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EFFECT OF TEMPERATURE AND REACTIVITY CHANGES IN OPERATION OF THE LOS ALAMOS PLUTONIUM REACTOR

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Effect of Temperature and Reactivity Changes in Fast Reactor Operation

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I. Introduction

The operation of the Fast Reactor is considered in terms of normal equilibrium conditions and normal shut-down. The proposed loading, control rod adjustment and subsequent "floating" operation are discussed. Safety devices and interlocks are described.

Temperature and reactivity changes are examined with respect to various system failures, phase changes, and "flashing" of the reactor. Slow changes due to faulty slug cooling are also considered.

The calculations were initially based upon 10 kw operation. Performance tests of the mercury system now indicate that 20 kw operation may be feasible.

II. General Reactor Information

In order to clarify the discussion which will follow, brief descriptions of the cooling system, safety circuits and interlocks are given, together with heat transfer data. A physical description of the unit is included in LAMS-567.

A. Cooling System Data

The reactor is an all metal system circulating mercury in the flow diagram shown in Fig. 1.

The steel reactor pot rests in an 18 inch cube of uranium which is cooled on all faces by small water tubes embedded in an aluminum jacket.

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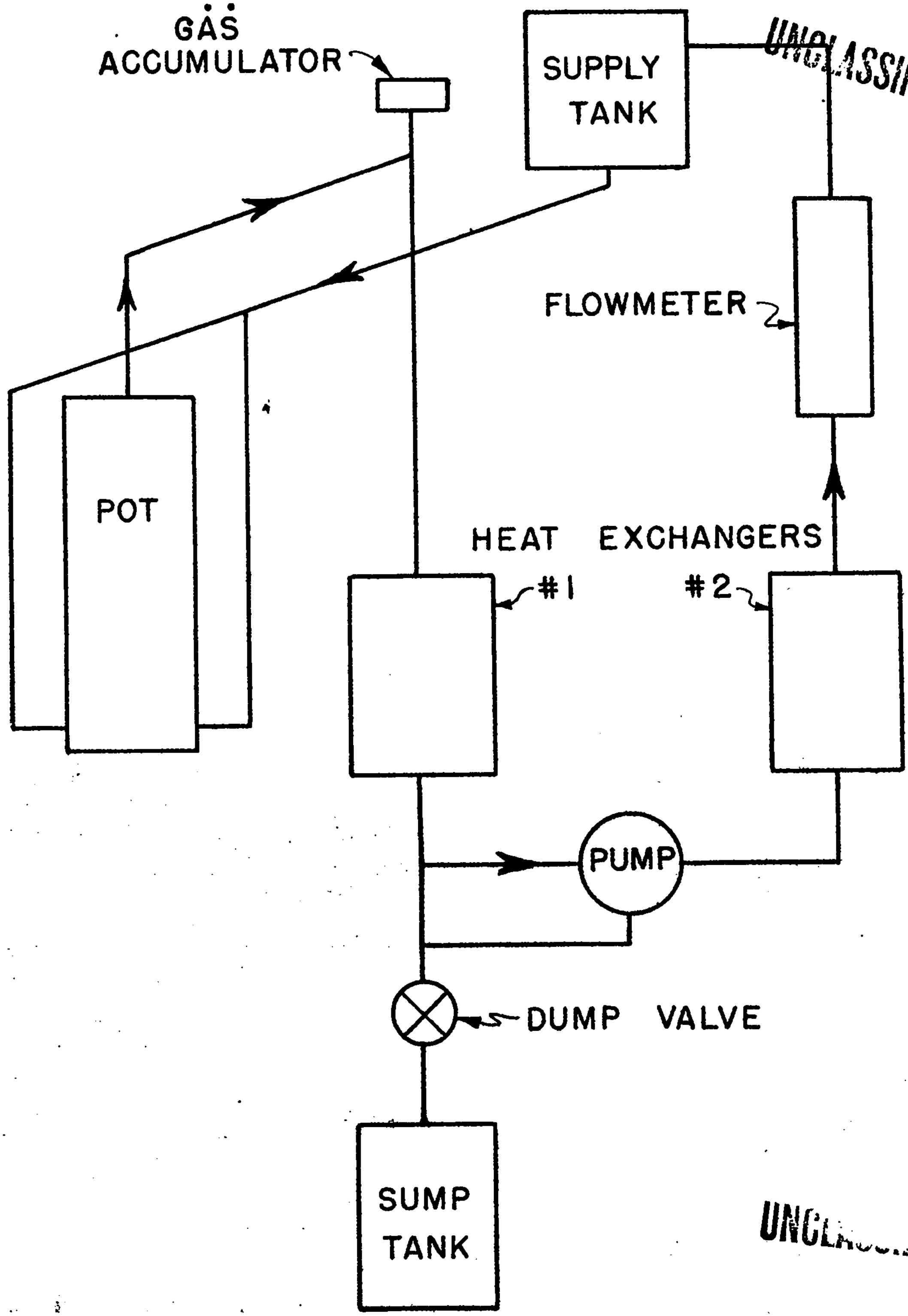

MERCURY FLOW DIAGRAM

FIG 1

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1. Heat Capacities

The heat capacities of the important parts of this system are:

Table I

Part	Material	Specific Heat (cal/gm°C)	Mass	Total Heat Capacity (cal/°C)
Fissionable Material	Pu slugs	0.03	35 slugs @ 450 gm	470
	U slugs	0.03	20 slugs @ 600 gm	360
	U spacers	0.03	55 @ 30 gm	50
Jackets on slugs	Fe	0.1	55 @ 45 gm	250
Mercury in pot	Hg	0.03	9 kg	270
Steel Pot (active region)	Fe	0.1	~ 4.5 kg	550
Squirrel Cage	Fe	0.1	~ 1 kg	
Heat Exchanger	Cu	0.09	~ 500 kg	4.5×10^4

2. Heat Transfers

(a) Pot to Tamper

Measurements with static mercury in the pot indicated that a 5°C temperature difference existed between the pot and tamper for 20 watts of heat (α - power) in the plutonium when no tamper cooling water was circulated.

(b) Heat Exchanger

Preliminary tests at normal flow rates show

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that the Heat Exchanger outlet mercury temperature approaches the outlet water temperature within a few degrees. Most of the gradient occurs across the mercury tube walls.

(c) Slug Gradients

Heat gradients will exist in four regions in a slug: through the plutonium bar, across the gas space, across the steel can wall, and across the mercury film on the outside of the can. An estimation of the heat gradients can be made as follows:

(1) Plutonium bar

The heat flow from a section one cm long is $- kA \frac{dt}{dr}$ where k is the coefficient of thermal conductivity, A is the surface area of the section and dt/dr the temperature gradient. This is equal to the heat present in a volume which varies in radius from r to the maximum radius of the slug r_o. If Q is the number of calories per second in the entire slug of length L, $\frac{Q}{L} \; \frac{r^2}{r_o^2}$ is the number of calories in a 1 cm long section of radius r.

$$- k (2 \pi r_o) \frac{dt}{dr} = \frac{Q}{L} \; \frac{r^2}{r_o^2}$$

and

$$\Delta T = \frac{Q}{4 \pi Lk} \left[1 - \frac{r^2}{r_o^2} \right]$$

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If the heat is considered to be produced where $r = 0$ then

$$\Delta T = \frac{Q}{4 \pi L k}$$

For the proposed loading of 35 slugs and at 10 kw power an average power of 300 watts per slug can be considered. $L = 14$ cm and $k = 0.02$ cal/cm^2/sec/$^\circ$C/cm. $\Delta T \cong 20^\circ C$ = temperature drop across the plutonium.

(2) Gas space

The heat flow across this space can be written

$$- k (2 \pi r) \frac{dt}{dr} = \frac{Q}{L}$$

or

$$\Delta T = \frac{Q}{Lk(2 \pi r)} dr$$

where $dr \sim 0.001$ cm or less and k for helium $= 3 \times 10^{-4}$. $r = 0.82$ cm and $Q = 120$ cal/sec.

$$T \cong 5^\circ C$$

(3) Steel Wall

The preceding equation in section (2) will apply here and for $r = 0.86$ cm, $dr = 0.05$ cm, and k for steel $= 0.1$, $\Delta T \cong 1^\circ C$.

(4) Mercury film coefficient

A simple underestimate of the mercury film transfer coefficient can be made by assuming conduction across a stationary layer 1 mm thick,

$$h = \frac{0.02 \text{ cal/cm}^2\text{/sec/}^\circ\text{C/cm}}{0.1 \text{ cm}} = 0.2 \text{ cal/cm}^2 \text{ sec } ^\circ \text{C}$$

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then

$$\Delta T = \frac{Q}{h\,(2\pi\ r)L} = 8^{\circ}C$$

Measurements at Argonne transmitted by W. H. Zinn give the relation $h = 2400\ V^{0.8}$ BTU/ft^2 $^{\circ}$F hr. In a mercury flow of 3 L/min and for 9 kg mercury present in the pot, the linear flow of mercury by a slug is about 68 cm/min or 134 ft/hr, or

$$h = (2400)\ (50) = 1.2 \times 10^5\ \text{BTU/ft}^2/^{\circ}\text{F/hr}$$

$$= 16\ \text{cal/cm}^2/\text{sec}/^{\circ}\text{C}.$$

Using this film coefficient, $\Delta T \sim 0.1^{\circ}$ C.

The sum of the heat gradients across a slug is

across plutonium	20° C
across gas space	5
across steel wall	1
across Hg film	10 (overestimate)
	35° C

3. Heat Loads

The heat load to be moved during normal operation is assumed to be 10 kw from the fissionable material in the pot, 2 kw from the tamper (appears as heat in the tamper cooling water) and 3 kw from the electromagnetic pump (this appears as heat in the mercury).

The heat load to be removed after a shut-down can be separated into two parts: that due to the delayed neutron fission and that due to heating from β and γ rays from the

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fission products. The curve shown in Fig. 2 indicates the two parts. The heat due to the delayed neutron fission is calculated for a change of k (due to the removal of the safety block and two safety rods) of 2.5 percent.* The instantaneous power drop is calculated from the following: Assume that the reactor is operating at a power level, P_1. When an amount of k is removed by dropping the safety block and rods, the power level falls with the time of the k removal and the delayed neutrons left constitute a new source $(\gamma\ f)P_1$ which, however, is multiplying promptly with a multiplication $1/(1 - k_p)$.

Hence $$P_2 = \frac{P_1(\gamma\ f)}{1 - k_p} = \frac{P_1(\gamma\ f)}{(1-k) + \gamma\ f}$$

If k is changed by 2.5 percent, since $\gamma f = 0.0025$,

$$\frac{P_2}{P_1} = \text{fractional power} = \frac{0.0025}{0.025 + 0.0025} = 0.091.$$

This fractional power then decreases with the decay of the delayed neutrons and can be calculated from the delayed neutron periods.

The heat due to the fission products can be found as follows: The energy release from fission is about 200 Mev of which about 15 Mev is due to γ and β rays from fission

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* Total k removal is now placed at 2.8 percent because of the addition of 2 safety rods made of B^{10} which will fall into the active region of the tamper when the uranium safety or shim rods fall out.

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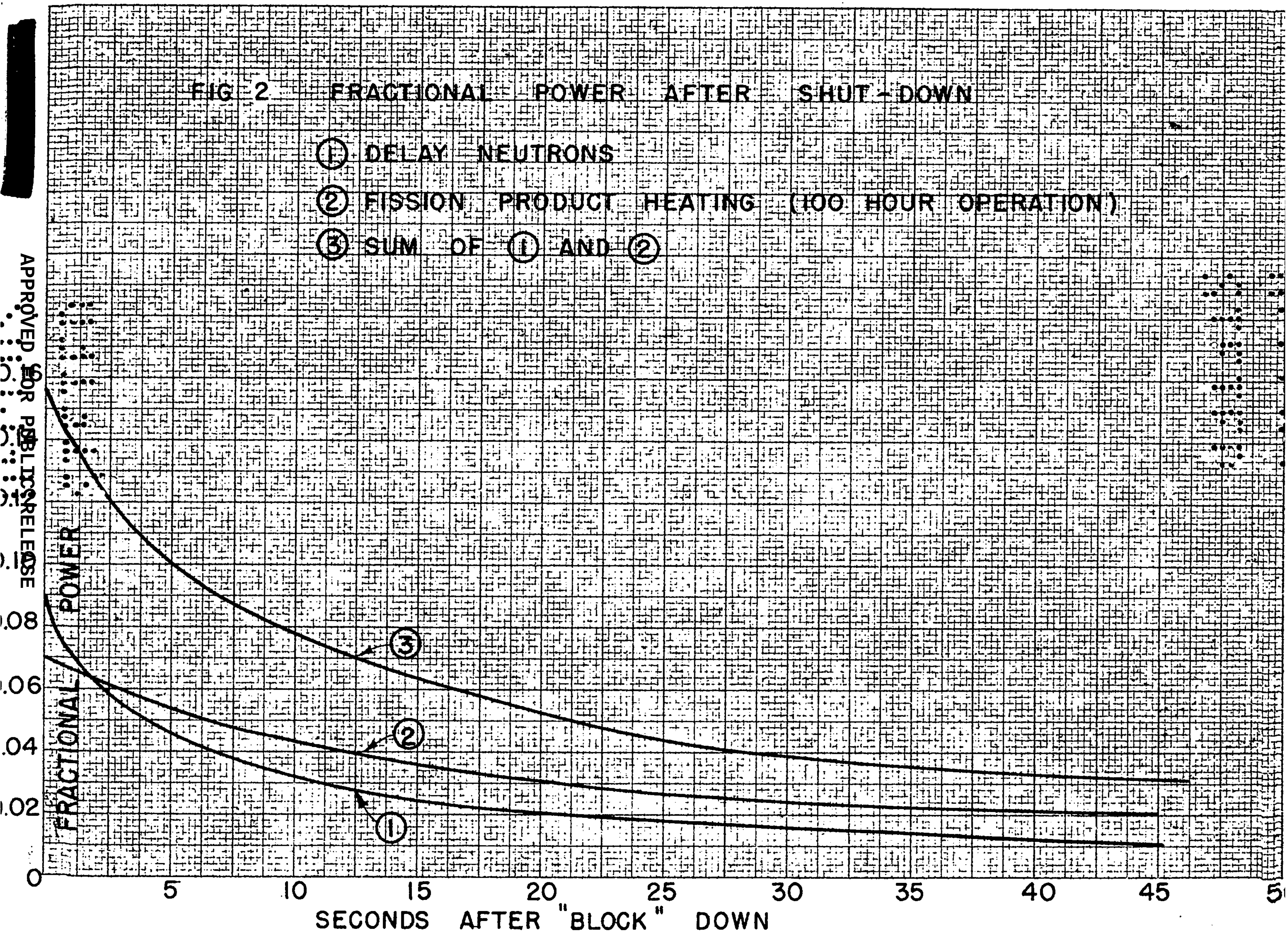

FIG 2 FRACTIONAL POWER AFTER SHUT-DOWN

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products and is delayed heat. It is shown in MonP-147 that if a pile is run at steady power P for a period of M seconds and G(T) is the rate of heat production at time T after shut-down the fraction of the operating power which is still being generated by the fission products T seconds after shut-down is

$$\frac{G(T)}{P} = \frac{2.7}{200} \int_{T}^{T + M} t^{-1.2} dt = 6.7 \times 10^{-2} \left[T^{-0.2} - (T + M)^{-0.2} \right]$$

The curve shown in Fig. 2 has been calculated for 100 hr operation. The smooth curve is the sum of the delayed neutrons and fission product heat decay curves.

4. Flow Rates

Preliminary tests of a complete mock-up of the reactor mercury system have given data upon which the following estimates are made. The connections shown in Fig. 1 are considered and counter flows are used in the two heat exchangers.

Power	10 kw	20 kw
Hg temp. into pot	20°C	20° C
Hg flow	6 L/min	6 L/min
Hg temp. out of pot	75° C	140° C
Pu temperature	110° C	210° C
Water flow	7 L/min	7 L/min
Water temp. into Exch. #1	10°C	10° C
Water temp. out	30°C	50° C

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Power	10 kw	20 kw
Hg temp. out of pot	20°C	20°C
Hg temp. into pump	20°C	20°C
Hg temp. out of pump	37°C	37°C
Water flow	3.5 L/min	3.5 L/min
Water temp. into Exch.#2	10°C	10°C
Water temp. out	∽ 25°C	25°C
Hg temp. out of Exch.#2	20°C	20°C

About 2 kw of heat at 10 kw operation will be developed in the uranium tamper from 25 and 28 fissions. For a temperature rise of about 30°C of the water a flow of one liter per minute will remove the heat.

B. Safety Devices, Interlocks and Indicators

Table II lists the various safety devices and interlocks which will shut down the reactor by causing the safety block and two safety rods to drop. Also listed are measurements which will be indicated by trouble lights and a buzzer. This table does not include all of the measurements which are routinely taken. Many of the measurements are not necessary for safe operation but serve for calibration purposes and are therefore only recorded on a tape or in a log book.

A sequence circuit is incorporated in the operation of the block and rods. The order in which the reactor has to be started is that the safety block must be up before any rods can be moved up, then the safety rods can only be moved one at

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a time, and finally the control rods can be moved one at a time, and one must be up before the other can move. Also, if a rod should accidentally be left in the up position when the reactor is shut off it is impossible to move the safety block up until this rod has been brought down. The speed at which the rods will move up will not exceed 0.1 inch/sec.

Table II

Measurement	Method	Interlock	Trouble Light and Buzzer
Neutron level	25 ion chamber	yes	yes
Neutron level	25 ion chamber Bucking Galv.	yes	yes
Log level and derivative	25 ion chamber	yes	yes
Temp. of central slug	Thermocouple	yes	yes
Hg flow	Magnetic field (pressure difference)	yes	yes
Heat exchanger water flows	Flowmeters	yes	yes
Tamper water flow	Flowmeter	yes	yes
Temp. of pot outlet Hg	Thermocouple	no	yes
Max. temp. of heat exchanger water	Resistance therm.	no	yes
Max. temp. of tamper water	Resistance therm.	no	yes
Three phase windings on Hg pump		no	yes
Level indicators for Hg supply tank		no	yes
Temperature of Hg pump stator		no	yes
Hg drip indicators beneath Hg pump, tank, heat exchanger		no	yes
Water drip indicators beneath heat exchanger		no	yes

[redacted]

It is planned to run the mercury pump from a 50 kw generator. In the event the city power fails the reactor will shut down but the pump will continue and essential circuits will automatically transfer, thereby providing shut down cooling and power level observations.

C. Contamination Problems

Many sources of contamination and health hazards exist around the reactor; and in order to minimize the danger, detecting instruments are incorporated wherever possible to monitor the hazards.

1. Mercury System

The saturated activity of the mercury will be about 100 curies per liter and the system will contain about 17 liters (See Section VII). Small leaks are collected and known by "drip" indicators. Leaks from the pot into the tamper will be detected by a G. E. mercury vapor detector sampling the helium stream which flushes the tamper. A G. M. tube will also detect any radioactive vapor. The tolerance for mercury is 0.1 mg per cubic meter of air. A G.M. tube can detect 10^{-4} tolerance for one count per second. In the event of a large leak--such as a break in the pump (the most probable place)--the mercury will run into a trough which will lead to the lead shielded dump tank.

2. Slug Leak

A leak in a slug will be detected by a neutron

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counter placed near a pot exit mercury pipe. The delayed neutrons from the fission of the plutonium in the mercury will be detected.

3. Water System

The water output of the heat exchanger will be monitored by a G. M. tube to detect the presence of any radioactive mercury in case of a leak in the heat exchanger.

The tamper cooling water will be monitored and will also be sampled and counted at intervals. This water is waste water and should not be allowed to go down Los Alamos Canyon if the activity is above tolerance.

4. Helium System

The helium (which flows slowly through the tamper in the gas seal is released to the atmosphere at the top of the building) will be filtered before releasing and will also be monitored by a G. M. tube in the stack. The relative humidity of the exit helium will also be monitored so that a water leak in the tamper cooling jacket can be detected.

D. Reactor Loading and Floating Operation

The over-all temperature coefficient of the reactor is about -1.1¢/° C measured at 1 watt. The loading of the reactor must therefore contain enough excess k to compensate for this at planned operating temperatures. It is planned to load so that with the two control rods completely out about $2.00 in reactivity is available. Fine adjustments on the

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amount of available reactivity can be made by the step character of the safety rods. One control rod can also be adjusted in weight so that it can control less k.

The over-all temperature coefficient can be separated into the coefficients due to the mercury, plutonium and steel by considering the relative expansion coefficients and subsequent density changes. The temperature coefficient for the plutonium is calculated to be about - 0.3¢/° C if the linear coefficient of expansion is taken to be $+ 5 \times 10^{-6}$. For mercury, the temperature coefficient is about - 0.4¢ and for the steel about - 0.4¢. Recent measurements done at 100 watts give - 0.3¢/° C for Pu and - 0.2¢/° C for mercury. The tamper coefficient was not determined because no tamper temperature change was observed during the experiment.

After the temperature coefficient has been measured at higher powers during the start-up measurements the control rods will be set so that at 10 or 20 kw operation only 5¢ or so of reactivity is left in the control rods and hence the reactor will "float" at this level and cannot rise further in power unless the reactivity is increased by inserting active material while the reactor is operating or by a phase change of the plutonium. The phase change will be discussed later.

III. Normal Operation

A. Start-up

In the discussion which follows it is assumed that

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the reactor is being taken to 10 kw and further that criticality exists with about three inches on one control rod, leaving about 75¢ available in one rod. We examine what happens when the rod is moved in at various speeds in terms of periods and powers existing at various times during the rod motion.

Assume the reactor initially below critical. At critical the neutron level is the number of source neutrons multiplied by the prompt multiplication.

At critical $M_p = \frac{1}{1 - k_p} = \frac{1}{1 - 0.9975} = 400.$

Source neutrons $= 5 \times 10^5$ n/sec, hence the power at the time critical is reached is

$$\frac{(5 \times 10^5)\ 400\ \text{n/sec}}{3\ (3 \times 10^{10})\ \text{n/sec watt}} = 2 \times 10^{-3}\ \text{watts.}$$

In order to reach an operating level of 10^4 watts, the power must rise by a factor of 10^7.

The reactor power equation is $\frac{dP}{dt} = \alpha P$, where $P =$ Power, $\alpha = 1/T$, T is the e-folding time of the power. α is a function of reactivity, which is assumed to increase linearly with time, due to the control rod motion.

$$\ln \frac{P}{P_o} = \int_o^t \alpha\, dt,$$

or, using Simpson's rule for expansion,

$$= \frac{\delta t}{3} \left[\alpha_o + \alpha_n + 4 \sum \alpha_{odd} + 2 \sum \alpha_{even} \right]$$

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where δt is the time interval between successive alphas. α_o is taken to be 0 when the reactor is just critical. α_n is taken to be 2, 1, 0.5, etc., depending on the minimum period permissible.

For convenience we take successive units of reactivity which are added to be 2¢. From the ¢ vs α relation the α sums can be found for additions in reactivity of 2¢ and the $\int \alpha \, dt$ evaluated for different α_n. From this we can find δt, the time between the additions of 2¢ of reactivity or the rod speed necessary to produce the chosen minimum value of T. Table III illustrates this.

Table III

Minimum T (sec)	α_n (sec^{-1})	$\int \alpha \, dt$	$\delta t/2¢$ (sec)	¢/sec	R(¢)
0.5	2.0	$12 \, \delta t$	1.33	1.5	88
1.0	1.08	$7.25 \, \delta t$	2.21	0.9	82
2.0	0.495	$3.94 \, \delta t$	4.06	0.5	72
5.0	0.205	$1.59 \, \delta t$	10.0	0.2	58

Thus, e.g. if the rod is run at a speed of 0.9¢/sec ($\simeq$ 0.1"/sec if the 10" rod ~ $1.00) for 82¢ (about 85 sec) the reactor would be at 10 kw and on a 1 second period. This is not a desirable operation and is merely indicated to show that if the rod were driven in at the highest rod speed possible (and actually farther than it could go since it is planned to

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only leave about 75¢ in the rod) the minimum period would still be only one second and the level and derivative safety circuits would stop the reactor.

Table IV shows the period and power present after times of running the rod, the subsequent power and period at that time, and the time thereafter required to reach 10 kw on the period present. Calculations are made for rod speed of 1¢/sec.

Table IV

Time of rod motion	Distance Beyond Critical	¢ added	Period of end of rod motion (sec)	Power	Time to reach 10 kw (min)
10 sec	1 inch	10	125	1.03 P_o	33
20 sec	2 inches	20	50	1.2 P_o	13
30 sec	3 inches	30	25	1.6 P_o	
40 sec	4 inches	40	13	3.0 P_o	6.5
50 sec	5 inches	50	8	8.1 P_o	2
72 sec	7.2 inches	72	2	$6x10^3$ P_o	15 sec
82 sec	8.2 inches	82	1	10^7 P_o	--

The above indicates that if the derivative safety is set to operate on a 2 second period and only 75¢ is available on a rod and the rod is run all the way up the minimum period will be 2 seconds and the power level will be about 30 watts when the reactor shuts down due to the fast period. 15 seconds would still be available before the power of 10 kw

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is reached if the derivative safety failed to operate. The level safety would then stop the reactor before the power had reached an excessive level.

A typical method of bringing a reactor to power would be to start the rod in at a speed of 1¢ per second, allow it to run for 40 seconds, at which time a 13 second period would be present. If the reactor is then allowed to operate on this period the power would increase as shown below.

Time	Power	Power ($P_o = 2 \times 10^{-3}$ watts)
0	3 P_o	6×10^{-3}
1 min	100 (3 P_o)	0.6 watts

This means that within an elapsed time of about two minutes the reactor power level would be clearly observable, which is a safer condition than if it were brought slowly to about 1 watt over many minutes.

At one minute the rod could be returned to a reactivity of about 20¢ where the period is 50 sec and the power would increase as follows from that time:

Time	Power
0	0.6 watts
1	2 watts
2	7 watts
5	240 watts

After 5 minutes the reactivity could be reduced to a slow period and 10 kw approached very slowly.

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The above discussion neglects the effects of the increase of the prompt multiplication due to the increasing reactivity.

$$M_p = \frac{1}{(1 - kp)} \quad \text{and} \quad M_p = \frac{1}{1 - (kp_o + \frac{\delta k}{\delta t}\, t)} = \frac{1}{1 - (kp_o + \frac{k}{¢} \cdot \frac{¢}{sec} \cdot sec)}$$

$$= \frac{1}{(1 - kp_o) - \left[\frac{\gamma f}{100} \cdot (\text{Rod Speed}) \cdot (\text{Time})\right]}$$

where kp_o is the prompt multiplication at critical = 0.9975 and $\frac{\gamma f}{100} = 2.5 \times 10^{-5}\ \frac{\text{k units}}{¢}$.

If this effect is included in a step-fashion in the power vs. time curve for a rod speed of 1¢/sec the following power rise is obtained:

Time	Power
0 inches	2.0×10^{-3} watts
10	2.3×10^{-3}
20	3.2×10^{-3}
30	4.8×10^{-3}
50	3.4×10^{-2}
70	10 watts
80	20 kw

The effect of including the prompt multiplication change is, of course, a higher power level than is calculated neglecting the prompt multiplication but the period remains

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the same. The power level reached at the maximum rod speed is not excessive, even so and no serious trouble would result even if this should accidentally occur through operator negligence.

The effect of the negative temperature coefficient is very small since the value for the plutonium coefficient (assuming instantaneous heating) is only about $-\frac{0.1¢}{\text{sec}}$ per kilowatt. The effect of the total temperature coefficient which is about $-\frac{0.3¢}{\text{sec}}$ per kilowatt will only be important after times necessary for heating of the entire assembly (material, cage and mercury). It could therefore have little effect on constant and moderate motion of a control rod.

B. Equilibrium Operation at 10 kw

The equilibrium temperatures and flows will be somewhat as shown in Section II-A-4.

C. Normal Shut-down

The normal reactor shut-down consists in dropping the safety block and two safety rods and allowing the mercury to circulate for a given time. The required circulation time can be estimated from the following considerations.

The instantaneous power = 10 kw = 2.4×10^3 cal/sec. (Assume that the time required for the safety block and rods to drop out is about 0.1 sec. This is an over-estimate, but will be used as a pessimistic value.) The shut-down power in the mercury will be due to fission from delayed neutrons, β and γ

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rays from fission products and the heat put in by the mercury pump. Shut-down in k due to the removal of the block and rods is about 2.5 percent, which brings the fission power to about 9 percent of its initial value (See II-A-3). The β and γ rays will contribute about 7 percent of the initial power (for 100 hour operation). Hence, the power given to the mercury from the reactor 0.1 second after shut-down signal is about 16 percent of the initial value. Thereafter the power diminishes slowly with the decay of the delayed neutrons and the fission products (See Fig. 2). In about one minute the power is about 3 percent (300 watts) of its initial value and the reactor is supplying only about 6 percent of the total heat load.

Assuming 60° rise in mercury temperature flowing through the pot, the mercury removes heat from the pot at the rate of about

$$\frac{2.4 \times 10^{3}\ \text{cal}}{60^{\circ}\ \text{C sec}} = 40\ \text{cal}/^{\circ}\ \text{C sec.}$$

Since the heat source decays to about 300 watts in one minute, within a few minutes the plutonium temperature is only about 2° C above the mercury temperature entering the pot. [At 1 minute Power = (0.03) (2.4×10^{3}) = 72 cal/sec. If mercury removes heat at rate of 40 cal/° C a 2° C temperature difference will exist.]

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At this point the pump could be shut off. The mercury and plutonium now contain a slowly decreasing heat source of about 30 cal/sec (Power at end of 5 minutes ~ 100 watts) which would cause the materials to increase in temperature at about 1° C/min if it were not for the tamper surrounding. Measurements made with static mercury at 100 watts operation showed an essentially equilibrium plutonium temperature of 37° C, a mercury temperature of 31° C, and a temperature increase of 0.4° C/min when the power rises from 0 - 100 watts. Shut-down at 100 watts indicated a cooling of about 0.1° C/min. The heat transfer to the tamper as measured from the α power indicates that for 100 watts a temperature difference of about 20° C will exist between pot and tamper. Hence, the mercury and plutonium temperature will slowly fall to about 50° C. Convective cooling will play a small role because of the particular design of the circulating system. Fig. 3 illustrates the expected cooling curve during normal shut-down.

IV. System Failure

A. Power Outage

As mentioned before, it is planned to operate the mercury pump from a 50 kw Diesel generator. In event of generator failure the load is automatically switched to city power. If the city power fails the reactor will shut-down but the mercury will remain circulating to provide shut-down cooling.

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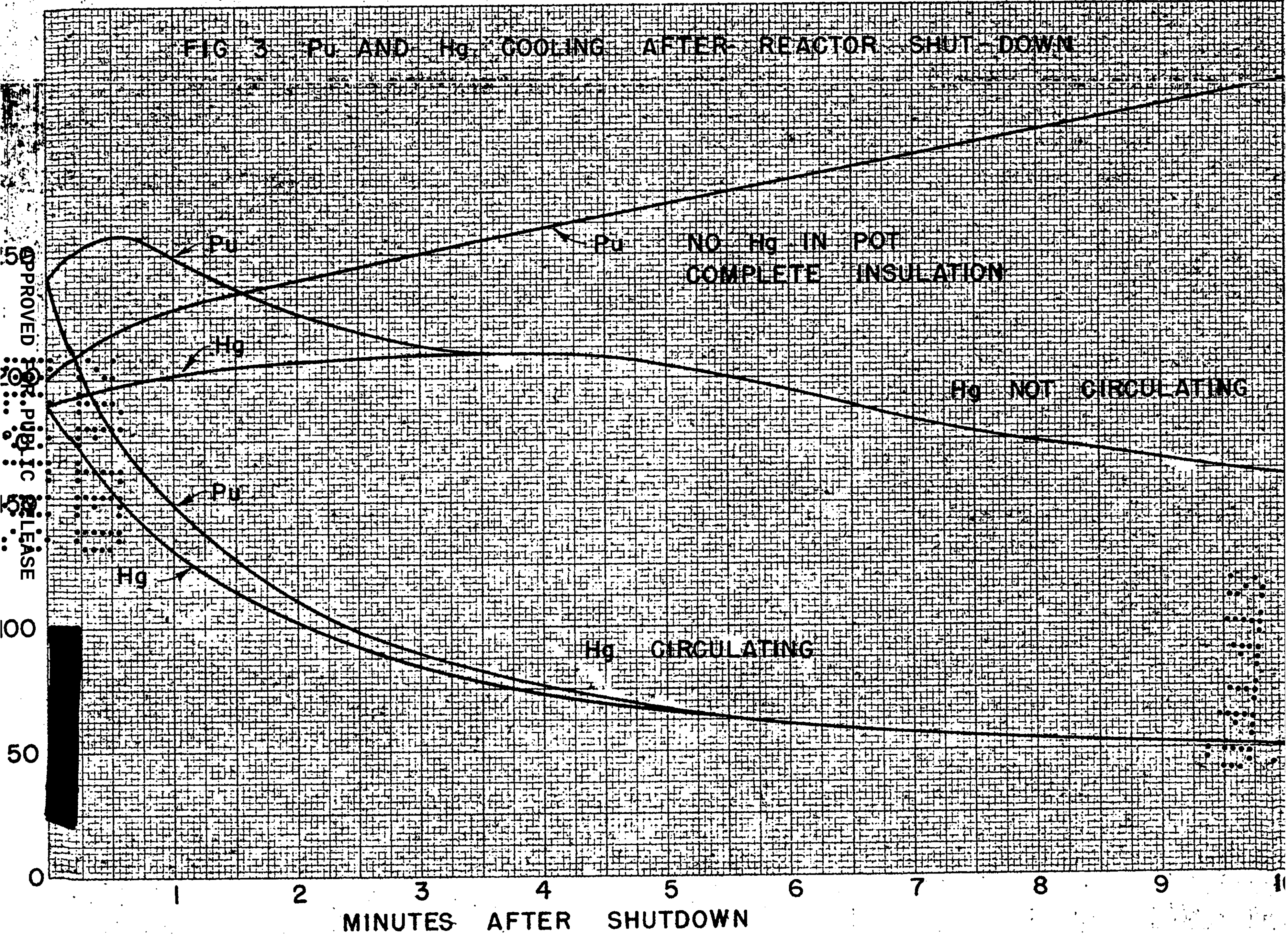
FIG 3 Pu AND Hg COOLING AFTER REACTOR SHUT-DOWN



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B. Mercury Stoppage

The flow of mercury can be accidentally stopped in three ways, power failure, pump winding burn out or leak in the system. If the Diesel power and city power fail simultaneously the mercury flow will stop but the city power failure will also shut down the reactor. The three-phase mercury pump winding has a relay in each leg which is connected to a trouble light. If a winding should burn out a trouble light will go on and a buzzer will sound. The operator will then recognize the trouble and can stop the reactor. Since the pump will operate on one or two phases and since it is rather improbable that all three windings would burn out simultaneously it is not necessary to interlock the pump windings with the safety circuits. Interlocked with the safety circuits are, however, the mercury flow and pot outlet mercury temperature. A large leak or stoppage in the system will cause the flow to decrease and the reactor to stop by means of the interlock system. A small leak in the pump, heat exchanger or supply tank will be known by means of trouble lights and buzzer through "drip" indicators. If a stoppage occurs the mercury temperature will rise beyond the interlock value and the reactor will stop.

It seems impossible in view of the safety circuits and interlocks to have the mercury flow stop without a reactor shut-down.

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The temperatures which would result from the above general condition, namely, simultaneous shut-down of the reactor and stoppage of the mercury flow can be roughly estimated as follows.

If we assume that the safety block and rods drop out in about 0.4 sec, which is a large over-estimate, the total heat produced as an average during the shut-down time is

$(2.4 \times 10^3)\ (0.4)\ (0.58) = 560$ calories where the factor 0.58 is the shut-down fraction at 0.2 sec. In the 0.6 second after the completion of shut-down the total heat produced is

$$(2.4 \times 10^3)\ (0.16)\ (0.6) = 230 \text{ calories.}$$

Hence, about 800 calories are produced in the first second.

The heat capacities of the fissionable material are (Table I):

35 Pu slugs = 470 cal/° C

$$\left.\begin{array}{l} 20 \text{ U slugs} = 90 \\ 55 \text{ U slugs} = \underline{10} \end{array}\right\}$$

570 cal/° C

We use 1/4 of the total heat capacities to account for the relative number of fissions occurring in uranium.

Thus the plutonium temperature will rise $\frac{800}{570}\ ^\circ\text{C} = 1.4^\circ$ C in the first second, assuming no cooling to the mercury in that time.

Table V is a compilation of rough estimates of the temperature rise of the plutonium after beginning of the shut-down.

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Table V

Time after shut-down	(P/Po)Av.	$\frac{\text{Cal}}{\text{sec}}$	Material	(CpM) cal/°C	°C/sec	Δ °C
0 - 0.4 sec	0.58	1.39×10^4	Pu	600	2.3	0.9
0.4 - 1	0.16	380	Pu	600	0.6	0.4
1 - 30	0.10	240	Pu	600	0.4	12.0
30 sec - 1 min	∽ 0.04	96	Pu, Hg, Fe	2000	0.05	1.5
1 min - 3 min	∽ 0.04	96	Pu, Hg, Fe	2000	0.05	6.0
3 min - 1 hour	∽ 0.02	48	Pu, Hg, Fe Tamper	5000	0.01	~ 30
1 hour						~ 50°C

Since 20 watt α heating produces ΔT of 5° C in pot over tamper, the shut-down power of 200 watts would establish a ΔT of about 50° C, which would slowly decay over a period of hours.

With flow stoppage and reactor shut-down the most likely events would therefore be:

1. Plutonium: A rapid rise of about 15° C in the first thirty seconds, followed by cooling to the mercury temperature, since the mercury is intially 50° C lower in temperature. We here assume that no cooling to the mercury results in the first thirty seconds.

2. Mercury: Moderate increase of temperature due to the plutonium heat source. At the end of one minute the mercury temperature will rise about 6° C and will then rise to a value which will be near the equilibrium temperature that would result from putting the plutonium slugs at 240° C into the mercury mass at 190° C. This will be followed by a slow

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decline to about 30° C above the tamper temperature.

3. Tamper: A small increase in temperature which will have long cooling characteristics will result.

Fig. 3 illustrates the expected temperature behavior.

C. <u>Water Stoppage</u>

In this event the interlocks on the water flow will cause a shut-down. The increase of mercury temperature due to lack of cooling water would also cause a shut-down in time. The large heat capacity (4.5×10^4 cal/° C) of the copper heat exchanger will limit the temperature rise to about 5° C/min at full power. It seems unnecessary to interlock the mercury pump with the water supply since the pump can be shut off manually before a high mercury temperature is reached.

D. <u>Loss of Mercury from the Reactor Pot</u>

In the event of a break in the connections, piping, pump, etc. of the mercury system the reactor pot will not drain (Fig. 1). Loss of mercury through such an accident will cause a reactor shut-down because of the mercury flow interlocks. The mercury left in the pot will allow some shut-down cooling and has been discussed in IV-B.

One way for mercury to leave the reactor pot is in the event that the weld which is at the bottom of the pot develops a crack. Mercury could leave through this crack rather slowly because this bottom is supported, a tight fit exists between the bottom and the side of the pot and between the pot and the tamper in which it is contained. Because the weld

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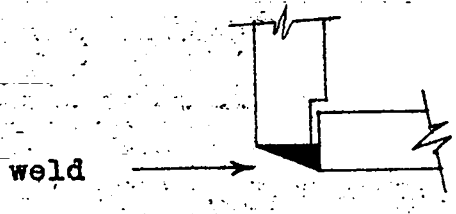
is made as shown the leakage would be very slow and the reactor



would be shut-down because of the level indicators long before the mercury had left the pot.

Another way for mercury to leave the pot is if the 0.25 inch bottom plate of the pot should open in the center region where it is not supported. (The 6 inch diameter pot sits on a one inch wide rim: the safety block rises against the pot through the resulting 4 inch diameter hole).

It seems highly unlikely that such events could occur. As the most unpleasant case that can be imagined consider that all the mercury in the pot suddenly escapes when the reactor is operating at 20 kw. Because the mercury has a positive effect equivalent to about 2 plutonium slugs, the loss from the pot will shut off the reactor. The 35 slugs remaining are no longer in a cooling medium. We examine what happens to the temperature of the slugs assuming no air convective or steel conduction cooling from the slug but complete insulation.

Assume that the plutonium was operating at 200°C at 20 kw. Further assume that the mercury is gone by the time the reactor is completely shut-off. The fractional power after shut-down is 0.16 (Fig. 2). If the fractional power decay curve is used and the total heat capacity of the fissionable material is taken to be 370 cal/°C the temperature of the material will rise as shown below:

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t	fractional power	average Heat Production (cal)	Δ° C	°C(T_o = 200°C)
0	0.16	- - - -	- - -	200°C
10"	0.08	5,700	~ 10°	210°C
20"	0.05	3,100	5.5	215.5
30"	0.04	2,200	4.0	219.5
40"	0.03	1,700	3.0	222.5
50"	0.03	1,400	2.5	225
60"	0.03	1,400	2.5	227.5

An over-estimate will be to now consider that the temperature rise is constant at the rate of about 12° C per minute. For the plutonium to rise to 600° C (the melting point) a time of about 30 minutes is required. Because this considers no heat convection or conduction or a decrease in the rise of temperature the time is underestimated. In 30 minutes it would be possible to open the outlet mercury line in the mercury chamber and blow helium through the pot to provide additional cooling.

V. Slow Changes

A. Slug Heating

The temperature of the central plutonium slug will be monitored and because the neutron distribution is essentially uniform in the peripheral loading to be used this temperature will be indicative of the other slug temperatures. It is

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possible, however, to have one or more slugs increase in temperature due, perhaps, to a clogging of the holes through which the mercury circulates. Assume one slug increasing in temperature. The plutonium temperature coefficient of -0.3¢/°C for 35 slugs means that one slug ~ 0.01¢/° C. If the slug is initially at 200° C (20 kw operation) and the reactivity is decreasing at the rate of 0.01¢/° C by the time the slug temperature has reached 400° C 2¢ of reactivity will have been lost. At 400° C, if a phase change should occur the reactivity will increase by 5¢ (see Section VI), making a net gain of 3¢. This net gain corresponds to a period of 500 seconds, or in terms of rod motion the control rod would have to be changed by 0.3 inch to maintain the critical operation. Thus, this condition of one slug increasing in temperature through a phase transition temperature would be known by having to move the rod in about 0.2 inch and then later having to move the rod out about 0.3 inch. These changes are relatively large and easily observable and would indicate the necessity for shutting off the reactor. If several slugs should be affected in this way the reactivity changes would be even more noticeable.

It seems very difficult to get this high temperature gradient, however, because of the heat flow paths even with several holes clogging (diameter of mercury entrance hole = 0.1" and the closest spacing between slugs = 0.05"). To minimize any clogging the mercury is filtered through wire mesh at the exit of the supply tank and at the entrance to the pot.

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B. Structural Changes

1. Blistering of Slugs

Hanford operation indicates that a blistering of the slugs begins when 1 atom in 3000 total atoms has fissioned. At the reactor operation of 10 kw about 7×10^{-12} fissions per atom per second occur.

$$\frac{(10^4 \text{ watts})\left(3 \times 10^{10}\ \frac{\text{fissions}}{\text{sec watt}}\right)}{\frac{6 \times 10^{23}}{240}\ \frac{\text{atoms}}{\text{gm}}\ (17 \times 10^3 \text{ gm})} = 7 \times 10^{-12}\ \frac{\text{fissions}}{\text{sec atom}}$$

For 1/3000 fissions/atom about 5×10^7 seconds are required. This time is equivalent to about 5 years of normal operation.

The central slug can be examined at infrequent intervals if necessary in order to check on the presence of any blistering which if present might impede the mercury flow and produce local heating.

2. Miscellaneous

The safety block and rods might likewise have blisters induced on the surfaces. These would take longer to appear than in the slug case because of the lower flux in which they are situated. It is not expected that this will cause trouble during the reactor's life-time.

The accumulation of fission products in the slugs should produce no reactivity or structural changes at the planned operation. The effect of neutron and γ radiation on the structural materials used (steel, e.g.) is expected to be unnoticeable.

VI. Phase Changes

Since the plutonium is stabilized in delta phase, which

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has the lowest density of all known phases, any phase change will increase the reactivity. This effect has been measured by inserting a slug of alpha phase material of the same mass as the delta phase in various regions of the active material and observing the reactivity increase. In the central position a density increase of one slug of 4 gm/cm^3(15.8 - 19.8 gm/cm^3) corresponds to a 30¢ increase in reactivity. At the extreme edge of the active material the value is 20¢. On this basis 35 slugs @ 30¢ per slug changing to alpha phase will increase the reactivity by $10.50. The reactor control is about $12.00. (Safety Block = 5.30, 2 Uranium Safetys = 3.20, 2 B^{10} Safetys = 3.40*, Total = $11.90.)

Even though it is thought that the most serious of all phase changes can be controlled the following possibilities are discussed.

A. Delta to Epsilon

In a change to epsilon phase through a sudden high increase of temperature, the normal operating temperature of the Pu will be about 200° C (20 kw). The transition temperature to epsilon phase occurs at 400° C. A sudden increase of about 200° C is therefore required. It has been demonstrated that this is probably impossible through failure of the mercury cooling system or through power failure. The remaining possibility

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*Recent experiments have indicated that about 300 gm B^{10} in the safety rod position in the tamper is equivalent to $1.70 decrease in reactivity. A 3kgm uranium rod in this position is equivalent to $1.60 increase. The B^{10} safety rod has been incorporated in the design such that where the uranium safety falls out of position, the B^{10} falls in. The control is thereby increased by $3.40.

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appears to be an accidental "flashing" of the pile. It will be shown in Section VI-C that this has very small probability and could require a complete, not-recognized, deliberate reorganization of the control and safety circuits. A transition of 35 slugs from delta to epsilon is equivalent to about $2.00.

B. Change from Delta to Alpha, Beta or Gamma Phase

These phases occur at lower temperatures than the delta to epsilon phase. Approximately, the alpha phase exists to about 100° C, the beta between 100° and 200° C, the gamma between 200° and 300° C, and the delta between 300° and 400° C. The Pu will normally operate in the temperature range where the beta or gamma phase is present in unstabilized material. The possibility of a slug changing to gamma phase during operation seems small, but if this should occur the slug which has changed to the more dense (16.8 gm/cm^3) and hence more reactive phase will immediately cause an increase in pile reactivity by about 8¢. This is equivalent to a period of about 3 minutes, which would be observable and which would also cause a shut-down of the reactor by the level safety.

The change to beta or alpha is probably impossible during normal operation because of the operating temperature of the reactor and no evidence exists which would indicate the possibility of a phase change of all rods to any phase during

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shut-down. If, however, a mechanism exists for a transition to alpha or beta phase during shut-down this is credible only on the basis of individual rods since the history of any two rods is not identical. Thus, one rod at a time would change phase with consequent increase in reactivity. One rod changing to alpha phase is worth about 30¢ in reactivity and since the block and rods together equal about $12.00, criticality would not be reached even if all rods changed to alpha.

C. Pile Flash

We wish to examine methods in which the reactivity can be raised so rapidly that the increased power will heat the Pu alone and thus produce delta to epsilon phase change. The temperature coefficient due to the Pu is only a third of the overall temperature coefficient so will have a smaller negative effect on the reactivity. The heating must be so rapid that the plutonium temperature will exceed the delta to epsilon transition temperature before δk is used up by the overall temperature coefficient.

1. Reactor at Low Power

Assume the Pu temperature is about 100°C and that the heating is rapid enough so that there is no heat flow to the mercury. Then $\Delta T = 300° C$ and assume that in 10 seconds there is no heat flow. Since the total heat capacity of the fissionable material is about 600 cal/° C,

(600) (300) (4.2) = 7.6×10^5 watt sec, and if the time in

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which this power must be injected is about 10 seconds, about 7×10^4 or 10^5 watts must be available. If the initial power is e.g. ~ 0.1 watt the power must rise by a factor of $P/P_o = 10^6$ to cause this rise in temperature, or $e^{\alpha t} = 10^6$ and $\alpha t = 14$. Hence $T = 1/1.4 = 0.7$ sec period ≅ 85¢. Hence to produce this power rise a reactivity change of 85¢ in 10 seconds or approximately 8.5¢ per second must be made. The maximum rod travel is 0.1 inch per second = 1¢ per second. The safety block is worth about $6.00 and moves at the rate of 0.07"/sec = 14¢/sec. If the reactor could be made critical with the safety block down and if the safety block were then raised completely into position the above condition could result. The sequence circuit described in II-B prohibits this.

2. Reactor at High Power

Assume reactor at 20 kw and slugs at 200° C. Then $\Delta T = 200^\circ$ C and $\frac{(600)\,(200)\,(4.2)}{10} = 5 \times 10^4$ watts. If this power is to be added to the rods in 10 seconds the power must rise $P/P_o \sim 5 \times 10^4$ or $T = 0.9" \sim 82¢$. The above arguments again apply. Further, the level safety would stop the reactor in about 0.6 second (level set at 40 kw) and at full power operation this amount of excess reactivity will not be available.

VII. Experiments

Experiments have been performed on the reactor to examine the operating characteristics. To date, the power level

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has not exceeded 100 watts and no circulating mercury has been used.

Some of the investigations which have been made are:

1. Temperature coefficient at 1 watt and at 100 watts. (At 1 watt overall coefficient = -1.1¢/°C; at 100 watts Pu = -0.3¢/° C, Hg = -0.2¢/° C.)

2. Power versus temperature of Pu and Hg (Hg not circulating). At 1 watt $T_{Pu} = 25°$ C, $T_{Hg} = 23°$ C. At 100 watts $T_{Pu} = 37°$ C, $T_{Hg} = 31°$ C. (Essentially equilibrium temperatures.)

3. Plutonium and mercury cooling after reactor shutdown (no circulation). After 1 hour operation at 100 watts Hg and Pu cool about 0.1° C/minute.

4. Effect of alpha phase plutonium upon reactivity. (See text.)

5. Use of B^{10} as a control rod. (See text.)

6. Activity of mercury:

An exposure of 1.5 hours of a mercury sample gave one activity of 43 minutes half-life. The calculated cross section for this reaction is about 10 millibarns. The activity caused by the this activation only will be about 40 curies per liter of mercury. The system contains about 17 liters. Longer-lived activities will be built up during operation which will

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further increase the curies per liter figure to a calculated value of about 100 curies per liter.

7. Neutron distribution in reactor pot (peripheral loading).

Distance from Center	Rel. Activity
0.0 inches	1.00
1.875	1.095
2.125	1.055
2.44	1.04
2.56	0.975
	1.03_3 per slug average

The distribution appears to be fairly constant in the reactor pot.

8. Effects of filling experimental holes with uranium.

This was done as a safety measure in order to know how much the reactivity would be increased if all the experimental holes were filled with uranium. Filling 9 vertical holes, 4 tangential and 3 central holes could result in about 80¢ reactivity increase. One slug of plutonium in a tangential hole is equivalent to only 55¢. This is as close in the tamper as one can get plutonium to the active material region.

9. Shielding Measurements.

Reactor

Preliminary measurements indicate the following decrease of neutrons in the shield.

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Distance		
0	Center	1.0
3"	Edge of pot	0.5
9"	6" Tu	0.16
15"	6" steel	0.07
19"	4" Pb	0.04
49"	30" laminated shield	4×10^{-10}
67"	18" concrete	1×10^{-12}

Thermal Column

The face of the thermal column is covered with 2.25 inches of boron plastic, 0.040 inch cadmium sheet and 8 inches of lead. The flux at the face of the column is about 5×10^{8} for 20 kw operation. 2.25 inches of the plastic causes a reduction of 10^{6}. The shielding appears adequate.

Reactor power start-up will consist, in part, in the measurement of the following:

1. Temperature coefficient.
2. Power versus control rod speed at very low powers.
3. Temperature gradient across a slug at various powers.
4. Temperature gradient from pot to tamper after shut-down.
5. Power versus temperatures with no mercury circulation.
6. Plutonium and mercury cooling at low powers after reactor shut-down (with and without mercury circulating).
7. Power decay after shut-down.

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VIII. Conclusions

Because the reactor has not been operated above 100 watts speculation about its characteristics at higher powers is difficult. We have, in this discussion, tried to examine all dangerous conditions which might arise during operation and where definite information was not available have over-estimated the expected trouble. It is believed that all dangerous conditions have been considered and the probability of occurrence minimized through the safety circuits, warning indicators, and the plans of operation. The experimental information which has been obtained has served to confirm this belief. It is planned to operate the reactor for several months at low power (100 watts) without mercury circulating in order to obtain information which is considered useful to other reactor groups as well as to ourselves. During this low power operation more observations of the reactor behavior will, of course, also be made.

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