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THE RESPONSE OF A WATER BOILER REACTOR TO VERY FAST POWER TRANSIENTS AND LINEARLY INCREASING REACTIVITY INPUTS* **

by

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I. INTRODUCTION

This paper is a report of the KEWB or Kinetic Experiment on Water Boiler Program being conducted by Atomics International for the Atomic Energy Commission.

The purpose of this program is to examine the dynamic behavior of homogeneous research reactors to obtain the information necessary for the evaluation of the nuclear safety of such reactors.

Step inputs of reactivity have been systematically increased and the first test core, which is a spherical core designed for stable power operation of 50 kw, has been examined under conditions of 4 percent reactivity release. This is the maximum normally installed in such reactors. A 4 percent reactivity release places the reactor on a 2 millisecond stable period and leads to a peak power of 530 Mw. This represents the fastest

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intentional power excursion of any thermal reactor. The reactivity release is more than twice that which any other reactor has withstood without damage. The maximum pressure seen in the system for this transient was a sharp pressure peak of 370 psia. This pressure is well below that required to cause yield of a typical water boiler core.

The experimental facility used for these experiments has been described in detail in previous reports but a brief description will be given here for those who are not familiar with the program. See Figure I.

The core of the reactor is a 12¼-inch inside diameter stainless steel sphere with a minimum wall thickness of 0.22 inches. The sphere contains 11.5 liters of enriched uranyl sulphate solution in a core volume of 13.6 liters. The core is surrounded by a graphite cube 56 inches on a side which serves as a reflector. Normal operation is controlled by four vertical control rods which enter the core in re-entrant thimbles and control about 7 percent reactivity. Cooling of the fuel solution is accomplished by 90 feet of 1/4-inch stainless steel coils placed in the spherical part of the core vessel. Transients are initiated by the rapid withdrawal of a large diameter poison rod from the central exposure tube.

During the transient tests information is obtained on neutron level, core pressure and core temperature and the data is recorded on a multi-channel recording oscillograph. The power or neutron level during an excursion is measured by neutron sensitive ionization chambers which drive groups of three linear recording channels whose sensitivities are adjusted so as to give a record of the last three decades of the power peak. Two such systems are used. Core temperature is recorded by thermocouples placed in contact with the fuel solution. Transient pressures are measured by two pressure transducers placed in the core vessel. One of these is placed in the gas phase one inch above the normal fuel level and the other is in contact with the fuel solution at the bottom of the core. A third transducer of the same type is placed in the graphite reflector near the outside surface of the core vessel to determine the sensitivity of these transducers to high radiation fields. Signals generated by these transducers are amplified and recorded by galvanometers whose response is flat to at least 3 kc.

The core is designed with an overflow chamber into which fuel solution is displaced during the larger transients. This fuel then drains back to the core proper through a 1/8-inch hole in the bottom of this chamber. It has been observed that transients with stable periods shorter than 30 milliseconds displace fuel solution to the overflow chamber. A 2 millisecond transient displaces 1.3 liters of solution which requires 2 minutes to drain back to the core.

II. EXPERIMENTAL DATA FOR STEP INPUTS

Figure II shows a portion of a typical oscillograph record taken of a transient. This particular record represents a transient with a 2 millisecond stable period. To establish the time scale for this record the vertical lines represent 10 millisecond intervals. The transient was run with an initial core temperature of 25°C and an initial core pressure of 15 cm Hg.

The three lower traces were produced by one of the linear power recording systems. The most sensitive channel has been electronically clipped at about 3 inches deflection to prevent the DC amplifier used to drive the galvanometer from becoming saturated. This enables the channel to record the power decay in the system as well as the power rise. Saturation of these amplifiers makes them inoperative for several seconds and would thus cause the system to miss the power decay. Period information for the transient is taken from the most sensitive and from the mid-sensitive channels. Peak power is taken from the least sensitive channel and for this case was 530 Mw. One can see from the trace that the power rise is deviating from an exponential during this last decade of power increase. The power rise for the last three decades of the burst takes place in less than 20 milliseconds.

The temperature trace here indicates that the temperature rise in the system is seen as a step by the thermocouples being used. For this run the couple used had a response time of 55 milliseconds. We now have installed in the system two thermocouples with 20 millisecond response times. These are still not fast enough for the very fast transients but are responsive enough to cover a wide range of the slower transient runs. These thermocouples are readily fabricated and are stainless steel clad to make them corrosion resistant and mechanically stable. Work is being conducted to develop a faster couple with these same characteristics.

Transient pressure data are recorded on the two upper traces. The third trace is the control transducer that is located in the graphite. As you see, a slight negative false pressure is recorded by this transducer. This corresponds to 3 psi for the fastest transient run. This is to be compared with over 300 psi pressures being recorded by the transducers actually in use in the core.

The first pressure pulse is seen by the transducer which is in the bottom of the core. This is a rather broad pulse with a maximum of 145 psi. Its maximum occurs 0.6 millisecond after the peak power. The next pressure pulse (170 psi) appears at the top of the sphere 1.9 milliseconds after peak power. 2.0 milliseconds later we see the maximum pressure recorded for this run. It is a sharply defined peak of 370 psi at the top of the core. This is followed by a fourth maximum of 230 psi at the bottom of the core, which occurs 9 milliseconds after peak power.

The first pressure increase in the system is due to the buildup of inertial pressure in the fuel solution due to the rapid evolution of radiolytic hydrogen and oxygen. The first sharp pulse seen at the top of the core is believed to result from the fuel solution surface slapping the transducer as fuel is being expelled to the overflow chamber. The two latter sharp pulses may be due to reflections in the system.

It is interesting to note that peak power has been experienced before the first pressure maximum is seen on the top transducer. This indicates that the shutdown mechanism responsible for the rapid shutdown of the reactor acts before the fuel solution level has raised the one inch necessary to strike the top transducer. This rapid shutdown is due to the negative reactivity effect of small hydrogen and oxygen bubbles formed by the radiolytic decomposition of water.

The remaining trace is that of a logarithmic power channel which was used for slower transients. As it can be seen here it does not respond fast enough to be useful for fast transient work.

Figure III is a plot of the inhour equation used for this reactor. Prompt critical is assumed to occur at 0.8 percent which corresponds to a stable period of 150 milliseconds. In the region of 4 percent reactivity it may be seen that it requires large changes in reactivity to give small changes in the stable period. The release of 4 percent corresponds to a stable period of 2 milliseconds whereas it would require the release of 7 percent to give a stable period of 1 millisecond.

Peak power as a function of stable period or reactivity release for three initial core pressures is shown in Figure IV. All these data were taken at an initial core temperature of 25°C. The lower curve is for an initial core pressure of 15 cm Hg and is the only one which has been carried to the 2 millisecond limit. The upper curves are for initial core pressure of 43 and 71 cm Hg respectively. These have been examined down to 4 millisecond periods. These higher pressure starts lead to peak powers that are higher by about 50 percent at 4 milliseconds. At longer periods, down to 80 milliseconds, the peak power remains higher in the transients with the higher initial core pressures. At about 80 milliseconds the three curves converge indicating very little pressure effect. For periods shorter than 80 milliseconds the higher pressure runs again give higher peak powers.

The effect of initial core temperature has been investigated at lower reactivity releases and shows that higher starting temperatures lead to lower peak powers.

Some of the power traces have been integrated to give energy released in the first burst. Figure V shows energy release in the first burst as a function of reactor period. These data were all obtained with an initial core pressure of 15 cm Hg and initial core temperature of 25°C. The energy release in this first burst is seen to increase with decreasing stable period. The energy release for a 2 millisecond transient is, however, still less than 4 Megawatt-seconds.

One of the parameters of chief interest to a safety program of this type is the maximum pressure experienced by the system during transients.

Figure VI shows the peak pressures as a function of stable period. The upper curve is the maximum pressure observed during each transient. This is the first peak on the top transducer for periods down to about 4 milliseconds. At this point the second peak on this transducer becomes larger and remains so down to 2 milliseconds.

The lower curve is the inertial pressure peak seen at the bottom of the core. This pressure pulse is always smaller and broader than the maxima observed at the top of the core, and appears to be leveling off to some saturation pressure. The maximum inertial pressure observed was 145 psi.

III. RAMP INPUT STUDIES

Another set of experiments was also run to determine the response of the system to reactivity inputs which increase linearly with time.

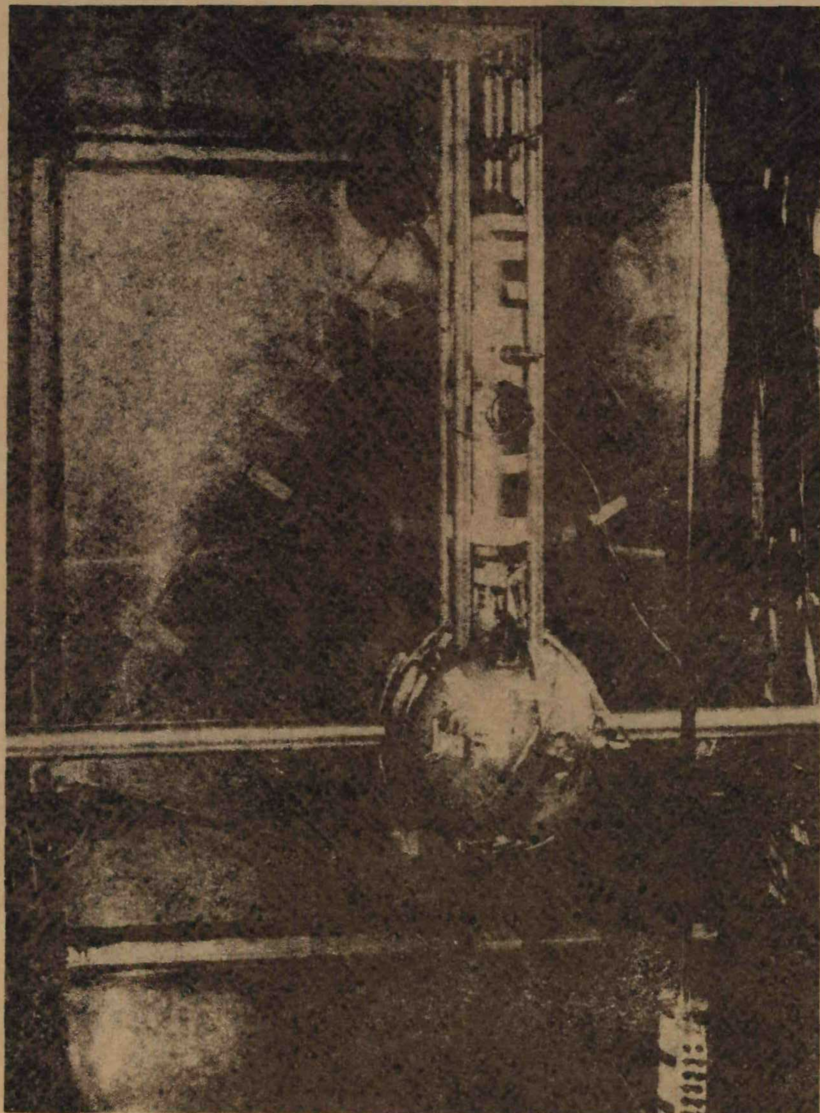
Four different ramp rates have been investigated, .03, .06, .09, and .13 percent/second. These insertions were initiated with the reactor essentially at zero power and a core temperature of 25°C and core pressure of 15 cm Hg. Two ramp limits were examined; 1.2 and 2.4 percent reactivity. These gave rise to periods which ranged from 460 milliseconds for the slowest ramp rate to 62 milliseconds for the fastest ramp rate. The excursions were allowed to continue for 1.5 minutes after peak power and were then terminated.

A typical sequence during a ramp input is a rapid rise in reactor power resulting in a peak pulse and then a minimum followed by a slow increase until the ramp input was stopped, at which time the power reaches an equilibrium level or slowly decreases. The maximum power obtained depended on the ramp rate and not on the total input for the ramps investigated. The power peaks were found to correspond to step input transients with periods similar to the minimum period observed during the ramp input.

Small highly damped oscillations with periods from 2 to 3 seconds sometimes occurred in the region after the power minimum. After the ramp input was terminated the power level approached an equilibrium value which depended on the total reactivity input. Average equilibrium powers with no coolant flowing were found to be 25 and 50 kw respectively for 1.2 and 2.4 percent total inputs.

A few special cases were investigated to determine the effect of coolant flow on the response of the system. It was found that the only change was in the equilibrium power reached after the ramp was terminated. One such run made was a ramp with .12 percent per second ramp rate, a total input of 2.4 percent, and coolant flow of 15 gpm. The peak power reached was 2.4 Mw and small stable oscillations occurred which damped out 35 seconds after peak power when the ramp input was terminated. This is the same response as for the no-coolant case except the equilibrium power reached after the ramp ended was 160 kw for the coolant flow case.

These experiments have provided a demonstration of the inherent safety of the homogeneous solution type reactor. Transient power excursions have been initiated to give stable reactor periods shorter than those experienced with any other thermal reactor and these excursions have been completely controlled by the self limiting action of the reactor with only modest pressures generated which resulted in no damage to the system.



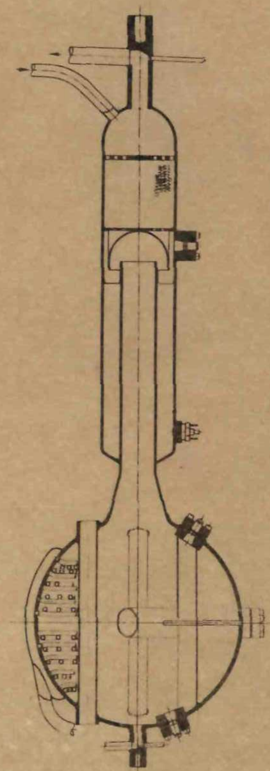


FIG. NO. 1

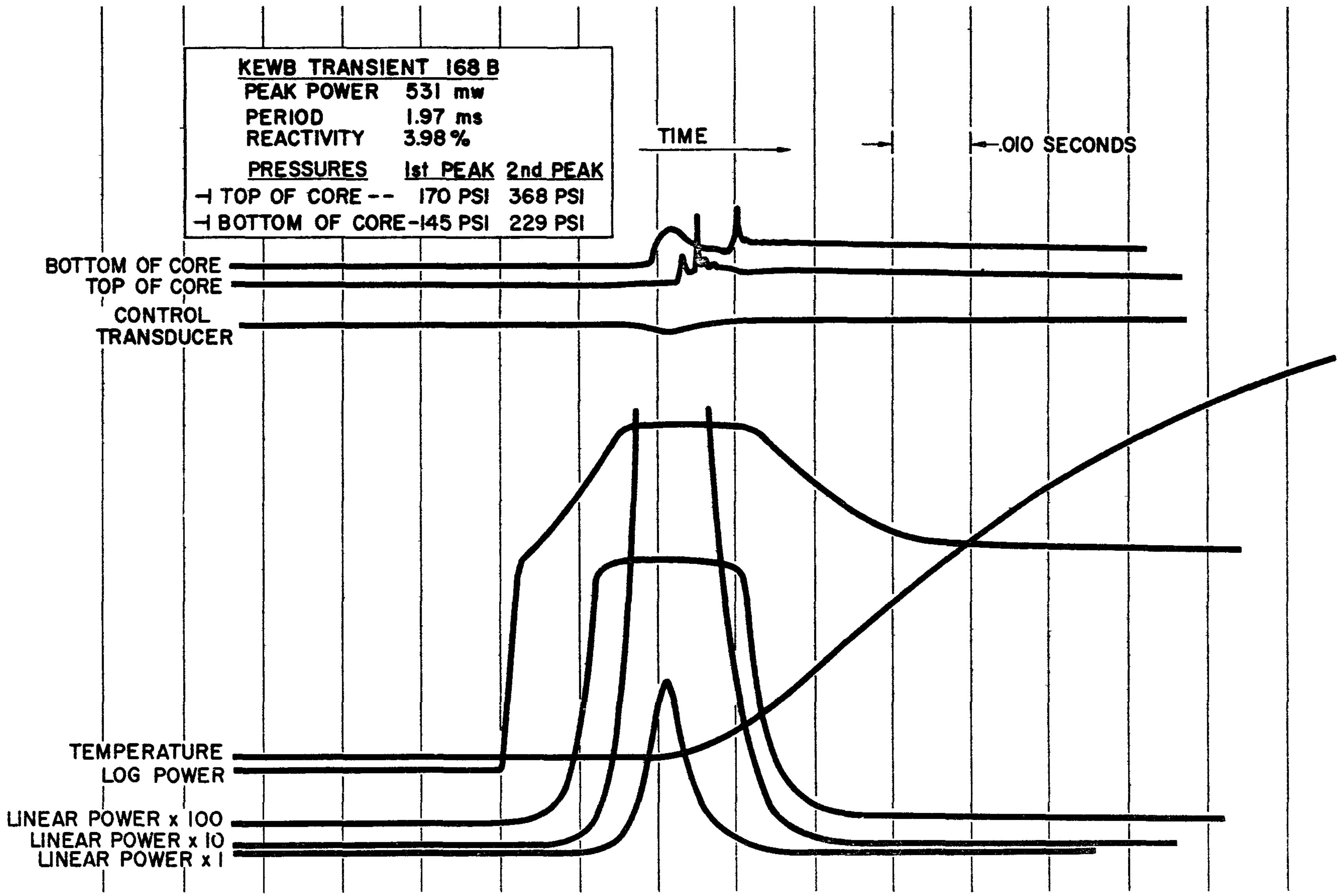


FIGURE II

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KEWB INHOUR EQUATION

OCTOBER 1957

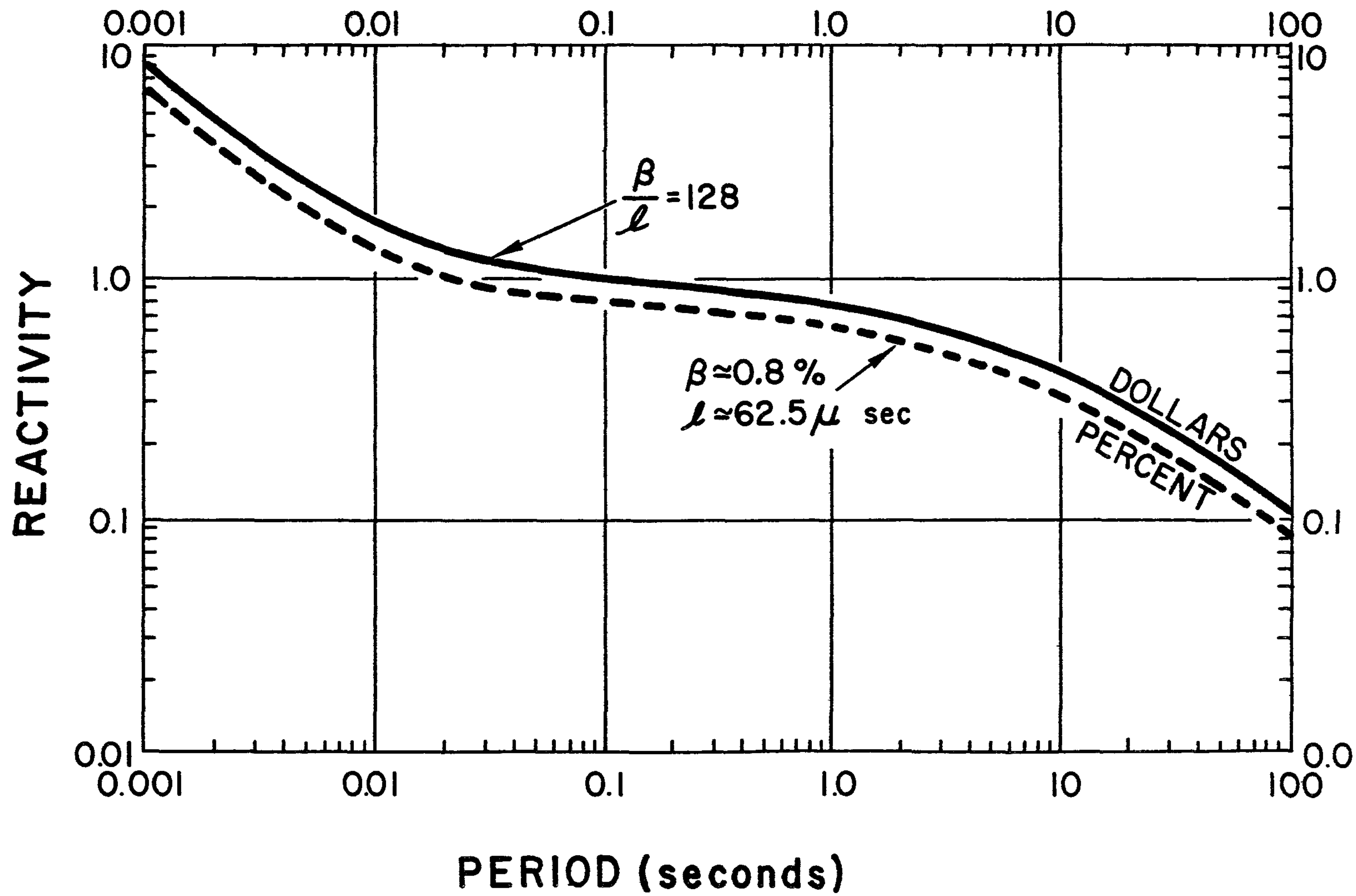

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Figure III

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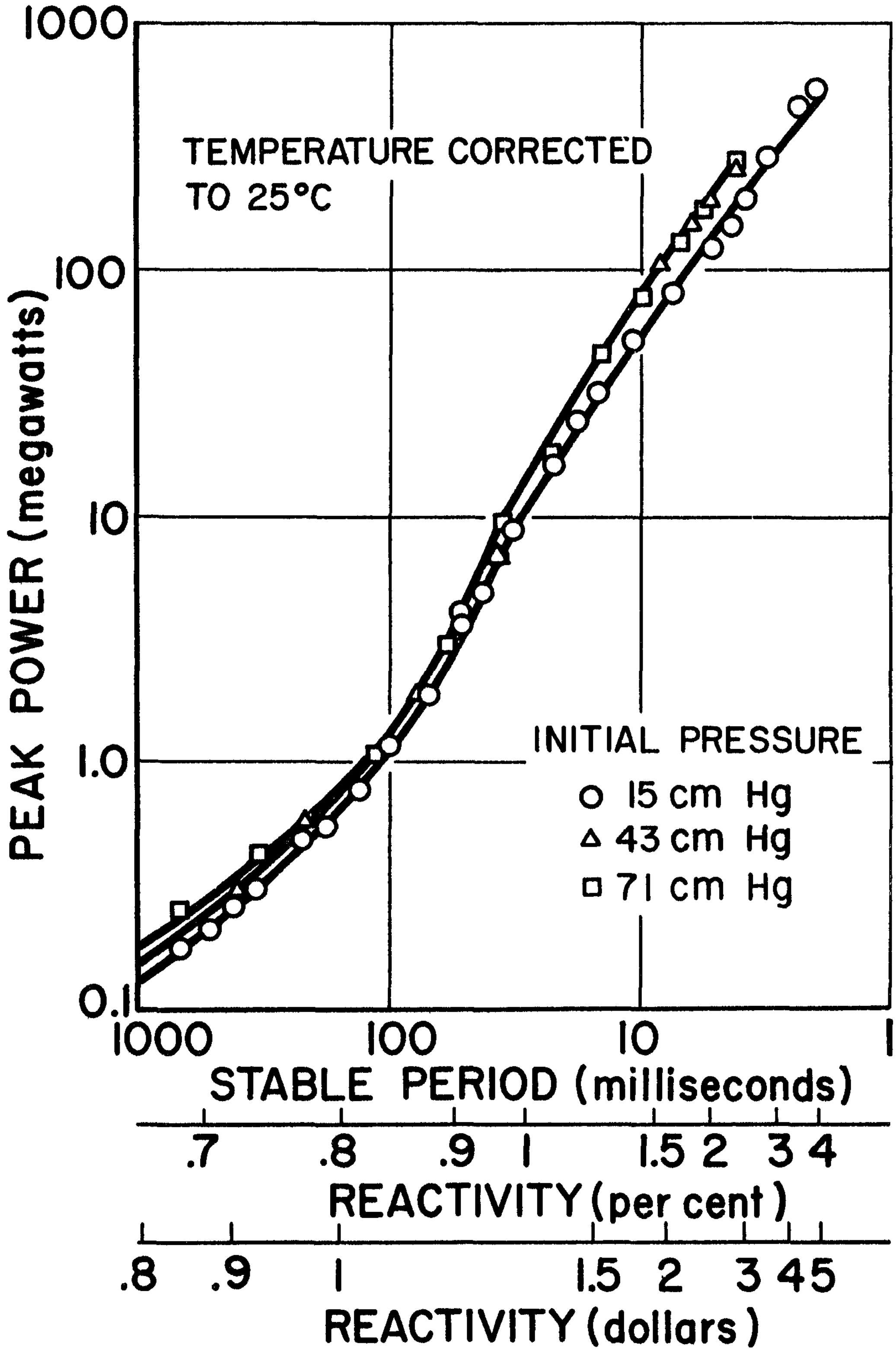
PEAK POWER VS STABLE PERIOD & REACTIVITY



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ENERGY RELEASE IN FIRST BURST VS. STABLE PERIOD AND REACTIVITY

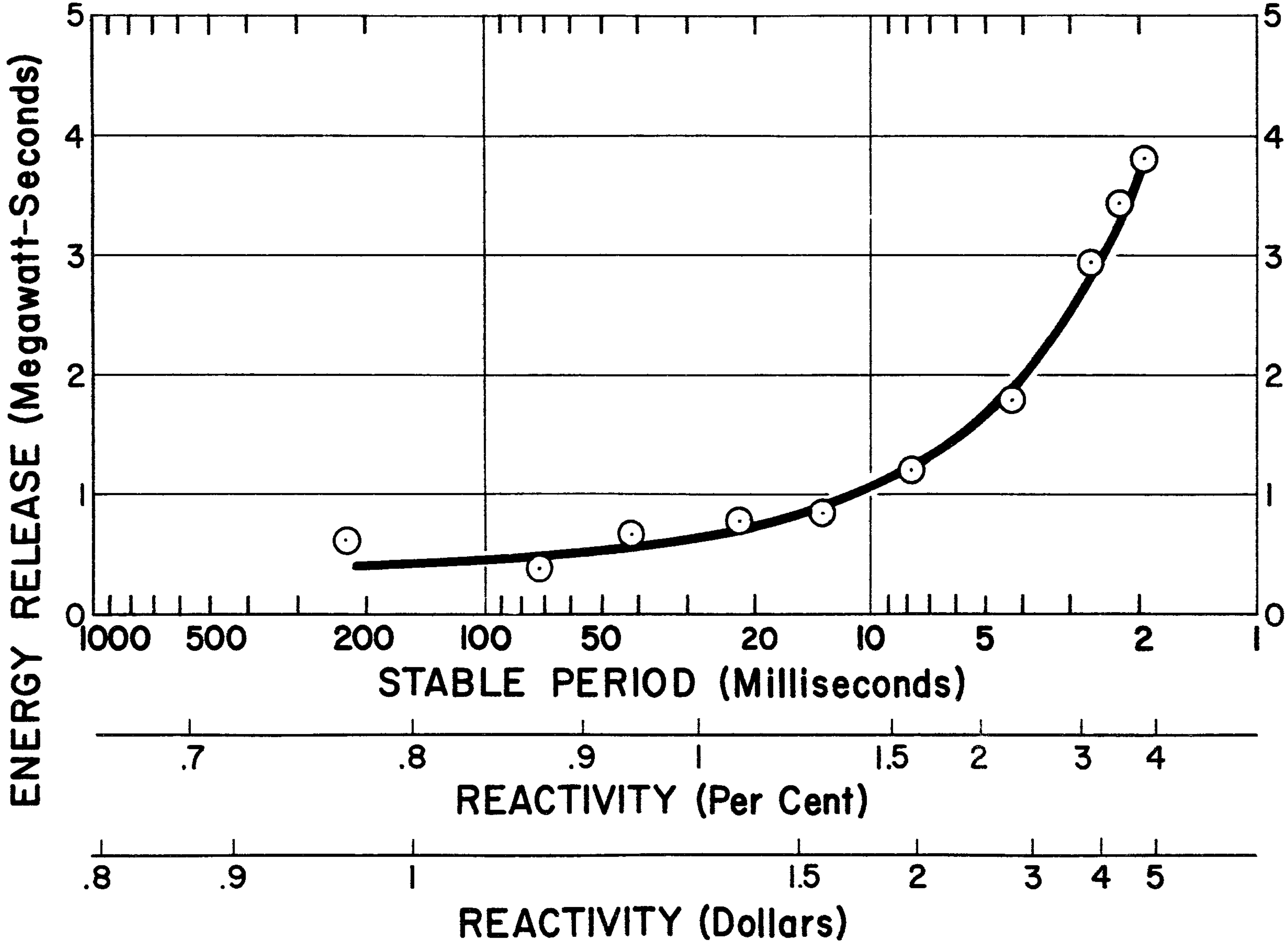

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Figure V

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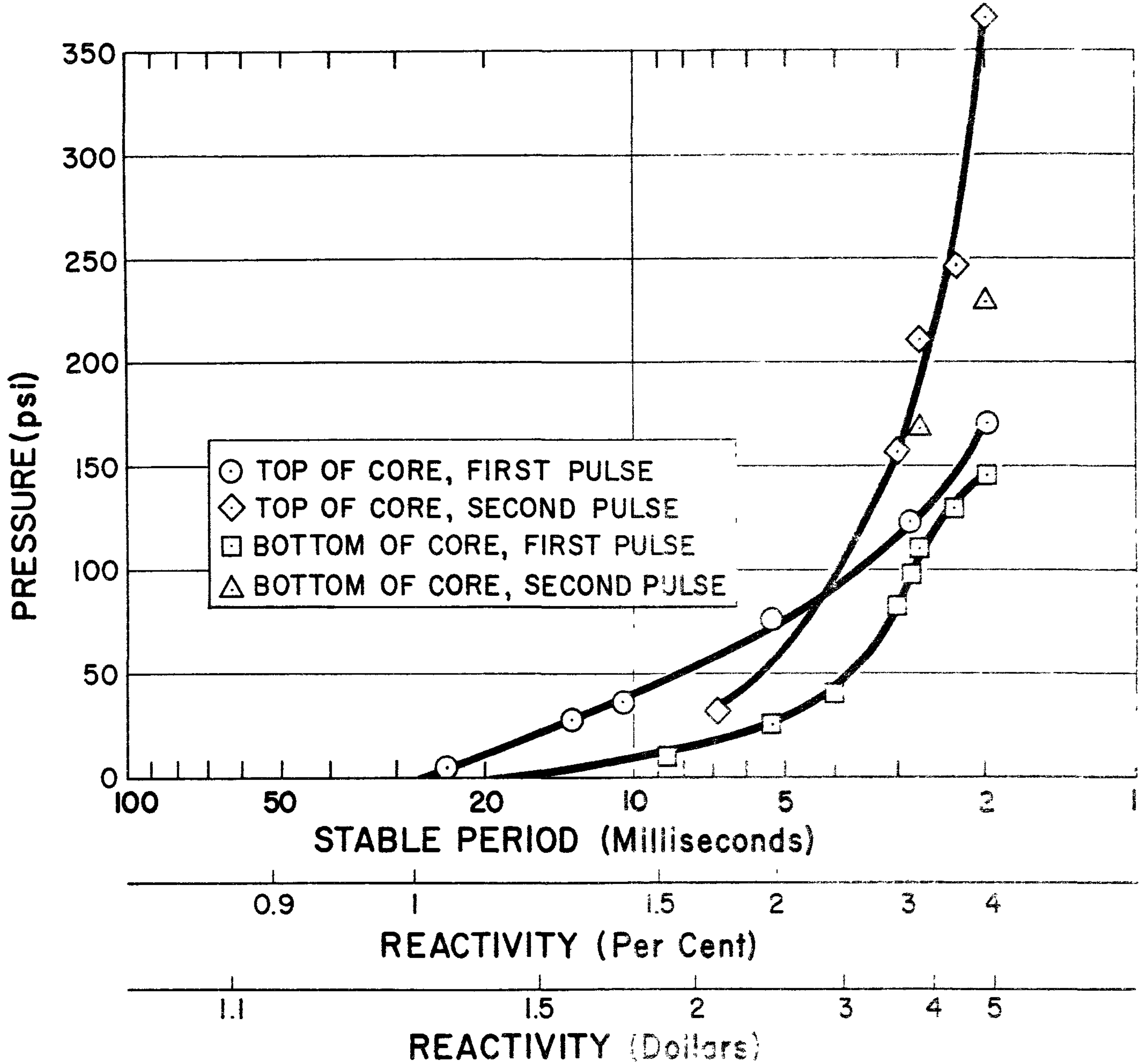
CORE PRESSURES vs. STABLE PERIOD AND REACTIVITY



6-3-58 Figure VI 9304-5011

WATER BOILER EXCURSIONS WITH AN INITIALLY FILLED CORE

by

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The following is a summary of recent experimental information on the behavior of the Kinetic Experiment Water Boiler (KEWB) with the core initially 100 percent filled. This additional information, which indicates that the effect of reduced initial void volume for a given input reactivity is less severe than had been originally anticipated, is applied to the consideration of a reactivity step of 2.5 percent in the Armour reactor.

It is concluded that the Armour reactor can safely withstand a reactivity step of 2.5 percent, even though the core is initially filled.

Figure 1 shows the effect of initial filling on peak power for various rates of reactivity insertion. The greatest rate shown is for simultaneous withdrawal of all four control rods at the maximum speed of 0.1 inch per second, which yields rates of change of reactivity of 0.10 percent per second for the full core and 0.12 percent per second for the partially filled core. In none of these cases was there any indication of transient pressures associated with the power transient. In the cases which were initiated with the recombiner in operation, slow inflammation of hydrogen and oxygen subsequently yielded pressure rises of at most 30 psi, which in turn initiated small power transients of the same order of magnitude as those shown in Figure 1. (0.5 to 1.5 megawatts.)

The total reactivity inserted in these experiments ranged from 1.25 to 4.0 percent, but each power transient was essentially complete well before the control rod motion ceased, so that the peak power and minimum reactor period observed is independent of the total reactivity. It may be noted that curves of peak power vs minimum period show much less dependence on the initial core filling, and when re-plotted in this manner the data of Figure 1 all fall close to the curve of peak power vs period obtained previously from step-initiated transients (periods ranging from 0.4 to 0.05 seconds).

In applying these results to the Armour reactor, it is assumed that the energy coefficient of reactivity and the effective fraction of delayed neutrons are the same for the two reactors. The dependence of peak power on the rate of reactivity insertion is, to a first approximation, independent of the neutron lifetime, so that the somewhat larger lifetime in the Armour reactor may be ignored here. It is concluded that the hazard represented by this type of "ramp transient" is very small, and is not increased by reducing the initial void volume above the solution.

Figure 2 shows peak pressures vs reactor period for the faster excursions initiated by step changes of reactivity in KEWB. The data for the partially filled core[2], (dashed lines), extending to a reactor period of 2.0 milliseconds, is characterized by the notable difference between the peak pressures experienced by the two transducers, one at the bottom of the core and the other at the top (the latter transducer is not initially submerged).

In contrast, when the core is filled, both transducers are submerged, and the pressure-time traces for the two are quite similar, yielding the peak pressure data shown by the solid curves in Figure 2.

The introduction of 2.5 percent reactivity in the Armour reactor (5 millisecond period) has been calculated[1] to result in peak powers equivalent to those experienced in KEWB at approximately 4 milliseconds period, the difference in the two periods arising from the different neutron lifetimes. Consider therefore a particular KEWB excursion with a full core, for which the period is 4.1 milliseconds and the peak pressures at top and bottom are respectively 117 and 135 psi. These are to be compared with a peak inertial pressure of about 40 psi at the bottom for the same reactor period with the core initially 85 percent full, and peak pressure of about 90 psi at the upper transducer.

The peak power experienced in the full-core excursion cited (initial pressure 71 cm Hg) was 200 megawatts. Even though the inertial pressures are about three times larger than for the partial filling, the peak power has not increased (peak powers for a 4 millisecond period with partial filling are about 170 and 220 megawatts for initial pressures of 15 and 71 cm Hg respectively). This is confirmation of the hypothesis that reactor shutdown in fast transients is largely due to very small bubbles whose internal pressure is high and whose size is therefore not affected by the overall system pressure.

The Armour reactor vessel was statically tested for 300 psi. It seems reasonable to assume that there is no situation between 85 percent filling and 100 percent filling which gives rise to very much higher pressures. Therefore, it may be concluded that the Armour reactor is safe in the event of a 2.5 percent reactivity release with any initial core volume in this range.

REFERENCES

1. D. L. Hetrick, "The Effect of a 2.5 Percent Reactivity Step in the Armour Reactor", AI-MEMO-2472, January 18, 1958.

2. R. K. Stitt, E. L. Gardner, J. H. Roecker, and R. E. Wimmer, "The Response of a Water Boiler Reactor to Very Fast Power Transients and Linearly Increasing Reactivity Inputs", Paper 21-6, 1958 Annual Meeting, American Nuclear Society, Los Angeles, California, June 4, 1958.

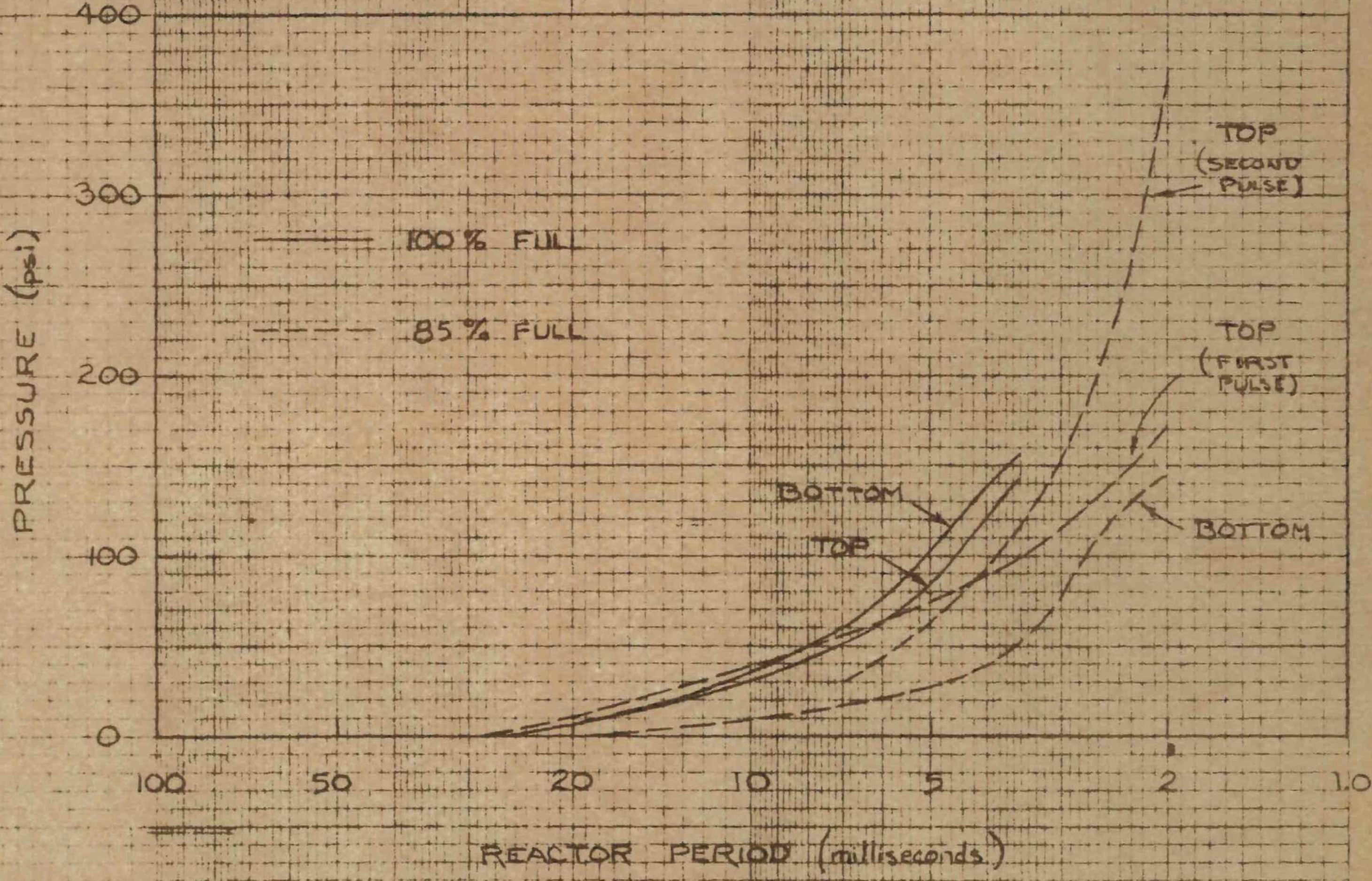

FIGURE 2

Peak Pressure vs Reactor Period for Reactivity Steps in KEWB

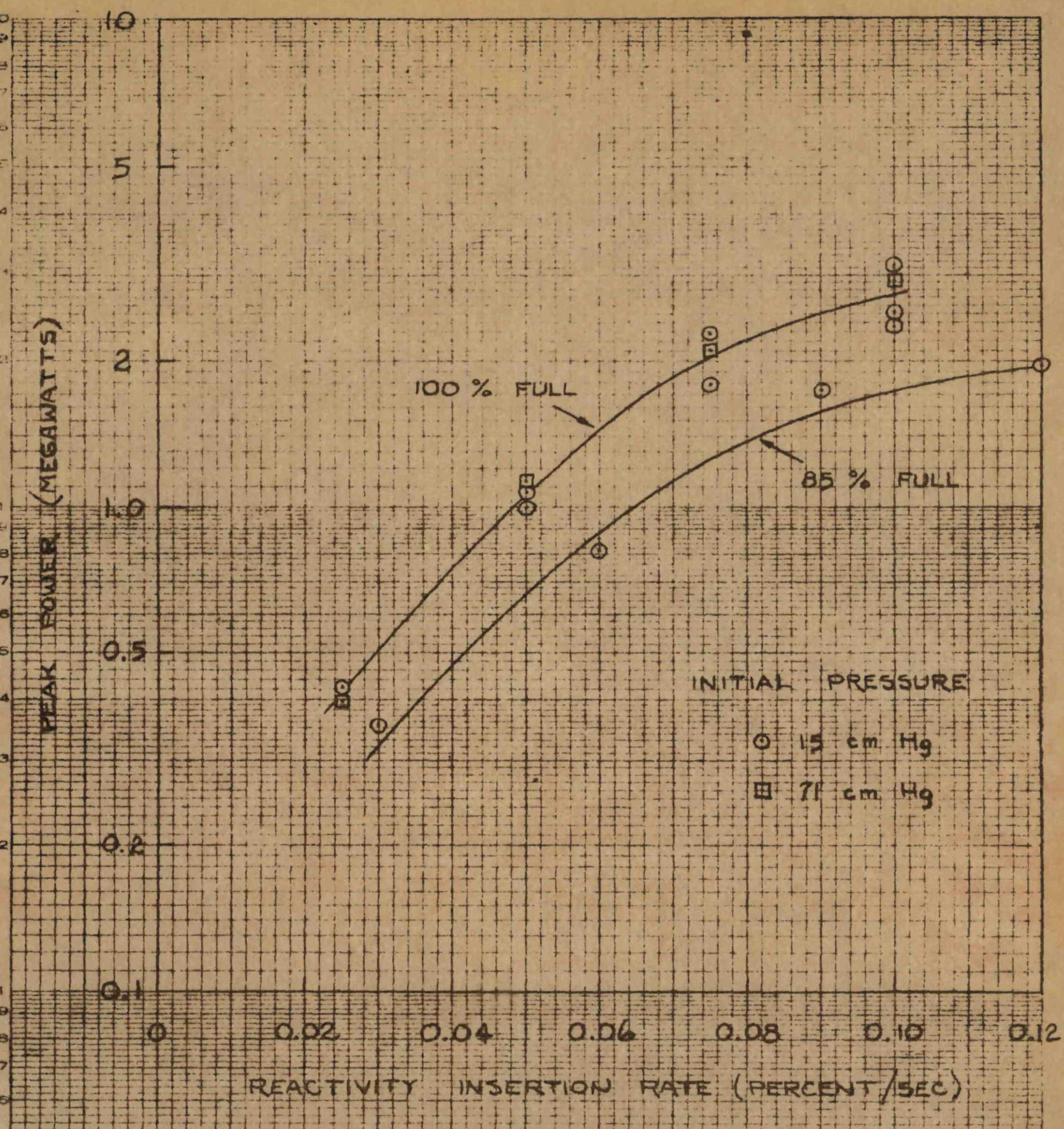

FIGURE 1

Peak Power vs Rate of Reactivity Insertion for Slow "Ramp Transients" in KEWB