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Safety Analysis of the Los Alamos Critical Experiments Facility

by

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CONTENTS

ABSTRACT	1
1. INTRODUCTION AND GENERAL DESCRIPTION OF FACILITY	1
1.1. Introduction	1
1.2. Facility Description	1
1.3. Comparisons with Similar Facilities	1
1.4. Organizational Features	1
2. SITE CHARACTERISTICS	2
2.1. Geography and Demography	2
2.2. Meteorology and Seismology	2
3. REACTOR	2
3.1. Description	2
3.2. Reactor Design	2
3.3. Nuclear Design	3
3.4. Thermal and Hydraulic Design	6
3.5. Integrity of Reactor Assembly	7
3.6. Reactor Vessel and Appurtenances	8
3.7. Components and Subsystem Design	8
3.8. Instrumentation Application	9
4. ENGINEERED SAFETY FEATURES	9
4.1. General	9
4.2. Confinement Systems	9
4.3. Other Engineered Safety Features	10
5. INSTRUMENTATION AND CONTROLS	10
5.1. Introduction	10
5.2. Reactor Trip System	11
5.3. Engineered Safety Feature Systems	11
5.4. Systems Required for Safe Shutdown	11
5.5. Safety-Related Display Instrumentation	11
5.6. All Other Systems Required for Safety	11
5.7. Control Systems	11
5.8. Power Systems	12
6. AUXILIARY SYSTEMS	12
6.1. Fuel Storage and Handling	12
6.2. Fire Protection System	12
6.3. Communication System	13
7. EXPERIMENTS: DESCRIPTION AND PURPOSE	13

8. RADIOACTIVE WASTE MANAGEMENT	13
9. RADIATION PROTECTION	13
9.1. Shielding	13
9.2. Ventilation	13
9.3. Health Physics Program	14
9.4. Emergency Planning	14
10. ACCIDENT ANALYSIS	14
10.1. Hazards Summary	14
10.2. Design-Basis Events	14
11. QUALITY ASSURANCE PROGRAM	14
REFERENCES	14

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SAFETY ANALYSIS OF THE LOS ALAMOS CRITICAL EXPERIMENTS FACILITY

by

Hugh C. Paxton

ABSTRACT

The Los Alamos critical assembly layout is designed to facilitate personnel protection by means of remote operation and stringent procedural controls during nonoperating periods. Public protection is straightforward because of the small fission-product inventory, essentially ambient pressures, and moderate temperatures.

1. INTRODUCTION AND GENERAL DESCRIPTION OF FACILITY

1.1. Introduction

This report, LA-6206, Vol. I,¹ and LA-4597-MS² constitute the safety analysis of the Los Alamos Critical Experiments Facility. It is foreseen that supplements will be published periodically.

Volume I, issued in a narrative style suitable for background information and training, contains basic elements. This report, Vol. II, presents the analysis in a format required by the US Energy Research and Development Administration (ERDA).

1.2. Facility Description

The facility, operated by LASL Group R-5, consists of three outlying buildings, "Kivas," in which critical experiments are conducted remotely from control rooms in a main building. The facility is described further in Vol. I, pp. 1-3, 6, and 10, and Figs. 2-4, 11, and 22, and in Ref. 2, p. 16, and Figs. 4 and 5.

1.3. Comparisons with Similar Facilities

The other active facilities for critical experiments, at ANL, ANL-West, Hanford, and Rocky Flats, use shielding instead of distance for personnel protection. Nevertheless, the degree of protection and their functions are similar. The ANL-West ZPPR facility is specifically for fast-reactor mockups with plutonium fuel. The Hanford critical-mass laboratory is a versatile facility set up especially for handling plutonium as solutions or solids to provide data for criticality safety guidance. Currently, relatively few plutonium-solution experiments are conducted elsewhere. Critical assemblies at Rocky Flats support the various plant operations, so flexibility is essential. The Los Alamos assemblies are set up to provide criticality safety guidance, to mock up reactor systems, to generate reactor-physics (weapon-physics) data, and to serve as sources of radiation.

1.4. Organizational Features

The operating organization, Group R-5, now consists of 30 employees but will probably grow beyond

this number. The Group's structure, functions, philosophy, and operating procedures are discussed in Vol. I, pp. 13-15. Training is also covered in Vol. I and in pp. 7 and 8 of Ref. 3. Approvals and audits are specified in Ref. 3.

2. SITE CHARACTERISTICS

2.1. Geography and Demography

2.1.1. Site Location and Description. As stated in Vol. I, the site is about 3 miles from the nearest residential area (the nearest residence) and about 1.4 mile from the closest technical area, Kappa Site. The somewhat closer distance (1100 ft) between the laboratory building at Kappa Site and Kiva 2 is effectively increased because of shadow shielding from an intervening canyon wall. There are usually 29 employees at Kappa Site. At Pajarito Site, independent of Group R-5 activities, there are about 19 employees in R-2, 10 in R-4, 4 in R-DO, and 6 part time from L-1.

2.1.2. Uses of Adjacent Lands. All adjacent land is ERDA controlled and is committed to Los Alamos Scientific Laboratory (LASL) activities. There is a public road past the site. The group at Kappa Site conducts research in detonation physics. At Pajarito Site, R-2 works on nuclear detection and identification and R-4 works on the safety of high-temperature gas-cooled reactors. Group L-1 is developing a power supply for gas-discharge lasers.

There is little interaction between other activities at or near Pajarito Site and the R-5 critical experiments. Operations with the R-2 accelerator and R-5 critical assemblies are sometimes coordinated to prevent interference with radiation-sensitive experiments. In the past, primarily with the retired Hydro assembly, operations outside Kiva 2 were conducted during off-normal shifts to minimize exposures at Kappa Site. However, no such restriction is required with the present assemblies.

2.2. Meteorology and Seismology

2.2.1. Meteorological Conditions. Pajarito Site is semiarid, but at its elevation of 6760 ft it gets some winter snow and is subject to summer thun-

derstorms, which are characteristic of the general region. Runoff from storms has not been severe in Pajarito Canyon. At no time during the 28-yr history of remote operation at the site has floodwater reached the floor elevation of any critical assembly building.

Because of the moderating effect of canyon walls and the Jemez mountains to the west, winds in Pajarito Canyon are not as severe as on the plateau above. Also, 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 26 yr. The highest wind velocity observed during this period was 60-65 mph, in the form of a gust.

2.2.2. Seismic Considerations. The earthquake potential at Los Alamos is discussed in Ref. 2, pp. 23 and 24, and Appendix III. The conclusion that Kinglet would withstand a shock far greater than the maximum suggested by US Geological Survey reports applies to all Pajarito assemblies.

3. REACTOR

3.1. Description

The "reactor" is the Pajarito facility with various critical assemblies, each limited to fission products such as would be generated in 0.01 s by a 1000-MWe reactor (Vol. I, p. 18).

3.2. Reactor Design

3.2.1. Fuel. Plutonium metal coated with 0.005-in.-thick nickel is the active material of the Jezebel assembly (Vol. I, p. 7), a core of the Flattop assembly (Vol. I, p. 7), and components used on the Comet machine (Vol. I, p. 8). A similarly coated ²³³U metal core also is available for Flattop. Highly enriched uranium metal fuels Godiva IV and IVA (Vol. I, pp. 12 and 13), Honeycomb, as foil (Vol. I, pp. 2 and 4), part of Big Ten (Vol. I, pp. 7-9), and temporary assemblies on Comet (Vol. I, p. 8), Supercomet (Vol. I, p. 13), and Venus (Vol. I, p. 4). Part of the Big Ten core is of U(10) metal. The remainder consists of U(93) plates interleaved with U(natural)

to average U(10). Uranium parts are uncoated except for a thin corrosion-resistant aluminum layer on Godiva components. Parka (Vol. I, pp. 11 and 12) contains Rover-type U(93)-graphite fuel elements.* Similar elements (most of them uncoated) or U(93) foil may be used to supplement U(93)F₆ in the Plasma Cavity Assembly (Vol. I, p. 5). Circulating U(93) solution is the active material used in Kinglet (Vol. I, pp. 5 and 6, and Ref. 2). No operation is conducted in which the fission-induced temperature rise exceeds that attained in Godiva. The nominal temperature rise measured in Godiva is about 350°C, and the maximum peak value will not exceed 900°C.

3.2.2. Reactor Assembly. The various assemblies are described by the references cited in Sec. 3.2.1. Special Jezebel and Flattop features, which provide for moderate reactivity adjustments beyond control-rod ranges, compensate for changes in the content of diametral holes through the assemblies. The 13 recesses at the Jezebel parting planes (Fig. 12, Vol. I) accommodate removable plutonium buttons, each worth about 0.22\$. Flattop has similar recesses of natural uranium, U(N), parts about each core. For the ²³⁵U and plutonium cores, U(N) buttons fitting six recesses are worth 0.20\$ and 0.31\$ each, respectively. For the U(93) core, U(93) replacing U(N) is worth 0.084\$ in each of the 11 recesses. The Godiva IV core, which is inflexible except for occasional substitution of refabricated parts, has no similar provision for stepwise adjustment of reactivity. Because restacking Big Ten to change available excess reactivity is a major undertaking, no further modification is planned. The Honeycomb, Plasma Cavity Assembly, and Parka cores are readily restacked. The Comet, Supercomet, and Venus assemblies are designed for specific experiments, usually of short term.

3.2.3. Reactor Control Systems. The assembly control systems are described by the references cited in Sec. 3.2.1 and by Ref. 2, pp. 43-46, and Figs. 12 and 13.

3.2.4. Beryllium Reflectors. Beryllium reflectors are inherent components of the Plasma Cavity

Assembly, Kinglet, and Parka. Beryllium components may be used in Honeycomb or as parts of temporary assemblies on Comet, Supercomet, or Venus.

3.3. Nuclear Design

3.3.1. Description. Nuclear designs of the various assemblies are described by the references cited in Sec. 3.2.1; by Vol. I, Figs. 5-10, 12-21, and 23-26; and by Ref. 2, Figs. 1 and 7-10. Following is a summary of control and safety-device worths for each machine and an estimate of available shutdown with the most effective safety device inoperative.

Big Ten

Worth of 2 control rods, 0.29\$ (≥0.09\$ available for shutdown)

Cart withdrawal, ~20\$ shutdown

Withdrawal of 11 safety rods, 0.95\$ shutdown

Shutdown with cart inoperative, ≥1.04\$

Comet (All Past Criticals)*

Control worths, >0.2\$

Lift retraction, >20\$ shutdown

Upper safety retraction, >10\$ shutdown

Shutdown with lift up, >10\$

Flattop

Worth of 3 control rods, ≥2.7\$ (2 worth ≥0.6\$ each), value is minimum for U(93) core

Retraction of both reflector quadrants, ~17\$ shutdown

Shutdown with one quadrant in place, ~8\$

Godiva IV or IVA

Worth of 2 control rods, 3.0\$ (≥2\$ available for shutdown)

Worth of burst rod, 1.5\$

Safety block withdrawal, 2 release mechanisms, >15\$ shutdown

Shutdown if both release mechanisms fail, >2\$

*Comet values also apply to Supercomet and Venus assemblies.

Honeycomb (4-ft Cube, Typical)

Worth of 2 control bundles, $\sim 0.8\%$
Cart withdrawal, $\sim 20\%$ shutdown
Retraction of 4 safety bundles, 1.5% shutdown
Shutdown with cart inoperative, $>1.5\%$

Jezebel

Control worth, 0.7%
Retraction of both caps, $\sim 100\%$ shutdown
Retraction of one cap, $\sim 50\%$ shutdown
Shutdown with one cap in place, $\sim 50\%$

Kinglet

Worth of control-safety sleeve, 18%
Pump off, $>20\%$ shutdown
Withdrawal of safety portion of sleeve, $>10\%$ shutdown
Shutdown with pump operating, $>10\%$

Parka (Typical)

Worth of 12 control-safety drums, 8.2%
Normal shutdown, $>5.0\%$
Shutdown with one drum inoperative, $>4.6\%$

Plasma Cavity Assembly (Mars Machine)

Worth of 18 control-safety drums, 4.0%
Retraction of core assembly, $>100\%$ shutdown
Shutdown with core in place, $\sim 2\%$

Each assembly satisfies the requirement "shutdown shall be at least 5% total and greater than 1% with any single safety device inoperative," given in Ref. 3, p. 6. Except for Big Ten, excess reactivity restrictions rely upon appropriate operating procedures instead of being inherent in the design. Although Big Ten can be stacked with more than 1% excess reactivity (as compared with its present 0.2%), this would be a major undertaking and no reason for the change is foreseen. However, all machines have some built-in protection against gross operating error, generally in the form of an additional $0.05\%/s$ maximum rate of reactivity during approach to criticality whenever the neutron multiplication is >100 . This design condition, a technical specification,³ gives appropriate operator response

time in case of a stacking error. The normal excess reactivity, also a technical specification, corresponds to a positive period of 5 s, which provides a $\geq 0.3\%$ margin to prompt criticality. Other technical specifications, which apply to Jezebel, Flattop, and Big Ten, and new approaches to criticality with Godiva IV and IVA, provide for "reproducibility-based" reactivity limits that may be less restrictive than the normal limit. Reactivity restrictions for fast-neutron bursts with Godiva IV and IVA and for Kinglet also are given in Ref. 3.

3.3.2. Evaluation. System designs are straightforward adaptations to applications that maintain an appropriate balance among utility, reliability, and economy. The nuclear designs are simple, yet consistent with objectives and safety requirements. To promote reliability and error-free operation, unnecessary flexibility of a critical assembly is avoided.

Metal assemblies are designed to preserve the negative temperature coefficient of reactivity associated with the materials' inherent expansion coefficient. Kinglet is also in this same category. The observed static temperature coefficient of Godiva IV is $-0.003\%/^{\circ}\text{C}$ and that of Jezebel is about $-0.007\%/^{\circ}\text{C}$; these coefficients are about equal in μk units. The coefficients for the reflected systems, Big Ten and Flattop with its U(93) core, are similar to that for Godiva. However, for Flattop with plutonium, the coefficient is only $-0.002\%/^{\circ}\text{C}$. The observed value for Kinglet is a generous $-0.04\%/^{\circ}\text{C}$ under static conditions and as great as $-0.08\%/^{\circ}\text{C}$ dynamically. By contrast, the Godiva coefficient that controls burst characteristics is an adequate $-0.002\%/^{\circ}\text{C}$, but less than the static value. Although Parka's temperature coefficient of reactivity is negative, this value is not currently used for reproducibility-based reactivity limits. Therefore, Parka is in the same class as Honeycomb, the Plasma Cavity Assembly, and assemblies on Comet, Supercomet, and Venus machines.

3.3.3. Tests and Inspections. The testing and inspection program is defined in Ref. 3, p. 7.

3.3.4. Instrumentation Application.

3.3.4.1. Scram Chain. The scram-chain logic for each Kiva is shown in Fig. 3-1. A scram results if one

Fig. 3-1.
Scram-chain logic, general.

of two or three redundant monitors is tripped, if the Kiva gate is opened, if a manual switch at the Kiva or control console is depressed, or if the console power fails. A fault leads to a positive scram without any intermediate state (unlike a power reactor). To prevent sneak circuits, the scram chain is as straightforward as possible. All actuating relays are in series, and parallel circuits are avoided.

The GE general-purpose, double-pole, double-throw relays were selected for reliability. The normally open contacts activate the safety chain so that power interruption leads to a scram. The relays in series provide redundancy in this regard. Because the power lines between the control console and Kiva and the scram-chain lines are in separate cables, a short between them is unlikely. However, a short to ground would result in a scram.

The fail-safe feature of the scram chain extends to lightning-induced surges, which are bypassed to ground by Thyrite arresters to prevent welding of relay contacts. The brief interruption of power

scrams the system, which is consistent with our policy of accepting a scram from any abnormality.

The features shown in Fig. 3-1, which are characteristic of all machines, are supplemented by Fig. 3-2 and Tables 3-1 and 3-II. The dotted area in the scram chain calls for adequate air pressure for operation of Jezebel, Godiva, and the typical Comet assembly, or for nitrogen pressure in the hydraulic-system accumulators of Big Ten, Flattop, and Honeycomb. (Big Ten has three accumulators, and Flattop has two.) The "spares" shown in Fig. 3-1 accommodate special elements in the scram chain without bypassing the normally active elements. An example was the special core-temperature scram on the now-retired Hydro assembly. A scram initiated by an experimental setup is another possible use.

3.3.4.2. Interlocks and Controls. The interlocks indicated in Fig. 3-2 establish a specific sequence of remote operation before the controls can add reactivity. The interlocks differ among assemblies. The

TABLE 3-11
INTERLOCKS BEYOND SCRAM CHAIN

<u>Assembly</u>	<u>Operational Sequence Dictated by Interlocks</u>
Big Ten	Control rods out, safety rods in, cart closed, 2 controls operable
Comet (typical)*	Control out, upper safety down, lift up, control operable
Flattop	Control rods out, quadrant A in, quadrant B in, 3 control rods operable
Godiva (delayed critical)*	Control rods out, safety block in, 2 control rods operable
Honeycomb	Control bundles out, safety bundles in, cart closed, 2 control bundles operable
Jezebel	Control rod out, upper cap down, lower cap up, control rod operable
Kinglet	Control-safety sleeve with safety part out, control part in, pump on, sleeve operable as control
Parka	Control-safety drums at minimum reactivity, power on, 12 drums operable as control
Plasma Cavity Assembly	Control-safety drums at minimum reactivity, 18 drums operable as control

*Comet interlocks also apply to Supercomet and Venus.

*For burst mode, an interlock prevents insertion of the burst rod when the safety block is withdrawn.

3.4.3. Testing and Verification. Flow tests using water established proper functioning before the solution was added (Ref. 2, pp. 55-58).

3.4.4. Instrumentation Application. See Ref. 2, pp. 27, 30, 31, and 33 and Sees. 3.3.1 and 3.3.4.

3.5. Integrity of Reactor Assembly

3.5.1. Design Criteria, Methods, and Procedures. Because all assemblies are at essentially ambient pressure and moderate temperature, elementary structural analysis is an adequate basis

for design. Conventional fabrication methods and assembly procedures are followed.

3.5.2. Overpressurization Protection. The only required protection against overpressurization is a 16-psig rupture disk on the Kinglet main solution tank. The normal pressure rise is only 1 psig (Ref. 2, p. 33).

3.5.3. Material Considerations. Conventional materials are used except where special nuclear characteristics are required. The beryllium is Brush Beryllium Co. grade S-200-C or equivalent, the Kinglet core tube is Zircaloy-2 (Ref. 2, p. 34), the Honeycomb matrix is 1100 F aluminum, and the

Plasma Cavity Assembly core fixtures are 6061 aluminum. Uranium and plutonium metal satisfy weapon component specifications.

3.5.4. Leakage Detection Systems. This applies only to Kinglet where leakage is observed visually or by a decrease of pressure in the main solution tank.

3.5.5. In-Service Inspection Program. See Sec. 3.3.3.

3.6. Reactor Vessel and Appurtenances

The only vessel is that of Kinglet, described in Ref. 2, pp. 31-34, including Fig. 9. See also Secs. 3.5.2 and 3.5.4.

3.7. Components and Subsystem Design

3.7.1. Power Supply. Power to the assembly machines is supplied independently of the safety chain, except for breaking the chain upon failure. The system shown in Fig. 3-3(A), in which power is supplied from the Kiva, applies to all assembly components except Parka and the Plasma Cavity Assembly control drums. For these two exceptions, console power is supplied as indicated by Fig. 3-3(B).

3.7.2. Hydraulic Systems. The hydraulic system for a simple lift without slowdown, as for the Mars machine (Plasma Cavity Assembly), is shown schematically in Fig. 3-4. Under the indicated scram condition, hydraulic fluid drains from the lower part of the hydraulic cylinder permitting the lift to drop by gravity. With all valves energized, fluid pumped into the lower part of the cylinder raises the lift. The hydraulic pump continues to operate at the upper limit of the lift's stroke. This system, available with the Venus and Supercomet machines, also actuates the Godiva safety block.

The more complicated system shown in Fig. 3-5 uses a hydraulic motor to drive the Big Ten cart. Under the illustrated scram condition, with all solenoid valves de-energized, the throttle valve is bypassed and the hydraulic motor is driven in the reverse (cart open) direction at full flow. A reverse drive with throttled flow is available with the three-way valve in the "reverse" position, "slowdown" inoperative,

Fig. 3-3.

Machine power circuit logic.

(A) *Big Ten, Comet, Flattop, Godiva, Honeycomb, Kinglet, Jezebel, and Plasma Cavity Assembly hydraulic systems.*

(B) *Parka and Plasma Cavity Assembly controls.*

and the other two valves energized. With the three-way valve in the "forward" position and the other valves the same as above, the motor drives the cart toward closure at throttled flow. Toward the end of the drive a position sensor activates the "slowdown" valve, throttling the flow further by means of the associated "flow control" valve.

The Honeycomb cart drive differs from Fig. 3-5 in that the three-way valve is replaced by a pair of two-way valves and the cart is driven by a hydraulic cylinder instead of a motor. Again, there is full-flow scram, throttled reverse and forward drives, and a slowdown toward the end of the forward stroke.

Fig. 3-4.

Hydraulic system for lift without slowdown (scram condition).

Fig. 3-5.

Hydraulic system for Big Ten cart drive (scram condition).

Hydraulic systems that actuate the Comet lift, the Flattop safety quadrants, and the Big Ten safety rods are essentially the same as above.

3.7.3. Pneumatic Systems. A typical pneumatic system, shown in Fig. 3-6, actuates both Jezebel safety caps. The scram condition is shown with solenoids de-energized, that is, the lower cap is depressed and the upper cap is raised. When the solenoid valves are energized, the upper cap drops all the way and the lower cap is raised to 0.2 in. short of closure. The lower cap and its pneumatic cylinder are driven the rest of the way by a low-speed motor to limit properly the final rate of reactivity addition.

Fig. 3-6.

Jezebel pneumatic system.

Other assemblies with pneumatically driven devices are the typical Comet setup (1 upper safety), Godiva (1 burst rod), and Honeycomb (4 safety bundles). The system for each device is like the part of Fig. 3-6 that actuates the upper cap of Jezebel.

3.8. Instrumentation Application

Instrumentation for data collection and analysis includes digital scalars for pulse counting, automatic timers for positive-period measurement, multichannel time analyzers for establishing Rossi α , multichannel pulse height analyzers for fission or activation measurements, and computers for data analysis. A digital minicomputer and analog computer provide on-line solution of the reactor kinetic equations for evaluating absolute reactivity and reactivity contributions of samples in an oscillator. The digital computer is also used for neutron spectroscopy and for prompt-neutron lifetime measurement by means of the Feynman variance technique.

For other applications, see Sec. 3.3.4.

4. ENGINEERED SAFETY FEATURES

4.1. General

Our assemblies require no special provision for after-heat removal because of their limited fission-product inventory (see Sec. 3.1). The Jezebel forced-air cooling system serves a different purpose; it controls the temperature rise from α -particle heating. Further, because the assemblies operate at essentially ambient pressure and moderate temperature, they lack the stored energy potential of a power reactor. Consequently, there is no need for conventional engineered safeguards. The distance at which personnel are removed during operation protects against numerous credible mishaps.

4.2. Confinement Systems

4.2.1. Confinement Functional Design. Kivas are designed as high-quality housing for critical assemblies and valuable fissile materials. Except for Kiva 3, which provides some shielding (Vol. I, p. 10), their remote location, instead of their structure,

provides radiological protection. Although the Kivas were not designed for containment, their confinement capability would be significant, as suggested by the >90% retention by housing in the SL-1 accident.⁵

There was no measurable fission-product release during the worst accidental excursion at Pajarito—the second Lady Godiva accident (Vol. I, Table I)—because after-the-fact monitoring concentrated on the direct radiation. Nevertheless, the quantity can be estimated from measurements taken from a planned burst of the White Sands reactor during pretesting at Los Alamos⁶ and from the Sandia model for release from surface layers.⁷ The Los Alamos measurement suggests $\sim 10^{-2}$ Ci outside the assembly after a 2-h delay, and the Sandia model gives $\sim 3 \times 10^{-2}$ Ci after 2 h or ~ 0.5 Ci after 10 min. The Sandia results, known to be overestimated in the absence of melting, are assumed to allow for the softening of material that occurred in Lady Godiva.

Taking 0.5 Ci as the source term at 10 min, or 3×10^{-2} Ci at 2 h, with 10% escaping from the Kiva, we may scale according to the SL-1 data for deposited activity (~ 100 Ci long-lived products outside the SL-1 building depositing ~ 0.04 R/h at 500 ft).⁵ The result at 500 ft from the Kiva (less than the exclusion distances) is 0.02 mR/h at 10 min or 0.001 mR/h at 2 h. According to a radioactive cloud model used in Ref. 8, the corresponding whole-body dose to a person at this distance would be 0.06 mrem. The Lady Godiva excursion yield of 1.2×10^{17} fissions led to these results.

These results, even if increased 10- or 100-fold, support the opinion that confinement and isolation distance offer adequate protection from airborne fission products arising from an accident.

The Kinglet solution tank provides containment for radioactive gases until conditions are appropriate for release through a filter and charcoal trap (Ref. 2, pp. 31, 33, 34, 40, and 41).

4.2.2. Confinement Ventilation, Isolation, and Filtration Systems. The only isolation and filtration system is that associated with the Kinglet main solution tank (Sec. 4.2.1). The Kivas do not have filtered ventilation systems. Note that Jezebel has been operated outside Kiva 2 for experiments requiring minimum neutron reflection.

4.2.3. Hazardous Gas Control in Confinement.

The only gases that might be considered hazardous are those collected in the Kinglet main solution tank. Radioactivity and hydrogen content of these gases are monitored, and the results govern discharge as described in Sec. 4.2.1.

4.3. Other Engineered Safety Features

Not applicable for reasons described in Sec. 4.1.

5. INSTRUMENTATION AND CONTROLS

5.1. Introduction

5.1.1. Identification of Safety-Related Systems. As noted in Sec. 3.3.4, the following systems are safety related: (1) the gate interlock system that prevents access to the Kiva area during remote operation, (2) the scram system consisting of safety devices that are actuated automatically by a signal from either a scram monitor or a manual control, (3) at least one vernier-control device with fission-rate indicators, and (4) a system of interlocks that establishes a favorable sequence of start-up operations.

5.1.2. Identification of Safety Criteria. Our basic criteria are that radiation exposures to personnel at the facility be limited to 5 rem/yr/person, that the contribution to public exposure be less than 0.5 rem/yr for any individual, and that equipment damage either be negligible or less than resulting benefit. A secondary criterion, the Operating Limit, controls fission-product inventory (Vol. I, p. 16). The Operating Limit is given in Ref. 3 in the following terms.

"Operation shall be controlled so that the fission product power generation in any assembly, when averaged over the first hour after shutdown, does not exceed 600 W. Figure 1 gives the information required to translate any fission product history into fission product power at any later time. Note that the 600-W limit is the first-hour average that would be generated by a burst of 10^{18} fissions."

These criteria are implemented by technical specifications listed under "Limiting Safety System Setting" and "Limiting Conditions for Operation."³

5.2. Reactor Trip System

5.2.1. Description. Safety devices for the various assembly machines are described in Secs. 3.3.1, 3.3.4, and Table 3-I. Scram chains and interlocks are discussed in Sec. 3.3.4. Scram-chain logic is presented in Figs. 3-1 and 3-2, and interlock functions are listed in Table 3-II.

5.2.2. Analysis. Unlike a power reactor where shutdown may constitute a serious interruption of service, immediate scram is the favored consequence of any malfunction of a critical assembly. The straightforward scram chain that results is "fail-safe" and relatively free of potential for sneak circuits (Sec. 3.3.4).

5.3. Engineered Safety Feature Systems

Not applicable, but see Secs. 4.1 and 4.2.

5.4. Systems Required for Safe Shutdown

The scram systems described in Secs. 3.3.1, 3.3.4, and 5.2.1 provide safe shutdown. The adequacy of a simple scram follows from the fact that no special provision is needed for after-heat removal.

If power loss occurs, the automatic scram actions of the various machines will take place as follows. The Comet and Plasma Cavity Assembly lifts, the Godiva safety block, and the Jezebel lower cap drop under the action of gravity. The Honeycomb safety rods are withdrawn, and the upper Comet safety and the upper Jezebel cap are raised by air pressure from a common reservoir. The Parka and Plasma Cavity Assembly safety-control drums are returned to the minimum reactivity position by built-in springs. Hydraulic accumulators separate the Big Ten and Honeycomb carts, withdraw the Big Ten safety rods, and retract the Flattop quadrants.

5.5. Safety-Related Display Instrumentation

5.5.1. Description. Indicators showing that scram monitors are active and that the fission-rate displays are functioning properly are safety related. Scram-chain indicator lights are shown in the Fig. 3-1 logic diagram. This diagram also includes power to fission-rate displays as "power switch for display meters."

Less directly, safety is influenced by indicator lights showing limiting positions of major components and by indicators of vernier-control positions.

5.5.2. Analysis. The listed displays are only of secondary safety significance because the primary safety provisions, scram chains and interlocks, function independently. The displays are of diagnostic value.

5.6. All Other Systems Required for Safety

5.6.1. Description. The gate to a Kiva area can be opened only by a captive console key that controls power to assemblies. This provision, that machine power must be interrupted before the gate can be opened, is a back-up for the automatic scram that would occur when the gate is raised (Fig. 3-1). Thus, a degree of redundancy is represented.

5.6.2. Analysis. This system prevents inadvertent entry.

5.7. Control Systems

5.7.1. Description. The three types of vernier-control drive systems at Pajarito Site are: a simple electric drive, such as that found on Jezebel; a servoelectric drive, such as that available for fine control of Big Ten; and the unique servohydraulic drive used on Kinglet (Ref. 2, pp. 35-38). The Jezebel system, shown schematically in Fig. 5-1, also applies to each control element of Flattop, Godiva, and Honeycomb, and to two of the Big Ten rods. This system, which has only manual control, requires that the scram chain be closed and that safety

Fig. 5-1.
Jezebel control rod drive system.

Fig. 5-2.
Big Ten servorod drive system.

devices be in maximum reactivity positions before operation is possible. Other features are a position indicator at the control console and an interlock that prevents resetting the safety devices unless the control element is in its minimum reactivity position (Table 3-II).

The system for the Big Ten servorod, Fig. 5-2, also applies in principle to each of the 12 control-safety drums of Parka and to the 18 drums of the Plasma Cavity Assembly. Manual control is still an option, but added to the Fig. 5-1 elements is a servosystem that can maintain constant fission power. Stepping motors that drive controls in these assemblies (as opposed to the older Selsyn motors or hydraulic drive) require special regulated voltages that place extra interlock requirements on the system.

The actual control elements and interlocks are described in Secs. 3.3.1 and 3.3.4.

5.7.2. Analysis. Interlocks prevent the assembly of major components unless control devices are at minimum reactivity positions (Table 3-II). Reactivity addition rates are limited to 0.05%/s maximum for near-critical approaches, as required by a technical specification.⁸ With these restrictions, controls contribute to safety through operational convenience instead of directly.

5.8. Power Systems

5.8.1. ac Power Systems. Power is provided by the normal LASL ac grid and is carried to machines as shown in Figs. 3-3 (A) and (B). Because power loss initiates scrams (Sec. 3.3.4) and no power is required

to maintain safe shutdown, continuity of the power supply is not a safety consideration.

5.8.2. dc Power Systems. Except for instrumentation power supplies, no dc power is required for operation. Emergency power is not a safety requirement, as noted in Sec. 5.8.1.

6. AUXILIARY SYSTEMS

6.1. Fuel Storage and Handling

Fissile materials are stored in a cliffside vault (the small, lower right-hand structure shown in Vol. 1, Fig. 2) and in storage rooms in Kivas 1 and 2 (Vol. 1, Figs. 4 and 11). A cage in Kiva 3 can be used for temporary fuel storage. As required by a technical specification,⁹ storage and handling of fissile material are governed by the American National Standard⁹ "Nuclear Criticality Safety Standard for Operations with Fissionable Materials Outside Reactors."

6.2. Fire Protection System

Smoke detectors in the Kivas and control rooms initiate central-station and local fire alarms. Manual CO₂ extinguishers and powder metal-fire extinguishers are available in each Kiva. There is a

CO₂ extinguisher in the Kinglet building. A fire hose and CO₂ extinguishers are near the control rooms.

6.3. Communication System

There is an audio communication system between each control room and its Kiva (a technical specification requirement³ for operation). The system consists of an amplifier between a speaker mounted on the control console and another that can be moved about in the Kiva. The speaker in the Kiva normally serves as a microphone so that there is normal communication to persons at the control. To reverse the communication, a spring-loaded switch on the console is held down.

7. EXPERIMENTS: DESCRIPTION AND PURPOSE

Types of experiments and their purposes are given in Secs. 1.3 and 3.3.4 references cited in Sec. 3.2.1, and Vol. 1, p. 1. As called for in Ref. 3, each critical (or near-critical) experiment is covered by a written experimental plan that includes operational limits, purpose, materials, description, procedures, and safety evaluation.

8. RADIOACTIVE WASTE MANAGEMENT

All waste generated at Pajarito Site is low-level, as defined in Ref. 10, pp. 100 and 102, or below detection level as discharged gas. Because radioactive waste disposal guidelines in Chap. X, Ref. 10, are observed, estimated doses are negligible.

9. RADIATION PROTECTION

9.1. Shielding

9.1.1. Design Objectives. The objective is to maintain the contribution to public exposure below 0.5 rem/yr for any individual and to control on-site exposures (Sec. 5.1.2).

9.1.2. Design Description. The 18-in.-thick concrete walls and ceiling of Kiva 3 (Vol. I, p. 10) are to maintain the same degree of accident protection offered by the other more distant Kivas (Vol. I, pp. 3 and 6). This shielding also eliminates the need for traffic control on the nearby limited-access road (Vol. I, Fig. 2) during high-level operation of Godiva IV or IVA. Partial shielding of the Kinglet tank is provided to simplify observance of the public-exposure limit on Pajarito Road (Vol. I, Fig. 1).

9.1.3. Source Terms. The maximum source term is defined by the Operating Limit that controls fission-product inventory (Sec. 5.1.2). For instantaneous operation, this limit is 10¹⁶ fissions.

9.1.4. Area Monitoring. Continuously recording neutron and gamma monitors are located on the roof of the main laboratory building of the facility, and gamma monitors are located in each Kiva. There is an accident dosimeter in the cliffside vault, and four film packs are located about the site. Three of the film packs are used primarily for monitoring radiation from an accelerator operated by Group R-2. Three other film packs are at the nearest neighboring technical area, Kappa Site, as described in Sec. 2.1.2.

9.1.5. Operating Procedures. Guidelines specified in LA-4400¹⁰ are observed.

9.1.6. Exposure Estimates. Kiva operations are estimated to give an annual exposure of 2.0 rem¹¹ at the rooftop monitors (Sec. 9.1.4). Based on a measured ratio, 2.0 rem would correspond to an average of 0.4 rem/yr within the main laboratory building (for full-time occupancy). Estimated doses for a normal 8-h occupancy are 0.1 rem/yr at Kappa Site, 0.3 rem/yr in the R-2 office building, and 0.07 rem/yr at the most exposed point on the Pajarito Road (allowing for 1/16 occupancy factor).¹¹

9.2. Ventilation

Not applicable, but see Sec. 4.2.

9.3. Health Physics Program

The health physics program is defined in LA-4400.¹⁰ Interpretation for emergencies is given in Ref. 12 "Pajarito Plan for Radiation Emergency."

9.4. Emergency Planning

The site emergency plan consists of general procedures that include Ref. 12 and interpretations for operating personnel.¹³

10. ACCIDENT ANALYSIS

10.1. Hazards Summary

Hazards are defined as direct radiation from an assembly attaining the Operating Limit of Ref. 3 (Sec. 5.1.2.), corresponding to 10^{18} fissions instantaneously, and the associated fission products. Based on Pajarito accident experience over 28 yr of remote operation, these hazards are so well controlled that the associated risk is less than \$200/yr (Vol. I, p. 17 and Table I).

10.2. Design-Basis Events

The only design-basis accident is that suggested in Ref. 2, pp. 66-79, namely, that all fission products are released from the Kinglet solution to the atmosphere immediately after a 10-s run of 1.3×10^{18} fissions (corresponding to the Operating Limit). Under the most adverse conditions it is shown that doses at 1000 ft, the closest approach during operation, would be less than 5 rad whole body or 20 rad to the thyroid—probably two orders of magnitude smaller.

As stated in Vol. I, p. 16, these results apply even more conservatively to the other Pajarito assemblies in which solid fuels tend to retain fission products. Examples of estimated doses from a 10^{18} fission burst within Kiva 3 (a typical location) are 70 mrem in the main laboratory building, 70 mrem in the R-2 office building, 25 mrem at Kappa Site, and 350 mrem at the off-site (limited-access) road nearest Kiva 3.¹¹

11. QUALITY ASSURANCE PROGRAM

As noted in Sec. 4.1, our assemblies have small fission product inventory and lack the stored energy of power reactors because of their essentially ambient pressure and moderate temperature. Therefore, conventional quality control procedures take the place of a quality assurance program. Where significant, specifications of material impurities are requested from the suppliers; specified tests, such as leak tests of Kinglet tanks, are observed by LASL designers (Ref. 2, p. 34); and lightweight supports for fissile components are proof tested with inert material before use. Usually, simple structural analysis and normal inspection for soundness provide adequate confirmation.

The following technical specification³ for new controls and safety devices contributes to quality assurance. "The satisfactory performance of new or altered safety equipment shall be established, and adherence to the reactivity addition rate limit shall be confirmed before initial critical operation."

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