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PRELIMINARY RESULTS ON THE KINETIC BEHAVIOR OF WATER BOILER REACTORS

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ABSTRACT

The response of the Kinetic Experiment Water Boiler (KEWB) to step inputs of reactivity has been explored in 62 self-limiting excursions, covering the range up to 0.94 per cent reactivity (approximately $1.10). Parameters affecting shut-down behavior were as follows:

1. Stable periods ranging from 80 seconds to 0.13 second.
2. Initial pressures in the 39-liter closed gas system communicating with the solution surface ranging from 15 to 71 centimeters of mercury.
3. Fuel loadings resulting in two values of excess reactivity, approximately 1.3 per cent and 4.0 per cent.
4. Gas-filled void space above the solution and within the spherical core: 2.5 liters at 1.3 per cent loading (11.1 liters of enriched uranyl sulphate solution in a 13.6 liter sphere) and 2.1 liters at 4.0 per cent loading (11.5 liters of solution).
5. Initial solution temperature fixed approximately at 25° C.
6. Reactivity insertion effectively step-input.
7. Initial power level held sufficiently low to ensure a stable period over several decades of rise.

No cooling water was flowing, and the gas recombining system was closed off.

It is concluded that radiolytic decomposition gas is approximately seven times as effective as thermal expansion in limiting a neutron burst in a water boiler reactor at atmospheric pressure, provided the burst is rapid enough that most gas bubbles remain in the solution until after peak power is attained, and provided the dynamic pressures achieved are not large enough to interfere with the effect of gas bubbles on the reactivity.

I. INTRODUCTION

The self-limiting dynamic behavior of a water boiler reactor was first investigated in 1953 by P. R. Kasten[1] of Oak Ridge National Laboratory, using the SUPO reactor at Los Alamos, and by Flora, Shortall, and Drummond,[2] using the reactor built in 1953 by North American Aviation, Inc., originally for the California Research and Development Corporation. The maximum reactivity step in any of these experiments, however, was about 0.42 per cent, or 50 cents, corresponding to a minimum reactor period of six seconds.

The Kinetic Experiment Water Boiler[3] was built by Atomics International for the Reactor Development Division of the Atomic Energy Commission. The reactor was made critical in July, 1956. During the first five months of operation, transient behavior has been explored in the range of reactor periods from 80 seconds (0.10 per cent reactivity) down to 0.13 second (0.94 per cent reactivity, or about $1.10), using initial pressure over the free surface of the fuel solution as a parameter. These experiments were initiated by withdrawal of the control and safety rods; before proceeding to shorter reactor periods it will be necessary to install the mechanism for very rapid ejection of a poison rod from the central exposure facility.

II. REACTIVITY COEFFICIENTS

A water boiler is unique in that it has a particularly large negative temperature coefficient of reactivity. In the case of the KEWB, this coefficient is -0.024 per cent per degree Centigrade. The heat capacity of the fuel solution, as used in the KEWB, is 11.1 kilocalories per degree Centigrade, yielding an "energy coefficient of reactivity," appropriate for discussing slow transient behavior,* of -0.5 per cent per megawatt-second.

This is a number which is consistent with experimental data for reactor periods greater than approximately 30 seconds, and it is indeed reasonable to expect that the formation of radiolytic decomposition gas should not have a noticeable effect during a transient whose time scale is long compared to the estimated

*"Slow transient behavior" refers to time scales that are short compared to the characteristic time for heat transfer, but longer than the time scales for radiolytic gas phenomena.

average residence time for a gas bubble in the solution. On the other hand, there is apparently a region of somewhat larger reactivity, in which the reactor period is short compared to the bubble residence time, but not yet so short that dynamic pressures during a neutron burst are great enough to inhibit the power-limiting effect of bubble formation.

Since most of the temperature coefficient of reactivity arises from the effect of core density on the nuclear parameters of the reactors, it is reasonable to estimate a density coefficient of reactivity by dividing the volume coefficient of thermal expansion for the solution into the temperature coefficient. This yields the result that at 30° C a one per cent volume change corresponds to 0.8 per cent reactivity. For the KEWB, this yields a distributed void volume coefficient of reactivity of -0.007 per cent reactivity per cm^3 of void.*

The use of two-group, two-region perturbation theory has given the result -0.008 per cent reactivity per cm^3 for a uniformly distributed density change.[4] The agreement with the number cited previously is remarkable, although it is possible that the contribution of neutron temperature to the temperature coefficient of reactivity, when subtracted, might change the -0.007 to -0.006. This is currently being studied in more detail.[4]

Using -0.007 per cent per cm^3 as an approximate value, together with the observed rate of gas production in steady state ($\sim$4 cm^3/sec at one kilowatt), yields a rather naively computed "energy coefficient of reactivity" for gas production of 28 per cent reactivity per megawatt-second ! This number, which is a limiting value appropriate for excursions in which the time scale is small compared to the bubble residence time in the core, is 56 times as large as the energy coefficient of reactivity obtained from thermal expansion. This possibility was first pointed out in 1954 by Weeks.[5]

However, the evidence from years of experience with water boilers shows that the real ratio of energy coefficients of reactivity, or the "relative shutdown effectiveness," could be perhaps 5 or 10, but not 56.[3,6] Carter and King at Los Alamos have provided evidence that a given change in solution volume attained by heating artificially from 20° C to 55° C requires more compensating reactivity

*Since the temperature coefficient was measured with an underfilled sphere, the effect of changing the surface-to-volume ratio by changing the density is automatically included in this number.

than does steady state operation at 15 kilowatts and 20° C, even though the same solution level is achieved.[6] The hypothesis is herewith advanced that this effect is due to a highly nonuniform bubble distribution, which could conceivably require appreciably less compensating reactivity than the same void volume distributed uniformly. This possibility is now being studied in detail.[4,7]

King[8] has provided data from which this situation may be assessed quantitatively. From the measured effect of power on reactivity at 74° C (Figure 23 of Ref. 8), one can calculate directly the power coefficient of reactivity at each power level.* This may be compared with the data on solution level as a function either of power, or of temperature attained by artificial heating (Figure 16 of Ref. 8). The results, obtained directly from the power coefficient curve, and indirectly from the solution level curve by using a reactivity coefficient of -0.007 per cent cm^3, are presented in Table I. Apparently the real void volume reactivity coefficient is only one-third as large as the value calculated for uniform bubble distribution.

TABLE I

POWER COEFFICIENT OF REACTIVITY FOR SUPO

Power (kw)	Reactivity† (per cent)	Reactivity Coefficient† (per cent/kilowatt)
5.1	-0.17	-0.033
20.4	-0.27	-0.013

Power (kw)	Volume Change (cm^3)	Reactivity†† (per cent)	Reactivity Coefficient†† (per cent/kilowatt)
5.1	70	-0.49	-0.096
20.4	110	-0.77	-0.038

†Observed in SUPO
††Calculated using a void volume reactivity coefficient of -0.007 per cent per cm^3

*This is not the slope of the curve of power vs reactivity, but rather the total reactivity compensated at the given power level.

It is also possible to calculate the average residence time for gas bubbles from the data presented in Table I. Knowing merely the power, the change in solution volume, and the rate of gas production, the values 3.4 seconds at 5.1 kilowatts and 1.4 seconds at 20.4 kilowatts are obtained, suggesting that higher power implies larger bubbles which rise more rapidly. (Note that these results are for a solution temperature of 74° C, so that some of the observed increase in solution volume is due to the water vapor content of the gas bubbles. The fact that the volume increase is not a sensitive function of temperature indicates that the effect of water vapor is not of major significance.)

The original computations of transient behavior for KEWB were performed with a reduced void volume coefficient of reactivity,[3] somewhat artibrarily estimated such that the ratio of energy coefficients was seven instead of 56. This was consistent with measurements[6] of the power coefficient of reactivity for SUPO, together with an estimated residence time of two seconds. As the transient data recently obtained in KEWB indicates, the factor seven was a fortuitous choice; however, this implies that the effective reactivity coefficient for transients is one-eighth as large as the computed value (instead of one-third as the SUPO data for steady-state operation would seem to indicate).

III. EXPERIMENTAL RESULTS

The response of the Kinetic Experiment Water Boiler to step inputs of reactivity has been explored in 62 self-limiting excursions, covering the range up to 0.94 per cent reactivity (approximately $1.10). Parameters affecting shutdown behavior were as follows:

1. Stable periods ranging from 80 seconds to 0.13 second.
2. Initial pressures in the 39-liter closed gas system communicating with the solution surface ranging from 15 to 71 centimeters of mercury.
3. Fuel loadings resulting in two values of excess reactivity, approximately 1.3 per cent and 4.0 per cent.

4. Gas-filled void space above the solution and within the spherical core: 2.5 liters at 1.3 per cent loading (11.1 liters of enriched uranyl sulphate solution in a 13.6-liter sphere) and 2.1 liters at 4.0 per cent loading (11.5 liters of solution).
5. Initial solution temperature fixed approximately at 25° C.
6. Reactivity insertion effectively step-input.
7. Initial power level held sufficiently low to ensure a stable period over several decades of rise.

No cooling water was flowing, and the gas recombining system was closed off.

Figures 1, 2, and 3 show typical power traces obtained for step inputs of reactivity in the KEWB reactor (the zero point for the time axis is arbitrary). These curves were traced from Brown recorder charts; oscillograms consistent with these charts also exist, and these include power (two ranges), instantaneous period (two ranges), and pressure and temperature traces.

Figure 2 shows a particularly interesting phenomenon — the nonlinear oscillation immediately following peak power, and having a frequency of approximately four cycles per minute. Analogue computer results,[3,9] using the theoretical model developed in 1954,[3] show that the system of equations is overdamped,* but that the total energy, or integrated power, is approximately that obtained in Fig. 2. However, the peak power, and hence the energy associated with the first power peak as obtained with the electronic simulator, is only about 40 per cent as high as shown in the data in Fig. 2. This indicates quite forcibly the incomplete nature of the original theoretical model.

Comparison of the power trace for one excursion (approximately 0.6 per cent reactivity) with its corresponding pressure trace showed that the maximum rate of pressure increase in the closed system occured approximately three seconds after the power peak, indicating for this excursion an average time lag of three seconds for the formation of bubbles by nucleation of dissolved radiolytic gas.**

*Damped oscillations with a frequency of one cycle per hour have been observed in a water boiler reactor.[2] This very slow oscillation seems to be understandable in terms of the original theoretical model.[3]

**Bethe[10] has recently concluded that reactor instability can result in the presence of a delayed power coefficient of reactivity, even if this delayed coefficient is negative. In our case, this indicates that a time delay in bubble formation could indeed give rise to damped oscillations which our original theoretical model did not predict.

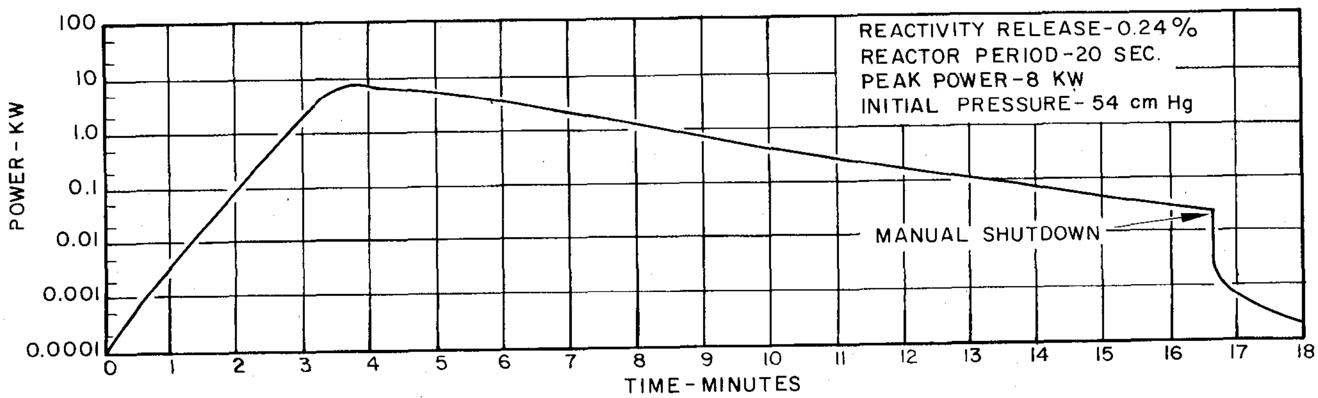

Fig. 1. Power vs Time for 0.24 Per Cent Reactivity at 54-cm Pressure

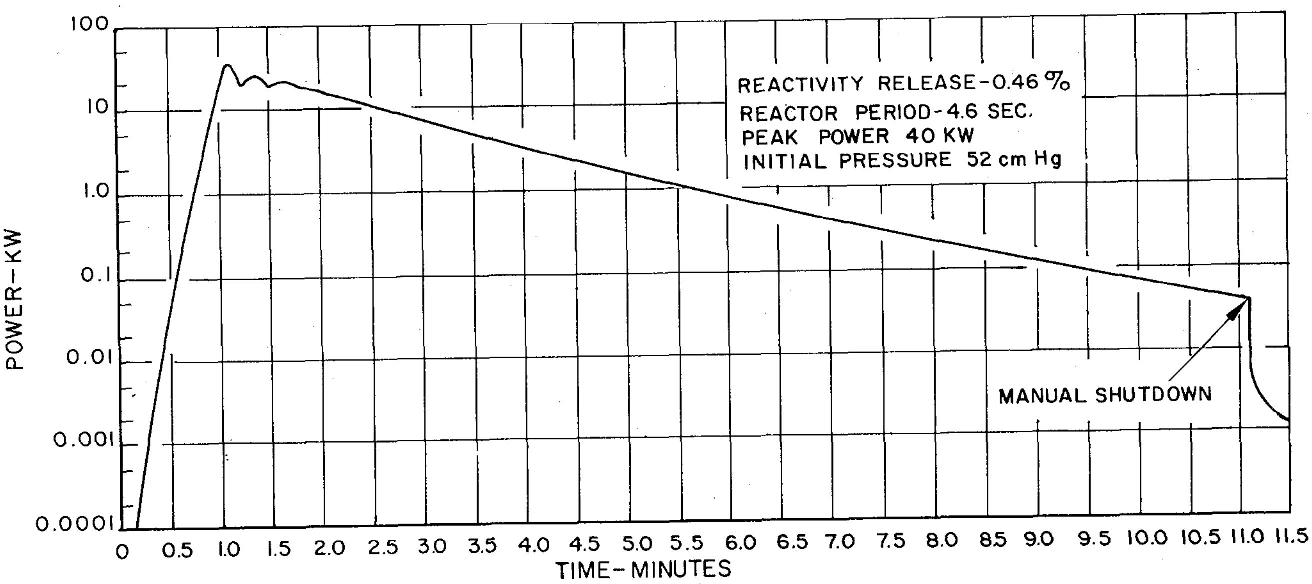

Fig. 2. Power vs Time for 0.46 Per Cent Reactivity at 52-cm Pressure

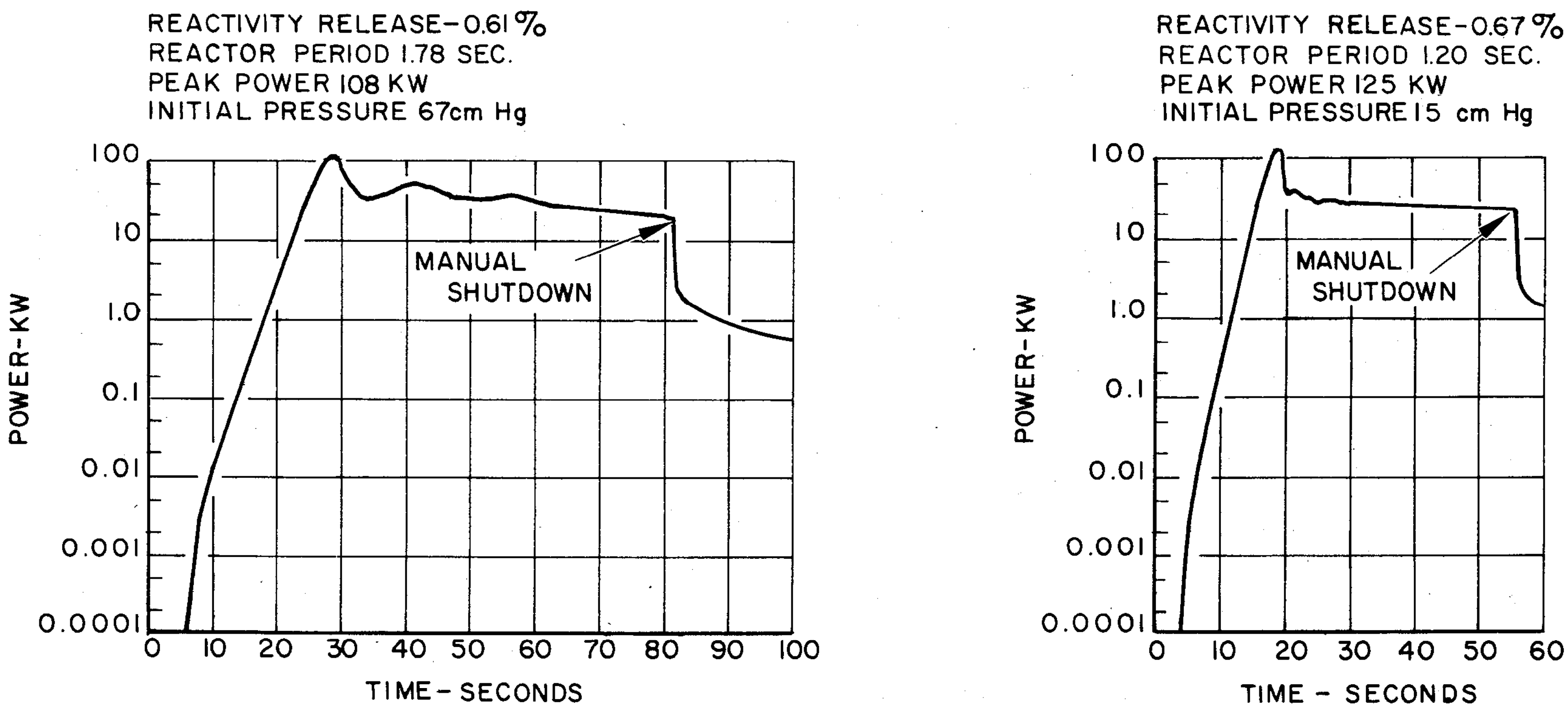

Fig. 3. Power vs Time for 0.61 Per Cent Reactivity at 67-cm Pressure and for 0.67 Per Cent Reactivity at 15-cm Pressure

More complex theoretical models are currently being studied with the aid of the electronic simulator; these include various types of representation for time delays in bubble formation, as well as provision for time-dependent coefficients in the reactor equations.

Note that an improved theoretical model must include the effect of initial pressure on the oscillations. Figure 3 shows how a reduced initial pressure nearly eliminates the oscillatory behavior, while noticeably reducing the peak power; the expected peak power for 0.67 per cent reactivity at 71 cm Hg is 180 kilowatts* instead of 125 kilowatts.

It is also possible that some spatially-dependent effect exists, such as a central region of bubbles which might be growing with a more or less "sharp" propagating front. Such a model would be very difficult to use in computation, and it is difficult to see how it alone could explain the presence of oscillation frequencies as low as four cycles per minute.

A summary of excursion data obtained with the KEWB facility is presented in Table II, and Fig. 4 shows a plot of peak power vs reactivity for 33 power excursions** at three different starting pressures. Note the gradual improvement in the self-limiting ability of the reactor as the reactor period is reduced from values which are large compared to bubble residence times. Note also the enhanced shutdown effect of reduced starting pressure, presumably arising from increased gas volume.

The data labelled Livermore and SUPO are of course for different reactors; in particular, the fuel solution volume and the heat capacity of the Livermore reactor are 26 per cent greater, while the pressure at Los Alamos is presumably 59 cm Hg.

The theoretical curve in Fig. 4 was obtained by solving the reactor kinetic equations analytically for the case of an adiabatic transient without radiolytic gas production.[9] This approach, originally suggested by Mills[11] in connection with another problem, can also be employed to solve the equations including gas

*Obtained by interpolation from other data on peak power vs reactivity at 71 cm Hg initial pressure.

**29 additional excursions, consistent with these 33 but at intermediate scattered starting pressures, are not plotted here.

TABLE II

SUMMARY OF KEWB EXCURSION DATA*

Date	Initial Pressure (cm. Hg)	Initial Temp. (°C)	Peak Power (kilowatts)	Period (seconds)	Peak Power x Period(kw-sec)	Reactivity Step (per cent)**
9-25-56	61***	29	3.5	36	126	0.17
	54	36	8	20	160	0.24†
	57	34	20	9.2	184	0.35
	52	32	40	4.6	190	0.46††
9-27-56	47	28	52	3.0	159	0.53
10-1-56	43	--	193	1.07	206	0.68
	43	--	205	0.88	180	0.71
10-2-56	43	21	500	0.43	215	0.79
	51	25	352	0.63	222	0.75
10-3-56	67	26	108	1.78	192	0.61†††
	15	29	125	1.20	150	0.67†††
11-8-56	68	25	17	10.6	182	0.33
	68	31	43	3.8	160	0.50
	68	32	178	0.82	146	0.72
	68	31	94	1.83	173	0.60
	22	26	14.4	9.0	130	0.35
	22	26	42	3.2	131	0.52
	22	25	161	0.92	148	0.70
11-15-56	68	25	10.7	12.2	146	0.30
	68	25	27	5.4	164	0.43
11-29-56	71	27	4.5	32	147	0.18
	71	27	9.4	15.5	146	0.27
	71	26	16.5	9.1	150	0.35
	43	25	15.3	8.9	135	0.35
	43	26	7.5	17.0	127	0.26
11-30-56	43	26	4.2	33	138	0.18
	15	25	14.6	9.2	134	0.35
	15	25	5.9	19.3	113	0.24
12-1-56	15	24	2.9	33	94	0.18
	43	25	124	1.37	170	0.65
	43	25	34	4.7	156	0.46
	43	25	66	2.6	173	0.54
12-4-56	15	24	37	4.5	166	0.46
	15	24	47	3.1	146	0.52
	15	23	153	1.02	156	0.68
12-5-56	71	24	157	1.38	217	0.64
	71	23	74	2.6	194	0.55
	71	23	36	4.9	177	0.45
12-6-56	15	24	296	0.60	177	0.75
	43	24	344	0.52	180	0.77
	71	24	285	0.70	198	0.74
12-10-56	15	26	1.15	82	94	0.10
	43	26	1.39	74	103	0.11
	71	26	1.68	64	121	0.12
	15	25	574§	0.30	172	0.83
	43	25	290	0.61	177	0.75
	71	26	617§	0.36	223	0.81
	43	24	456§	0.34	153	0.82
	15	27	735§	0.22	160	0.87
	71	25	1300§	0.13	170	0.94

*Reactivity loading 9-25-56 to 10-3-56 inclusive: 1.3 per cent; 4.0 per cent after 10-3-56.

**Assuming an effective fraction of delayed neutrons of 0.87 per cent.

***Only those excursions having initial pressures 14, 43, and 72 cm are plotted in Fig. 4 through 7.

†See Fig. 1 for power trace

††See Fig. 2 for power trace

†††See Fig. 3 for power trace

§ Peak power for these excursions is regarded as tentative pending resolution of some uncertainties in the power calibration at these higher levels.

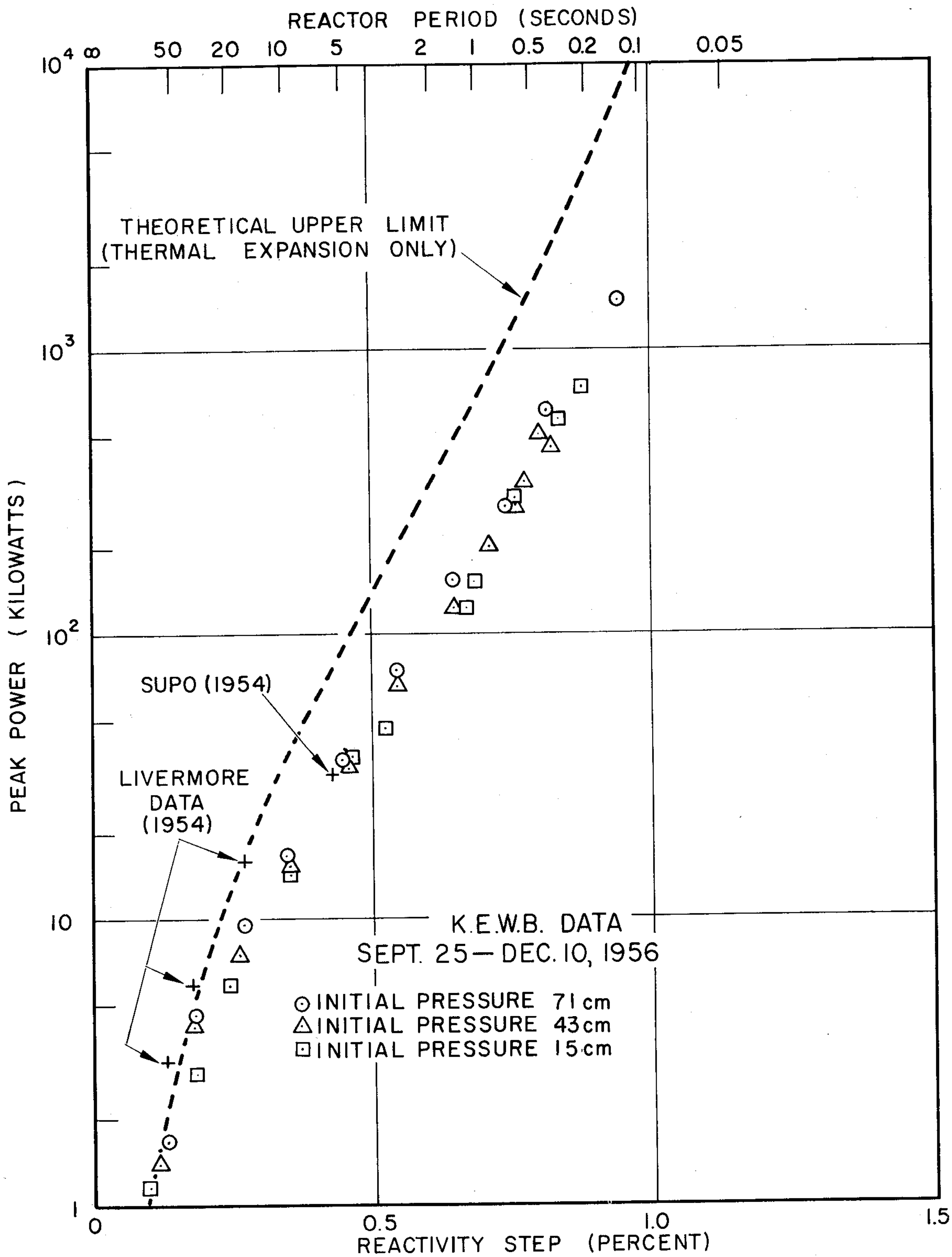

Fig. 4. Peak Power vs Reactivity Step for Various Pressures

formation, but assuming infinite residence time for bubbles; this allows discussion of the case in which the reactor period is small compared to the residence time. The major result of this computation is that the product of peak power times reactor period is proportional to the reactivity step; the constant of proportionality is one-half the reciprocal of the energy coefficient of reactivity. Hence, in the case of thermal expansion only, peak power times period in kilowatt-seconds is equal to 1000 times the reactivity in per cent, while for shorter periods a straight line, having a smaller slope determined by the sum of the two energy coefficients of reactivity, should be expected.

Such is apparently the case, as seen in Fig. 5, 6, and 7, where the importance of radiolytic gas is clearly evident for reactor periods smaller than 20 seconds. Since the theoretical model mentioned above is capable of dealing only with limiting cases, and not with a finite bubble residence time, the model cannot predict the intercepts for the straight lines that have been drawn among the data points.

These intercepts are certainly dependent upon the bubble residence time, and probably also dependent upon the heat capacity as well as the volume of the core. Note that in Fig. 5 the larger heat capacity of the Livermore reactor core yields a computed straight line for thermal expansion whose slope is 1260 instead of 1000. However, because of the larger core volume, the limited data available do not indicate the region at which the radiolytic gas production would cause the curve for that reactor to deviate from the theoretical curve for thermal expansion.

The ratios of slopes in Fig. 5, 6, and 7 have been used in preparing Table III, which shows the relative effectiveness of shutdown mechanisms for three different starting pressures. It is to be emphasized that these results are preliminary in nature, and much additional experimental information is forthcoming.

TABLE III

RELATIVE EFFECTIVENESS OF SHUTDOWN MECHANISMS IN KEWB

Initial Pressure (Cm Hg)	Ratio of Slopes in Fig. 5 through 7	Effectiveness of Gas Production Relative to Thermal Expansion
15	11.8	10.8
43	9.5	8.5
71	8.0	7.0

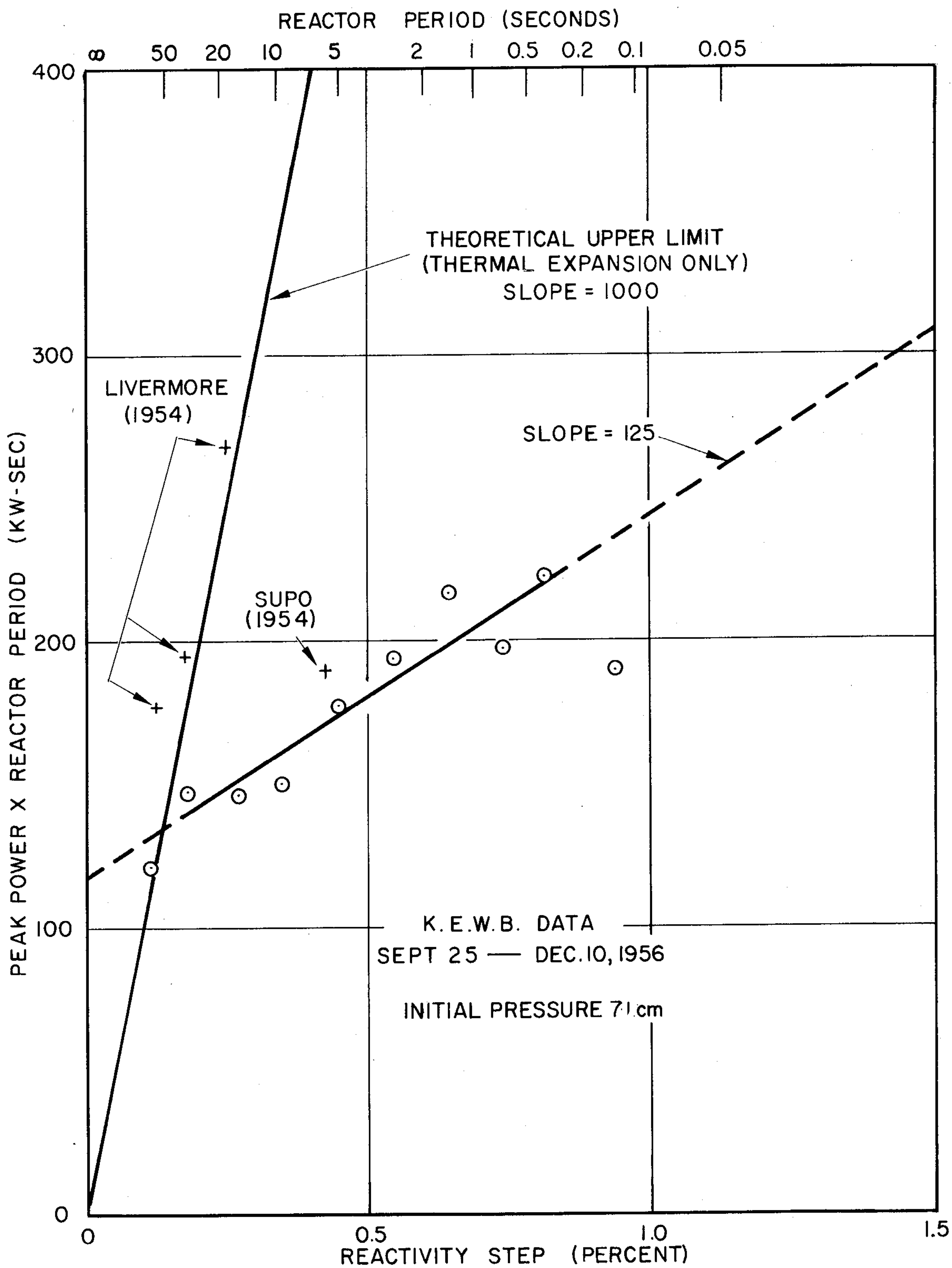

Fig. 5. Peak Power Times Reactor Period vs Reactivity Step at 71-cm Pressure

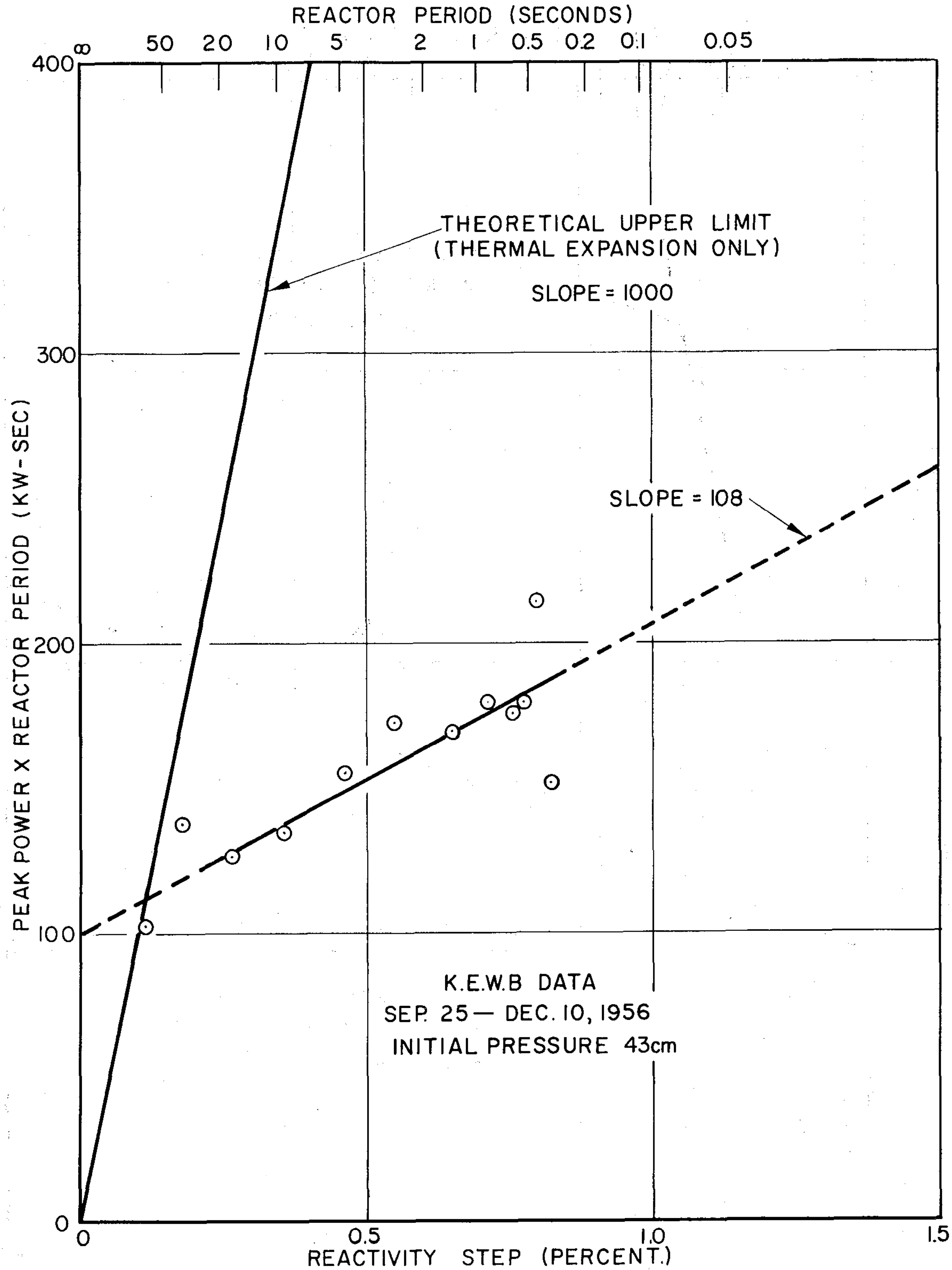

Fig. 6. Peak Power Times Reactor Period vs Reactivity Step at 43-cm Pressure

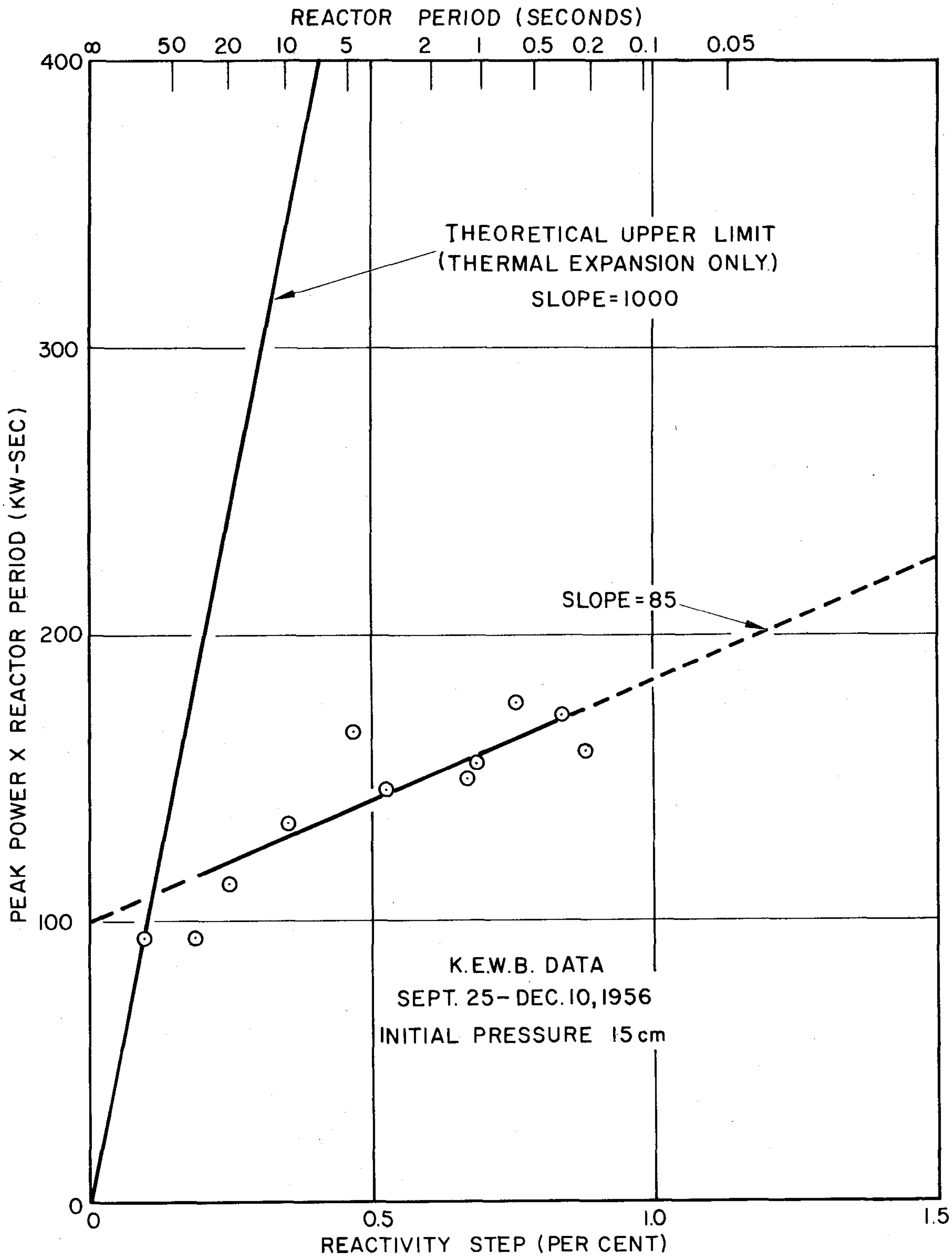

Fig. 7. Peak Power Times Reactor Period vs Reactivity Step at 15-cm Pressure

IV. CONCLUSIONS

The important conclusions to be drawn from the data presented here are the following:

1. The effect of radiolytic gas in self-limitation of neutron bursts in a water boiler reactor is extremely important.
2. Damped power oscillations are present which indicate the probable existence of a time delay in gas bubble formation.
3. The potential effect of radiolytic gas as a shutdown mechanism would be even greater if gas bubbles were uniformly distributed throughout the solution, or if their formation were instantaneous.

Much additional theoretical work is needed. Currently, improved simulator computations, which include (1) a better understanding of the effect of bubble distribution on reactivity, (2) allowance for time delays in bubble formation, and (3) provision for power-dependent coefficients in the reactor equations, are being initiated. Other phenomena which are being studied theoretically include boiling shutdown, large dynamic pressures, and limited void space above the solution; preliminary discussion of these has already been published elsewhere.[3]

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