{17}$ fissions/burst and $\sim 3 \times 10^{18}$ fissions total).

Malfunctions. Protection against certain control and equipment malfunctions, and consequences of others, have been discussed before. To reiterate, it is intended that a scram be triggered if anything goes wrong with Kinglet, and that there be no adjustment of equipment or circuitry during operation. This contrasts with requirements for power reactors, such as parts of Standard IEEE 279 that establish conditions for channel bypass and for instrument testing during operation. A multiplicity of scram lines, independent circuits from Kiva 1 and the Kinglet building, and others actuated manually and by interruption of power supply, protect against scram failure. The following comments expand further upon ways in which effects of malfunctions are controlled.

As noted earlier, both fuel-storage tank and main tank have been He leak tested, the storage tank will be retested before filling, and the circulating system has been checked thoroughly for water leakage. Nevertheless, the stainless steel pan under the main tank, pump, and piping is designed to accommodate all the fuel without exceeding a depth of three inches. As indicated by Fig. 11 of TID-7028, "Critical Dimensions of Systems Containing U^{235}, Pu^{239}, and U^{233}," an infinite semi-reflected solution slab of this depth would be subcritical.

To avoid a combination of leakage and flooding, water lines in the building will be drained whenever fuel is in the circulating system.

It is clear that pump malfunction amounts to a scram, and that failure of the flow-control valve to open slows such scram action but does not prevent it. Abnormal operation of the flow-control valve during a run would be observed as a change in reactor power, a condition readily corrected by adjustment of the shim or by scram action. If circulation should stop suddenly, a transient reactivity increase of less than one dollar could occur before drainage, because all delayed-neutron precursors would be retained. It follows that the total excess reactivity must still be less than two dollars. As shown by a later discussion of power excursions, a local temperature rise of 40°C is the worst that can result.

If the solution were highly activated and the fuel-transfer valve should lock in the closed position, it would be necessary to allow time for fission-product decay before draining the solution by means of a manual bypass valve and effecting repair. Within a few days, however, it would be permissible to enter the building.

Although there is no mechanism for igniting the radiolytic hydrogen in the cover gas, an interlock discussed earlier will prevent operation unless the hydrogen concentration is below 5%. Hydrogen gas production is estimated at ~ 140 liters (STP) for the most extreme experiment. This results in a maximum hydrogen concentration of about 4-1/2%, which is significantly below explosive limits that have been quoted in the literature.*

The inconsequential effect of control shim locking in position has been described, which leaves unintended withdrawal to be considered. At the maximum travel rate of 2 in./sec, an excursion would occur, triggering a radiation-level scram. But, as shown by Appendix V, the probability of developing a yield corresponding to full excess reactivity is less than 10^{-6}, even without an external neutron source. For a reasonable chance of obtaining full yield, there would have to be simultaneous failures of several specific interlocks and the shim activator. Then, if the shim were locked out of the core, its position indicator ignored, and the pump started at high speed, the core could fill in about one second. With unactivated fuel and no source, there might occur an excursion such as that discussed in the following section.

*H. F. Coward and G. W. Jones, "Limits of Flammability of Gases and Vapors," Bull. 503, U. S. Bureau of Mines (1952); D. W. Kuhn, et al, "Explosion Limits in Mixtures of Hydrogen, Oxygen, Steam, and Helium", U. S. AEC Report Y-731, Oak Ridge Y-12 Plant (1951).

The extreme excursion. The effect of instantaneously introducing the maximum available excess reactivity, as, for example, a consequence of the incredible series of events just discussed, is calculated in Appendix VI. The result is a burst of ~ 1.3×10^{17} fissions with a width (at one-half height) of about 10 msec. Such a burst would give only 10% of the fission-product limitation specified in Operating Limits. This excursion would cause a radiation-level scram which removes power from the pump, hence would terminate any residual fissioning even if the shim could not be inserted.

The maximum core pressure generated in the above burst is computed to be ~ 200 psig, which is far below the pressure tolerance (~ 5000 psig) of the Zircaloy core tube. The maximum volume of steam produced in such a burst is 640 liters, which would eject fuel from the core and increase overpressure within the main tank by less than 3 psi. An overpressure of this magnitude is clearly tolerable, because the initial tank pressure would differ little from atmospheric and the pressure tolerance is greater than 20 psig.

Radiolytic gas voids have been ignored in the above predictions because of uncertainties in their generation rate. Gas-void considerations could result in a slightly larger reactivity quench, hence reduce the predicted excursion yield. Total radiolytic gas generated in the above excursion is about 14 liters. Release of this gas to form voids at a maximum possible rate would increase the core pressure at peak power by < 75 psi, as estimated in Appendix VII. But the larger vapor-pressure rise immediately after the power peak (Fig. 21) would be reduced or even eliminated because of lower solution temperature.

It is concluded that neither damage nor personnel hazard would result from any excursion that could occur during remote operation. Further, the above results greatly relieve the concern about mishaps and channel failures.

Fission-product release. It has just been shown that even extreme reactivity-insertion accidents with Kinglet are of little consequence as compared with the greatest permissible run of 1.3×10^{17} fissions/sec for 10 sec. In addition, tests of this magnitude are expected to be few, spaced by at least several days, and with volatile fission products vented in between. Thus, for purpose of considering fission-product release, the maximum inventory can be considered as due to the 1.3×10^{18} fissions of a single extreme run.

Conditions that minimize the potential for radiation hazard are listed below.

1.) The over-riding factor is the very small inventory of fission products associated with

Kinglet or any other critical assembly, as compared to that in any reactor.

2.) Confinement is effected in a large tank that is capable of containing many times the quantity of steam or gas that can be generated in the core.

3.) Operating pressures will not exceed ambient by more than the order of 1 psi.

4.) The shortest exclusion distance, to the area gate, is greater than 1000 ft.

5.) The large shutdown mechanisms inherent in solution systems quenches any conceivable excursion before significant kinetic energy can be liberated.

In this instance there is little point to hypothesizing various types of accidents that might happen. The most extreme situation is presented in order to show that radiation hazard is non-existent. Probably the worst incident from the radiation standpoint is for the tank or associated plumbing to rupture by some mysterious means and dump the solution into the catch-pan immediately following a full-power run. A violent rupture of the main tank above the solution level would be less serious because of higher and more diffuse release.

The thyroid dose generally is the limiting inhalation dose in accidents in which the iodines are released. This is particularly true when fissioning is short term and the long-lived Sr and Cs are not saturated. Because of the short running time and the short time for cloud arrival, the dose from external exposure in the case of Kinglet is almost completely due to a few short-lived isotopes. In this study both cases are presented. In the following, 100% release of the iodines and gaseous fission products is assumed following 1.3×10^{18} fissions in 10 seconds. Activities are calculated with a computer code devised by Sandia Corporation.*

Thyroid dose: The dispersion of airborne material has been studied extensively by many people. The basic equation (Eq. 1) comes from the Sutton model+ of atmospheric diffusion neglecting depletion of the cloud by scavenging during transit. The particular formulas used here are from the AEC report TID-14844, "Calculation of Distance Factors for Power and Test Reactor Sites" (1962).

The Sutton diffusion equation in the integrated form for total exposure in curie-seconds per cubic meter is:

$$A = \frac{2\,Q}{\pi C_y C_z\, \bar{u} d^{(2-n)}}. \qquad (1)$$

*L. L. Bonzon and J. B. Rivard, "Computational Method for Calculation of Radiological Dose Resulting from Hypothetical Fission Product Release", US AEC report SC-RR-70-338, Sandia Corp. (July 1970).

+O. G. Sutton, "A Theory of Eddy Diffusion in the Atmosphere", Proc. Royal Soc. (London), 135A, 143 (1932).

The product of this exposure, the breathing rate, and the thyroid exposure per curie inhaled gives the total dose to the thyroid:

$$D_t = \frac{2B \sum_i Q_i Di/Ai}{\pi C_y C_z \, \overline{u} d^{(2-n)}}, \qquad (2)$$

where:

D_t = total thyroid dose (rads)

B = breathing rate, m^3/sec

C_y = lateral diffusion coefficient

C_z = vertical diffusion coefficient

n = stability parameter

$\overline{u}$ = mean wind speed, m/sec

d = distance (m)

Q_i = i^{th} isotopes activity, C_i (Table 5)

Di/Ai = thyroid dose per curie inhaled (Table 5).

Only stable atmospheric conditions have been considered since they result in highest doses. Values used are

$$\begin{aligned} C_y &= 0.4 \\ C_z &= 0.07 \\ n &= 0.5 \\ \overline{u} &= 1 \end{aligned}$$

Other values substituted in Eq. 2 are

$B = 3.47 \times 10^{-4}$

$\Sigma_i Q_i D_i/A_i = 1.2 \times 10^7$ rads

d = 300 m (~ 1000 ft).

Table 5

Input for Dose Calculations

Isotope	Q_i Curies	D_i/A_i Thyroid Dose Per Curie Inhaled	E_i Average Energy MeV
^{131}I	0.065	1.48×10^6	0.4
^{132}I	1.21	5.35×10^4	0.8
^{133}I	4.08	4.0×10^5	0.55
^{134}I	111	2.5×10^4	1.3
^{135}I	60	1.24×10^5	1.5
^{131}Xe	0		0.16
^{133}Xe	0.002		0.23
^{133}Xe	0		0.081
^{135}Xe	2.00		0.52
^{135}Xe	3.29		0.25
^{137}Xe	2121		0.44
^{138}Xe	964		1.28
^{139}Xe	40		0.30
^{83}Kr	0.28		0.02
^{87}Kr	123		2.0
^{88}Kr	84		2.0
^{89}Kr	1426		1.0
^{90}Kr	9.4		1.0
1% Solids	350		0.7

$$\Sigma\, Q_i\, D_i/A_i = 1.2 \times 10^7 \text{ Rad}$$

$$\Sigma\, Q_i\, E_i = 4.5 \times 10^3\ C_i\text{-MeV}$$

Iodine activities for short times following 1.3×10^{18} fissions are shown in Fig. 19. The total amount at any time, is assumed to be distributed in the cloud. A value for that amount, $\Sigma Q_i D_i/A_i$, has been taken at 400 seconds as a realistic upper limit. This would require a time following the accident of ~ 300-500 sec for the cloud to arrive, plus an exposure time of 400 sec. It is unreasonable to expect a person to remain in the vicinity for longer periods. In any case, after only 100 sec the iodine dose-weighted activity is about one-half that at 1000 sec. Up to ~ 5000 seconds the iodine activity is increasing as it grows in from chain decay. Beyond 5000 sec the iodine decay dominates.

Substitution of values into Eq. (2) gives 20 rads for the extreme upper limit of thyroid dose.

External gamma dose: Various references* show the relationship between body dose and exposure to one curie-second per cubic meter to be

$$D = 0.25E, \qquad (3)$$

*"Meterology and Atomic Energy", US AEC report AECU-3066 (July 1955); "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Plants", US AEC report WASH-740 (March 1957); Hanson Blatz, Ed., Radiation Hygiene Handbook, McGraw-Hill, New York (1959).

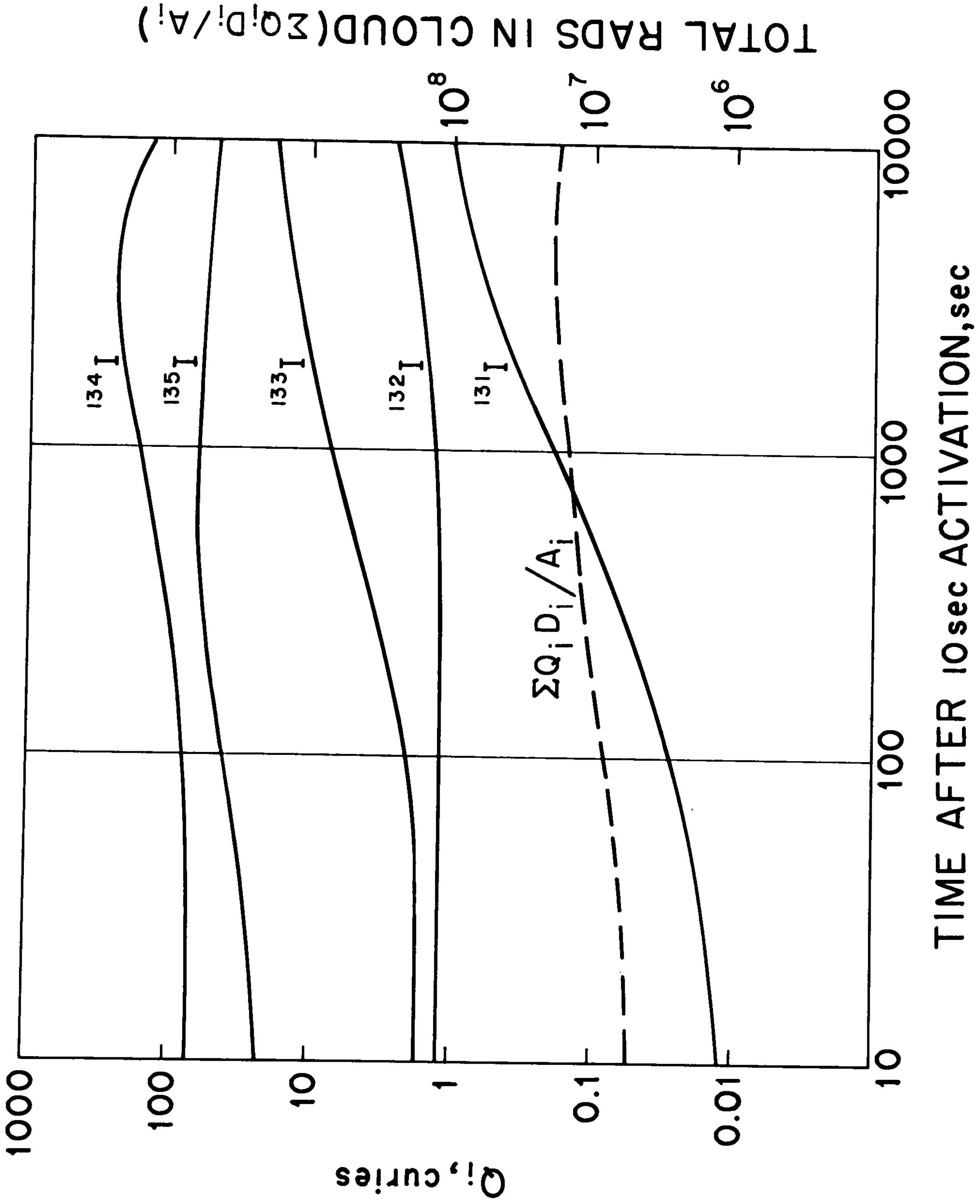


Fig. 19. Fission-product activity for computing thyroid dose.

where:

D = external gamma dose (rads)

E = energy (MeV).

By combining Eq. (3) and Eq. (1) the external gamma exposure may be written as

$$D = \frac{0.5 \sum_i Q_i E_i}{\pi C_y C_z \bar{u} d^{(2-n)}},$$

where the values of Q_i and E_i are specified in Table 5. Values for fission products other than the iodines are evaluated at 400 sec. Wind velocity and radioactive decay are mutually compensating factors at these early times so that the dose is relatively insensitive to the wind velocity. Increasing or decreasing $\bar{u}$ to 2-1/2 m/sec or 1/4 m/sec changes the dose by only a few percent. Insertion of the value 4.5×10^3 for $\sum_i Q_i E_i$ results in an external dose prediction of 5 rad.

Both the inhalation dose and the external dose values deduced are likely to be a couple orders of magnitude higher than the probable value from a 1.3×10^{18}-fission release because of the following limiting assumptions.

1.) 100% of iodines and gaseous products were assumed to be released instantaneously.

2.) Distance used was the very minimum possible and personnel were assumed to remain at this distance for the duration of cloud passage.

3.) Meteorological conditions assumed were for conservatively slow dispersion.

4.) The building housing the Kinglet assembly was assumed to have no effect on the release while in fact it would very effectively throttle the release.

It should be pointed out that exposures calculated for persons other than those at Pajarito site would be much smaller than the values just obtained. As Fig. 3 shows, the nearest residence is more than two miles distant. Further, persons on off-site roads, that are at greater distance than the Kiva 1 gate, would receive only transient exposures.

The moderate results of this extreme computational exercise demonstrate that Kinglet is compatible with the Pajarito facility, and is properly classed as a critical assembly.

APPENDIX I

STANDARD

ANS-STD. 1-1967

A CODE OF GOOD PRACTICES FOR THE PERFORMANCE OF CRITICAL EXPERIMENTS

1. Scope

This Code of Good Practices is for guidance in the performance of critical experiments. It is intended for catholic applicability and is formulated in general terms in order to avoid imposing undue limitations on specific local experiment practices.

2. Definitions

2.1 Limitations.

The definitions given below should not be regarded as encyclopedic. Other terms whose definitions are accepted by usage and by standardization in the nuclear field are not included.

2.2 Glossary of Terms.

2.2.1 Shall, Should, and May.

The word "shall" is used to denote a requirement, the word "should" to denote a recommendation, and the word "may" to denote permission, neither a requirement nor a recommendation. In order to conform with this standard all operations shall be performed in accordance with its requirements, but not necessarily with its recommendations.

2.2.2 Critical Experiment (Experiment).

An experiment or series of experiments performed with fissionable material which may be at or near the critical state.

2.2.3 Critical Assembly (Assembly).

A device or physical system, containing fissionable material, with which critical experiments are performed.

2.2.4 Nuclear Excursion.

The liberation of an undesirable quantity of energy as the result of a criticality accident.

2.2.5 Assembly Area.

A region in the vicinity of a critical assembly where there would be inadequate personnel protection in the event of a nuclear excursion.

2.2.6 Neutron Source.

Any material, combination of materials, or device emitting neutrons, including materials undergoing fission.

2.2.7 Safety Device.

A mechanism designed to reduce the reactivity of a critical assembly.

2.2.8 Scram.

A rapid reduction of reactivity to subcriticality.

3. Administrative Practices

3.1

Responsibility for the safety of a critical experiment shall be assigned unambiguously by management.

3.2

Each new experimental program shall be reviewed in a manner approved by management with particular emphasis on safety features.

3.3

Before an experiment begins, an experiment plan shall be reviewed by all who are expected to take part in the experiment.

3.4

At least two persons shall be present while a critical experiment is being performed.

3.5

Manual operations with fissionable material, such as storage, transfer, and nonremote addition of reactivity to an assembly, shall be in accordance with USA Safety Standard for Operations with Fissionable Materials Outside Reactors, USA N6.1-1964.

3.6

Additions of reactivity beyond those permitted by 3.5 shall be made by remote operation. Such additions of reactivity shall be reversible and continuously adjustable except when the resulting assembly will be subcritical or supercritical by a known amount.

3.7

No person shall enter an assembly area during the performance of a critical experiment without the approval of the person responsible for safety. During an addition of reactivity that requires remote operation, personnel shall be protected from unacceptable consequences of a nuclear excursion.

3.8

If anyone participating in the operation of an experiment expresses doubt of the safety of a particular action or step, the experiment shall be suspended until the doubt is resolved.

3.9

A record of the status and operation of the assembly, with particular reference to its safety features, shall be maintained.

3.10

An emergency plan approved by management shall be in effect.

3.11

Adequate personnel radiation monitoring shall be provided.

4. Equipment Criteria

4.1

There shall be safeguards against operation of critical assembly equipment by unauthorized personnel.

4.2

Communication shall exist between personnel at the control console and those who may be at the critical assembly.

4.3

A signal audible to personnel within the assembly area shall provide an indication of the neutron level during adjustments affecting reactivity.

4.4

A source of neutrons sufficient to produce a meaningful indication of multiplication shall be present during any approach to criticality, except that special experiments in which reactivity effects are known may be performed without a source present.

4.5

Each assembly shall be provided with a safety device that is actuated automatically at a preset radiation level and can be actuated manually. This safety device shall be capable of removing reactivity more rapidly than it can be added by any normal operation.

4.6

At least two radiation monitors shall be capable of independently initiating a scram of the assembly at a preset radiation level.

4.7

Loss of actuating power to any safety device shall produce a scram.

4.8

A scram signal shall prevent further significant increase of reactivity.

4.9

During critical experiments there shall be at least two instruments providing indication of the neutron level within the assembly. These may be the same as those required by paragraph 4.6.

4.10

The status of any variable for fine control of reactivity shall be continuously displayed at the control console. The limiting conditions or positions of safety devices shall also be displayed.

5. Operational Practices

5.1

The satisfactory performance of newly installed or significantly altered control equipment or safety devices shall be established before achieving initial criticality.

5.2

The proper functioning of the required number of safety devices shall be established prior to starting operations each day that an experiment is to be initiated. In the course of these tests or early in each day's operation, the response of each required detector system to a change in neutron or gamma-ray level shall be noted.

5.3

Additions of reactivity requiring remote operation shall be guided by neutron detector response. During an initial approach to criticality, a reactivity addition shall not be made unless the effects of any preceding additions have been observed and understood.

5.4

Any unexpected behavior of the assembly or its associated equipment should be evaluated promptly.

5.5

Additions of reactivity requiring remote operation shall not be made simultaneously by two or more persons, unless the effect of such additions has been measured.

5.6

Additions of reactivity requiring remote operation shall not be made simultaneously by two or more distinct methods (e.g., by rod motion and by water addition), unless the effect of such additions has been measured.

APPENDIX II

PAJARITO PLAN FOR RADIATION EMERGENCY

Excursion in Kiva with Personnel Present.

An excursion during handling of fissile material at a Kiva* would create an emergency requiring prompt action. Such an event would be indicated as follows.

1. Abnormal response of audible counters, shock effects including falling parts of an assembly, or blue glow would be apparent to those involved.
2. The radiation alarm in the H-1 office, Rm 117 Bldg 30, would alert personnel outside the Kiva area.

Action to be observed. 1) The Kiva area will be evacuated as promptly as consistent with necessary rescue operations. Note that a high-level portable radiation detector is located near the main Kiva entrance.

2) Persons involved will report to a Health Physics Surveyor (Rm 117 Bldg 30).

3) The Senior Health Physics Surveyor at the site (or the H-1 Group Leader) will advise the N-2 Group Leader about further action. Such action will be based upon the H-1 document "STANDARD OPERATING PROCEDURES, General and Emergency, Pajarito Site, TA-18",

*Except when in Kivas, fissile material of significant quantity is either in containers designed for safe handling or subject to procedures for maintaining safe configurations.

in particular, Part VII, "EMERGENCY MONITORING PROCEDURES".

4) The N-Division Leader and the LASL Director will be notified promptly.

Accidental Excursion During Remote Operation.

An accidental excursion during remote operation of a critical assembly is unlikely to create an emergency requiring prompt action. Such an excursion would be indicated by abnormal response of instrumentation in the control room, and by the radiation alarm in the H-1 office, Rm 117 Bldg 30. The monitoring television would give an idea of the extent of damage, if any.

Action to be observed. 1) The gate to the Kiva area will remain locked until the N-2 Group Leader permits reentry.

2) The Senior Health Physics Surveyor at the site will advise the N-2 Group Leader about further action in accordance with his "STANDARD OPERATING PROCEDURES, General and Emergency, Pajarito Site, TA-18". In particular, his advice will be sought before reentry into the Kiva area.

3) The N-Division Leader and the LASL Director will be notified promptly.

Emergency Requiring Site Evacuation.

The remote location of each Kiva is such that an excursion at least an order of magnitude greater than the largest that has occurred accidentally would not create a radiation emergency outside the Kiva area. A disaster of external origin, which might require site evacuation, would call into effect the "GENERAL RADIOLOGICAL EMERGENCY PLAN for Los Alamos Scientific Laboratory". This plan is coordinated by the Health Physics Group Office with the help of Health Physics Surveyors at the site. Required communication between the H-1 office, Rm 117 Bldg 30, and other buildings at the site would be with the assistance of the Group N-2 secretary, Rm 109 Bldg 30. A listing of local telephone numbers and intercom stations to be called in case of such an emergency is posted in both offices.

P. G. Koontz

P. G. Koontz
N-2 Safety Committee

Hugh C. Paxton

H. C. Paxton
N-2 Group Leader

April 6, 1971

APPENDIX III

EARTHQUAKE POTENTIAL

T. E. Kelly and F. C. Koopman, U. S. Geological Survey, report to LASL, Sept. 9, 1970.

Los Alamos County, located on the east flank of the Jemez Mountains, is an area which has been very active tectonically until quite recently in the geologic past. The youngest rocks in the area are estimated to be approximately 50,000 to 100,000 years old and are some of the youngest volcanic rocks in the state. Subsequent to the eruption of these rocks the area has been dormant, except for the activity of fumaroles and thermal springs.

During historic time a number of earthquakes have been recorded in central New Mexico, particularly along the Rio Grande trough south of Albuquerque; most of these were of small magnitude. Early Spanish records do not contain mention of earthquakes; although the population was sparse and widely scattered, an earthquake of major proportions undoubtedly would have been recorded. Also the adobe pueblos and prehistoric ruins are susceptible to earthquake damage, yet none is apparent or has been reported.

Only two earthquakes have been recorded in the vicinity of Los Alamos. One tremor, with a magnitude of

5.0 on the Richter scale, occurred at 0345 on August 17, 1952. Only minor damage at Los Alamos was caused by this quake. A quake of 7.0 magnitude occurred near Dulce, New Mexico, north of Los Alamos at 0156 on January 23, 1966. This quake was not felt in Los Alamos although 119 aftershocks were recorded by seismographs at Albuquerque.

In March and April, 1966, Willden and Criley made a detailed study of the earthquake potential at the site of the proposed Meson facility. Four portable seismograph stations were established and operated continuously for a 10-day period. During this study 13 seismic events were recorded, nearly all of which originated at centers more than 100 kilometers distant from Los Alamos. No local events of as much as 1.0 magnitude were recorded. Willden and Criley concluded that "There was no active, creeping fault at Los Alamos during the observation period . . .", although a number of major geologic faults are known to be present beneath the study area (Baltz, Abrahams, and Purtymun, 1963).

In an independent study of earthquake activity in New Mexico, Sanford (1965) predicted a tremor of 3.5 magnitude on a 25-year cycle for west-central New Mexico.

A number of boulder-capped erosional remnants have formed in Rendija Canyon north of Los Alamos. Although some of these features exceed 50 feet in height, they are eroded into relatively unconsolidated conglomerate and are considered to be extremely unstable. Willden and Criley (1966) estimated that they may have required more than 50,000 years to form. Presumably a major earth tremor during this time would have dislodged the unstable capping boulders on these features.

Observations and published studies indicate that the Los Alamos area is reasonably stable. Although earthquakes have occurred in the area, none have been of sufficient magnitude to cause apparent damage; the delicate balance of the erosional remnants in Rendija Canyon were not affected by a local quake of 5.0 magnitude.

APPENDIX IV

CHEMICAL STABILITY

A number of investigations at the Oak Ridge National Laboratory relate to the compatibility of Zircaloy-2 and uranyl-sulfate fuel solutions. This is best summarized in ORNL-3039 (TID-4500, 16th ed.) by G. H. Jenks. Concentrations of UO_2SO_4 ranged from 0.04 $\underline{M}$ to 1.3$\underline{M}$, and H_2SO_4 concentrations from 0.025 $\underline{M}$ to 0.45 $\underline{M}$. Temperatures used in these studies varied from 225°C to 330°C. Specific powers extended up to 110 kw/liter, and the fuel velocity range was 1 to 40 ft per second. Results of this work indicate that corrosion was increased by an increase in specific power and fuel temperature, and was decreased by increased velocity and increased H_2SO_4 concentration. The latter two beneficial effects are due to a decrease in uranium sorption on the surfaces.

Since the corrosion and oxidation rates of Zircaloy-2 in fuel and water decrease by almost a factor of 10 as the temperature is dropped from 300° to 250°C, and the Kinglet fuel will operate at < 100°C, no corrosion problems are anticipated in the Kinglet experiments. Corrosion studies for Homogeneous Reactor Test chemical processing (ORNL-2735) show, for example, that Zircaloy-2 was fully resistant to boiling 4 $\underline{M}$ H_2SO_4 solution and was only attacked at rates of 5 to 10 mil/yr in boiling 10.8 $\underline{M}$ H_2SO_4 solutions. The Kinglet fuel uses a concentration of only 0.5 $\underline{M}$ H_2SO_4.

Laboratory measurements have shown that one risks the possible precipitation of solid UO_4 if the radiolytically produced H_2O_2 concentration of the fuel is allowed to exceed 0.0093 $\underline{M}$. A theoretical estimate of the energy requirements for the production of H_2O_2 indicates that a ΔT of 25-30°C per fuel pass is permissible in Kinglet. This corresponds to about 3.3×10^{16} fissions in the Kinglet core per pass or over 2.3×10^{18} fissions for a once through of the 600 liters of fuel. This is substantially higher than the limitation of 1.3×10^{18} fissions set per run for Kinglet.

Experiments are planned for Kinglet to check the actual H_2O_2 concentrations formed as a function of specific fuel power generation. Precipitated UO_4 even if produced in Kinglet would not produce hot spots in the core due to its geometry. The smooth wall of the vertical core pipe of uniform cross section is not well suited for the settling out of any precipitate during fuel flow through the core. Other regions containing fuel will not have sufficiently high neutron flux to produce hot spots.

APPENDIX V

EXCURSION PROBABILITIES

The probability of attaining a given excess reactivity above prompt criticality, ρ_p, with a ramp, R ($/sec), decreases as the neutron source, S, increases. A very large source initiates a fission-chain reaction that quenches reactivity before the ramp is fully effective. Analyses by Hansen and by Bell* show that the above probability is roughly

$$P(\rho_p) = \exp\left(\frac{-\rho_p^2 S\beta}{2R}\right).$$

Consider a ramp generated by the control shim at the maximum withdrawal rate of 2 in./sec, which increases reactivity by at most 2$/sec. Taking ρ_p as the upper limit of available prompt reactivity, $5, a value of 10^{-10} for P(5$) requires a source, S, of 460 n/sec, or 10^{-6} requires only 140 n/sec. A source within this range is present in the solution due to spontaneous fission and gamma activity.

Consider next the ramp produced by solution filling the core with shim completely withdrawn. Under these conditions, the maximum effectiveness is ~ 1$/in., somewhat below the reflector top. Assuming that the solution has reached maximum velocity of ~ 280 in./sec in that

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*G. E. Hansen, "Assembly of Fissionable Material in the Presence of a Weak Neutron Source," Nucl. Sci. and Eng. 8, 709-719 (1960); G. I. Bell, et al., "Probability Distribution of Neutrons and Precursors in Multiplying Medium, II," Nucl. Sci. and Eng. 16, 118-123 (1963).

region, R becomes 280\$/sec. With this ramp rate, a value $P(5\$) = 10^{-10}$ results from a source of 6.4×10^{4} n/sec, which is less than the typical source to be used for startup. With this ramp, however, the excursion probability, P(5\$) approaches unity if there is no external neutron source. In other words, it is possible deliberately to initiate an excursion by suitably bypassing safety interlocks.

APPENDIX VI

NUCLEAR KINETIC THEORY AND POWER-EXCURSION PREDICTION

Characteristic neutronic parameters. The nuclear kinetic behavior of the Kinglet assembly is determined primarily by the effective delayed neutrons from ^{235}U fission, effective abundance and lifetime of neutrons returned to the core from the Be reflector, and the core-neutron lifetime, Ω. The basic effective delayed-neutron fraction, $\beta_{25} = .008$, was obtained from the reported results of KEWB calculations for uranyl sulfate (op cit), with a small increase to account for (γ,n) reactions in the Be reflector resulting from delayed fission-gamma radiation.

Transport calculations, confirmed over the accessible experimental range by Rossi-alpha measurements, provide appropriate data for estimation of both core-neutron lifetime and reflector-neutron parameters. Results of a series of k and alpha calculations (one-dimensional DTF IV) for several fuel enrichments were compared with experiments and extrapolated to appropriate values for the design fuel loading. The calculations (without ^{235}U delayed neutrons) provided a set of values for reciprocal period (α) versus excess reactivity. These were then used to determine parameters in the following point kinetics equation:

$$\frac{\Delta k}{1+\Delta k} = \alpha \; (\Omega + \frac{\beta_7}{\alpha+\lambda_7}), \tag{4}$$

where β_7, λ_7 are, respectively, the effective one-group delayed fraction and decay constant for reflector neutrons.

For 75 g $^{235}U/\ell$ fuel concentration, the computed result for Rossi alpha is $\alpha_R = 48 \pm 10$ sec^{-1} which compares favorably with the experimental determination, $\alpha_R = 55.7$ sec^{-1}. Such calculations indicate an increase of one-percent between 75 g/ℓ and 86 g/ℓ loading, or $\alpha_R \simeq 56$ sec^{-1} is the expected value at design fuel loading. Other results obtained in the above calculations for 86 g/ℓ fuel loading are:

$$\Omega = 17.8 \times 10^{-6} \text{ sec},$$
$$\beta_7 = 0.169,$$
$$\lambda_7 = 1180 \text{ sec}^{-1}.$$

From these parameters, one can evaluate an apparent prompt neutron lifetime, ℓ, at or near critical by taking the limit of Eq. (4) as α goes toward zero to obtain

$$\ell = \Omega + \frac{\beta_7}{\lambda_7},$$

which yields $\ell = 161$ μsec using the above parameters. The probable uncertainty of this number is ± 10%. However, the separate parameters, Ω, β_7, and λ_7, are expected to introduce less uncertainty into the kinetics calculations where they tend to be carried in the same functional form as in Eq. (4).

"Inhour" relation. If the reflector-neutron group is treated as a seventh group of delayed neutrons* in the usual "inhour equation", the resulting period-reactivity relation is shown in Fig. 18 as the curve marked "No fuel flow". For comparison, two curves taken from KEWB data are included and illustrate shorter period behavior in the KEWB graphite-reflected system (Core 3) and still shorter periods for the unreflected case (Core 5).

If the fuel solution is circulating through the core, a fraction of the ^{235}U delayed-neutron precursors will be carried out of the core region (depending on their lifetimes and fuel velocity) before they release neutrons. The resulting reduction in delayed-neutron effectiveness can be readily calculated by assuming a sinusoidal axial power distribution and zero effectiveness for neutrons born in the fuel above the reflector. The resulting inhour equation is

$$\rho = \frac{\alpha}{\alpha_R} + \frac{\beta_7}{\beta_{25}} \left(\frac{\alpha}{\alpha+\lambda_7}\right) + \sum_{i=1}^{6} \frac{a_i}{(\alpha+\lambda_i)} \left\{\alpha + \frac{\pi^2 \lambda_i}{2} \left[\frac{1 + e^{-(\alpha+\lambda_i)T}}{\pi^2 + T^2(\alpha+\lambda_i)^2}\right]\right\}, \quad (5)$$

*R. N. Cordy, "Measurement of the Kinetic Experiment Water Boiler Reactor Transfer Function by Reactor Modulation Techniques," Trans. ANS 3, No. 1, 120-124 (June 1960).

where ρ is excess reactivity defined as $\Delta k/\beta_{25}$, β_{25} is ^{235}U delayed-neutron fraction, $\alpha_R = \beta_{25}/\Omega$, $a_i \equiv \beta_i/\beta_{25}$, λ_i is decay constant of i^{th} group, $T \equiv L/V$ is core transit time in core of length, L, when fuel velocity is V. Results obtained from Eq. (5) indicate that ~ 98% of delayed neutrons are effectively lost at maximum flow, or T = 0.1 sec, as illustrated in Fig. 18 by the curve (broken line) that is nearly vertical for reactivity below one dollar.

Dependence of reactivity on fuel temperature. Under static conditions (uniform temperature in core) the thermal reactivity coefficient, C_s, was measured in the range 30-35°C for two ^{235}U fuel loadings, 75 and 84.4 g/ℓ. The results for the two cases were C_s = 0.043 and 0.046 \$/°C respectively. Experimental difficulties prevented the extension of these measurements up to 100°C. Again, neutron-transport calculations proved useful, not only in predicting excess reactivities over the larger range of temperature, but also in evaluating the different processes responsible for reactivity quenching. These calculations (DTF IV) were performed at several temperatures with the appropriate solution densities. Next, neutron temperature effects were introduced by altering the appropriate thermal cross sections (hydrogen and ^{235}U)

according to temperature using Westcott's* g values. The two effects contribute equally to reactivity quench at ~ 50°C above room temperature. Combining both effects, the calculations yielded results in good agreement with the experiments mentioned above.

Similar calculations at 86 g/ℓ fuel loading with temperatures from 20°C to 140°C assumed liquid phase at all temperature. The resulting reactivity-temperature relation is shown in Fig. 20 as the "static" curve. It may be noted that experimental data from KEWB, core 3 (op cit) follow this curve with a deviation of only 0.1$ at 4$ reactivity loss. (Fuel loading in the KEWB assembly was 92 g ^{235}U/ℓ.)

If the fuel temperature were to increase rapidly, as in a power excursion, the reactivity-temperature relation would be different from that of the static case. Fuel temperature would tend to follow the power distribution function over the core, with a maximum near the center. In order to calculate reactivity loss as a function of, say, average fuel temperature rise, one needs

1) reactivity loss per unit fuel volume as a function of temperature rise,

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*C. H. Westcott "Effective Cross Section Values for Well-Moderated Thermal Reactor Spectra," CRRD-787 (1958).

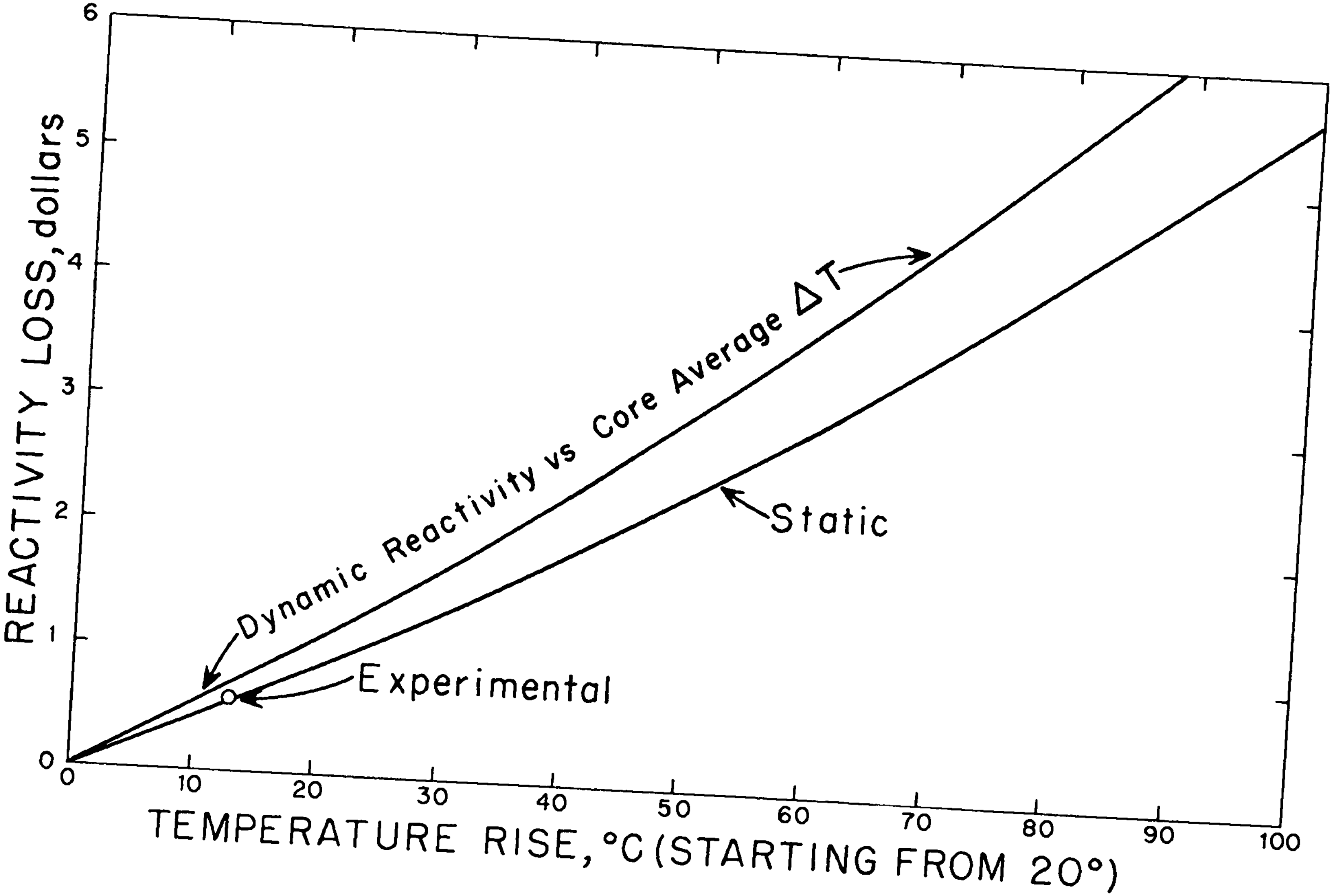

Fig. 20. Calculated reactivity loss vs core temperature rise.

2) temperature rise as a function of position in the core, and

3) relative effectiveness as a function of position.

A function for 1) was generated from the static curve of Fig. 20. Transport calculations indicate small radial variation in flux or power and a roughly sinusoidal variation axially, so we chose for 2), $\Delta T = \Delta T_c \sin \frac{\pi z}{L}$, where ΔT_c is central temperature rise, z is axial position. An experiment, in which a small void was positioned along the core axis and reactivity measured as a function of position, provided a reasonable function for 3), viz., $E(z) = \frac{E_c}{3} (2 \sin^2 \frac{\pi z}{L} + \sin \frac{\pi z}{L})$ where E is reactivity effectiveness (per unit volume), E_c is central effectiveness, and L is core height.

By integrating the product of the three functions given above over the core volume, the reactivity loss was calculated for an instantaneous fission energy release giving an average core temperature rise of ΔT_a. The resulting relationship between reactivity loss and ΔT_a appears in the upper curve of Fig. 20. The expected reactivity loss is shown to be roughly 30% greater at a given average temperature rise from a burst than that from an equal but uniform increase in fuel temperature.

Power excursions. Power excursion, or burst, behavior of a reflected assembly such as Kinglet may be predicted by machine calculations as in the KEWB studies.

For the purpose of predicting the maximum Kinglet excursion, however, analytic methods using perturbation theory are more feasible. Accordingly, point-kinetic approximations developed for fast-burst reactor studies, were checked by the reported KEWB results in order to verify the applicability. There was good agreement between predictions and experiment for power bursts in all five KEWB cores.

Burst kinetics: Neglecting delayed-neutron effects, the burst-kinetic equation for a reactor is

$$\frac{d^2E}{dt^2} = C_1 \left[\rho_o - R(E)\right] \frac{dE}{dt}, \tag{6}$$

where E is fission energy release, C_1 is a constant (usually α_R), ρ_o is initial excess prompt reactivity, R(E) is reactivity loss as a function (nonlinear) of fission-energy release in the core. By inspection, the condition for maximum power is $R(E_p) = \rho_o$, where E_p is the energy released at time of power peak.

For Kinglet, R(E) is obtained from the upper curve in Fig. 20 since fuel temperature rise, ΔT, is a linear function of E if the fuel is in the liquid phase. An adiabatic process is assumed in the sense that the temperature change takes place in a time short compared with thermal relaxation times in the core. From Fig. 18, the 5¢ maximum available value of excess reactivity would correspond to a positive reactor period of ~ 3.5 msec, which is longer than the average time (λ_7^{-1}) for reflector neutrons to return and interact with the core. Accordingly, Eq. 6 must be modified to include reflector-neutron effects.

An analytic approximation is presented in a paper on Godiva II* which takes into account delayed-neutron effects, particularly where $\lambda_i \sim \alpha_o$, the initial reciprocal positive period. The result can be written as follows:

$$E_p = \rho_p + \frac{2}{\alpha_o} \sum_{i=1}^{q} a_i \lambda_i \left(1 - 1.39 \frac{\lambda_i}{\alpha_o} + 1.64 \frac{\lambda_i^2}{\alpha_o^2} - \ldots .\right)$$
$$+ \sum_{j=q+1}^{m} a_j \left(1 - \frac{\alpha_o^2}{2\lambda_i^2} + \frac{\alpha_o^4}{\lambda_i^4} + \ldots\right), \qquad (7)$$

where E_p is energy release in reactivity units, a_i = relative abundance of i^{th} delayed neutron group, and $\lambda_q < \alpha_o < \lambda_{q+1}$. For our excursion, we use the conservative value, $\alpha_o = 300$. Clearly, for ^{235}U delayed neutrons, $\lambda_{1-6} < \alpha_o$, but $\lambda_7 > \alpha_o$. The prompt reactivity term, ρ_p, for Kinglet in 6-delayed-group dollars becomes $\rho_p = \rho_o - \beta_7/\beta_{25}$, and Eq. (7) reduces to

*T. F. Wimett, R. H. White, et al., "Godiva II--An Unmoderated Pulse-Irradiation Reactor," p 706, Nucl. Sci. and Eng. 8, 691-708 (1960).

$$E_p = \rho_o + \frac{2\bar{\lambda}}{\alpha_o} - \frac{\beta_7}{\beta_{25}}\left(\frac{\alpha_o^{\,2}}{2\lambda_7^{\,2}} - \frac{\alpha_o^{\,4}}{\lambda_7^{\,4}} + \ldots.\right), \tag{8}$$

where $\bar{\lambda} \equiv \sum_{i=1}^{6} a_i\lambda_i$ is the average decay constant for ^{235}U. Inserting $\lambda_7 = 1180$, $\beta_7 = 0.169$, $\beta_{25} = .008$, $\alpha_o = 300$, $\bar{\lambda} = 0.43$, $\rho_o = 5\$$; Eq. (8) yields $E_p = 4.41\$$. (This is to be compared with 5$ which would be the value if reflector neutrons were ignored.)

The average core temperature rise corresponding to this E_p is found in Fig. 20 to be ~ 69°C. This means that central fuel temperature approaches ~ 128°C at the time of peak power if the excursion starts at 20°C. Significant features of the leading side of the burst have now been evaluated including: E_p = 69°C or 2.6 MJ; peak power, $\dot{E}_p = \frac{\alpha_o}{2} E_p$ = 10350°C/sec or 389 MW. (For our 9 liter core, the conversion factor from °C to Megajoules is 9000 cal/°C x 4.18 x 10^{-6} MJ/cal = 0.0376 MJ/°C.)

The trailing side of this excursion is tedious to calculate. In order to determine power after peak, it is necessary to examine in detail fuel-solution dynamics after the burst peak. Because of rapid heating, solution above the core center is in upward motion. The velocity would remain constant following the peak, because the rate of expansion is proportional to power. The result would be a small overquenching of power owing to reduced fuel density.

However, the presence of superheated fuel in the central core region where temperature is increasing, generates vapor pressure at an increasing rate until it finally produces acceleration of the surface and quickly reduces the trailing power. This action was examined quantitatively by an iterative approach, and a trailing power was predicted which drops to half-maximum in a time of ~ 1.2 $\tau_o = 1.2\ \alpha_o^{-1}$ after peak. (Without over-quench, this time would be ~ 1.8 τ_o, the same as the rise time.) Energy release in the trailing edge is therefore ~ 60% E_p, and the total energy release for the excursion is ~ 1.6 E_p, ~ 4.15 MJ, or ~ 1.3 x 10^{17} fissions. It is now clear that burst time duration measured at half-maximum power is ~ 3 τ_o or about 10 milliseconds.

A starting temperature of 20°C was assumed in the foregoing discussion because that is considered to be the lowest probable value and would therefore result in the maximum initial excess reactivity. Calculations confirm the fact that excursions initiated at higher temperatures develop sufficiently smaller temperature rises such that maximum fuel temperatures attained are less than for initiations at lower temperatures.

Hydrodynamic pressure generated by the maximum power excursion: Three possible mechanisms which convert fuel energy release into solution pressure are, 1) rapid thermal expansion of solution, 2) evolution of steam, and 3) formation of radiolytic-gas bubbles. The last of these is considered separately in Appendix VII. Mechanisms 1) and 2) will be treated by detailed analysis of the excursion neglecting, for now, the gas-bubble effect.

The initial pressure phase arises from thermal expansion of fuel (mechanism 1) and varies roughly as the time derivative of power. This proportionality follows from the fact that solution displacement varies as energy release, hence expansion rate varies as the core power. The inertial pressure follows fuel acceleration, hence the time derivative of power.

Analytically, the inertial pressure is derived from the momentum conservation law for fluids, which is

$$\text{grad } P = \frac{dP}{dz} = -\delta \frac{dv(z)}{dt}$$

from which $P(z,t) = P(o,t) - \int_o^z \delta \frac{dv(z,t)}{dt} dz,$ (9)

where δ is fluid density, $v(z,t)$ is the fuel displacement rate at z, and $P(z,t)$ is the pressure at position z and time t. The velocity function that applies before the power peak is derived by integrating displacement per unit volume over the core to position z and then differentiating with respect to time. The assumption is that fuel is displaced upward only, because inertia of the long column of solution in the pipe below the core region tends to limit downward displacement. This assumption would result in an excessive pressure prediction except that the effect is essentially compensated by the further assumption that the fuel surface is only as high as the Be reflector. The function P(z,t) from Eq. (9) becomes

$$P(z,t) = P(0,t) - \frac{L\ a\ E''}{2}\left(z - \frac{L}{\pi}\sin\frac{\pi z}{L}\right)$$

$$- \frac{\pi\ L\ b(E^2)''}{8}\left[\frac{\pi z^2}{2L} - \frac{L}{2\pi}\left(1-\cos^2\frac{\pi z}{L}\right)\right], \quad (10)$$

where $P(0,t) = \dfrac{L^2 a\ E''}{2} + \dfrac{\pi^2\ L^2 b(E^2)''}{16}$,

and E(t) is the burst energy-release function in units of average core temperature rise and E'' is its second time derivative, a and b are constant coefficients in a relation between volume expansion of solution, ΔT, and ΔT^2. This expression gives the variation of maximum inertial pressure with time up to the burst peak that is shown in Fig. 21. Notice the occurrence of a pressure peak before the burst power peak, and the drop of pressure from a peak of 49 psi to 34.2 psi at zero time.

To continue evaluating pressure as a function of time after the power peak, vapor pressure resulting from superheated fuel must be considered. At peak power, the central fuel temperature has reached ~ 128°C as noted

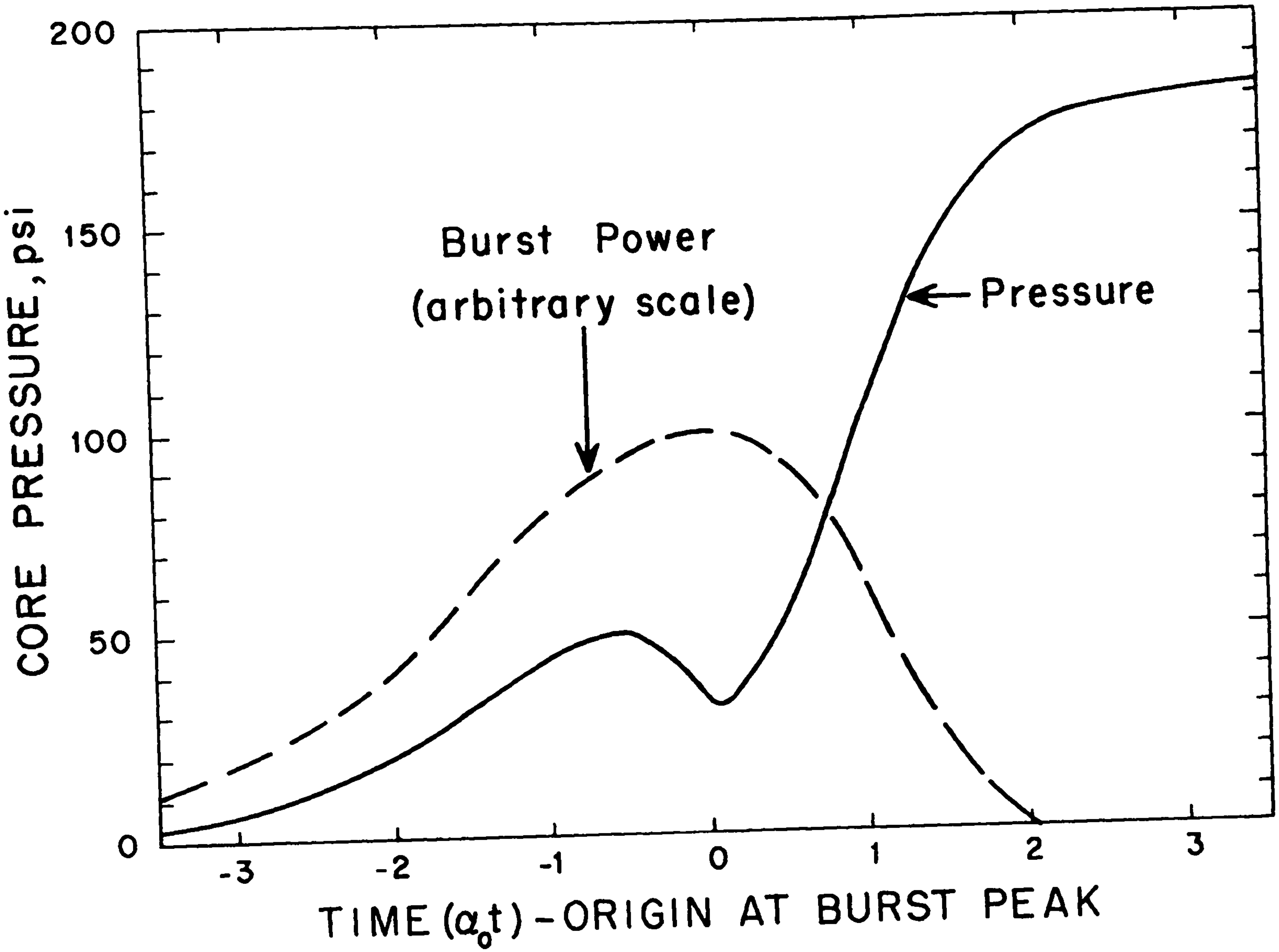

Fig. 21. Predicted pressure transient associated with greatest-possible fission burst.

earlier. Although the vapor pressure at this temperature is ~ 22 psig, no vapor will have been released up to this time, because of the greater inertial pressure (32.6 psig) at the core center. In a very short time, however, the central fuel temperature rises and vapor pressure becomes the major quench by forcing fuel out of the inner core region. The continuation of the pressure curve of Fig. 21 was evaluated by simultaneous iterative solution of Eqs. (6) and (10). Eventually the potential steam volume (~ 640 ℓ) would blow out through the top of the core tube along with a large part of the fuel.

APPENDIX VII

CORE PRESSURE FROM RADIOLYTIC-GAS BUBBLE FORMATION

According to P. Spiegler, et al., in a paper* entitled "Production of Void and Pressure by Fission Track Nucleation of Radiolytic Gas Bubbles during Power Bursts in a Solution Reactor," the gases produced by radiolysis of water are removed continuously in the form of gas bubbles under steady-state reactor operation. The bubbles are nucleated at various metallic surfaces. During fast excursions, however, diffusion of the gas to such surfaces is too slow to be effective. Instead, the gas concentration increases to a critical point where bubbles are nucleated by fission tracks. Results of the above authors' analysis of the process will be used here in an attempt to predict gas pressure in Kinglet under excursion conditions.

A semiempirical equation developed by the authors for peak inertial pressure is

$$p_m = C' \frac{G_{H_2}}{G_o} \left(\frac{P_o}{V_c} \right) - p_c, \qquad (11)$$

where G_{H_2} is the number of hydrogen molecules formed per unit energy release, G_o is a constant (1 mol H_2 per 100 eV), P_o is the reactor power at critical gas concentration, V_c is core volume, C' and p_c are experimental

*P. Spiegler, C. F. Bumpus, and A. Norman, US AEC report NAA-SR-7086, Atomics International (Dec. 1962).

constants determined by comparison with KEWB experiments. The reactor power must be computed from the critical energy release, E_c, given by

$$E_c = \left(\epsilon \frac{V_c}{G_{H_2}} \right) \frac{\bar{\varphi}}{\varphi_p} C_c , \qquad (12)$$

where $\bar{\varphi}/\varphi_p$ is the ratio of spatial average-to-peak power in the reactor (0.62 for Kinglet), C_c is the critical concentration of H_2, and ϵ is a conversion factor. Using a value of 7.8×10^{18} molecules/cc for C_c calculated by B. Thamer,* $\epsilon = 1.6 \times 10^{-25}$ MJ/eV, $G_{H_2} = 1.4 \times 10^{-2}$ molecules/eV, and $V_c = 9000$ cc, Eq. (12) yields

$E_c = 0.5$ Megajoules at 25°C,

or 0.46 Megajoules at 50°C.

Examining the Kinglet burst time function, one finds $P_o = 136$ MW at energy release $E_c = 0.5$ MJ, and the burst time for saturation is

$\alpha_o t_c = -2.24$ at 25°C,

or -2.33 at 50°C.

Substituting $P_o = 136$ MW into Eq. (11) with KEWB constants $p_c = 15$ psi, and $C' = 4.2$ psi/cm^3 kW:

$p_m = 74$ psi at 25°C,

or 67 psi at 50°C.

If indeed the core pressure were to reach 74 psi at

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*B. Thamer, Memo to L. D. P. King, Feb. 16, 1971.

burst peak, it would result in considerable reactivity quench as can be inferred from examination of Fig. 21. Starting at $\alpha_o t_c = -2.24$ and peaking at $t = 0$, the pressure would generate nearly twice the calculated fuel expansion hence reduce yield significantly up to peak. Thereafter, central core temperature would be below 100°C for a considerable time, and very little vapor pressure would result, essentially eliminating the final pressure rise shown in the figure. In other words, gas void considerations only lead to a reduced predicted value of maximum core pressure.