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**THE KINETIC BEHAVIOR OF
WATER BOILER TYPE REACTORS**

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I. INTRODUCTION

The increasing demand for low power research and training reactors plus the desire to locate the reactors in highly populated regions has precipitated detailed consideration of their ultimate safety. Experimental tests conducted by the Argonne National Laboratory¹ during the past two years have provided data from which the safety aspects of the pool-type research reactor can be judged and, in addition, have firmly established the value of such tests.

The Atomic Energy Commission has deemed it necessary also to determine experimentally the behavior of homogeneous reactors intended for general research, medical and industrial applications. Such a program has been undertaken at the Commission's direction by Atomics International. The prime objective of this program is to establish a firm basis for evaluation of the safety of homogeneous reactor designs with regard to accidental release of large quantities of reactivity. The intent is to investigate a sufficient number of the parameters during the study to permit optimization of core design. The optimum design may be defined as that which, in the event all potential reactivity is released, presents no hazards to the reactor operating personnel, the installation, or the environs.

II. PROGRAM REVIEW

A comprehensive investigation of all the parameters which affect the severity and magnitude of accidental power excursions in low power homogenous reactors should include the following:

- i. Core geometry
 - a. Sphere
 - (1) Orifice size
 - (2) Orifice geometry
 - b. Cylinder
 - (1) Open ended
 - (2) Flat ends and orificed
 - (3) Domed and orificed

2. Reflector
 - a. Material
 - b. Thickness
 - c. Density
3. Initial fuel solution temperature
4. Initial core atmosphere pressure
5. Amount of reactivity released
6. Reactivity addition rate
7. Initial power level
8. Configuration of internal components of core
9. Void volume above fuel
10. Overflow chamber effect
11. Gas explosions

To keep the current study from becoming almost interminable, the program has been restricted to a reactor model of prime interest and to a study of those parameters which bear most directly on the transient characteristics of that reactor. Thus the initial experiments, KEWB I, will be performed with a reactor core patterned after the Los Alamos SUPO reactor.² The only specific difference between the test core and the SUPO core which is likely to make their transient behavior somewhat dissimilar is the amount of free volume in their effluent lines - the test model being more favorable in this respect.

Immediately following the completion of the transient study of the SUPO-type core, the program will be concerned with a similar study of an open cylindrical core and then with an orificed cylinder as is used in the North Carolina State Research Reactor.³

The operating parameters which will affect the energy release in the first core under transient conditions (other than the amount of reactivity involved and the time scale on which it is released) are, in the expected order of importance:

1. Void volume above solution
2. Initial solution temperature
3. Initial core pressure
4. Initial power level

The above variables, together with variations in the amounts of reactivity and rates of reactivity release, constitute the basis of the experimental program

as presently conceived. The void volume above the fuel solution will be varied from 0 to about 20 per cent of the core volume. Solution temperatures will range from about 20° to 90° C. Core pressures will be varied over the practical working range of the gas-recombination system, i. e. 0 to minus 100 inches of water, gage pressure. Initial power levels from "zero" to at least 50 kw will be investigated. Reactivities up to approximately 4 per cent will be introduced on time scales ranging from about 0.040 to 3 seconds.

The pre-transient phase of the experimental program will be concerned mainly with calibrations of the equipment and determinations of the nuclear constants of the test reactor. Mass and temperature coefficients of reactivity along with calibrations of control, safety, and poison rods will be determined during loading of excess reactivity. With an amount of reactivity representative of operating conditions, the prompt neutron lifetime and the effective fraction of delayed neutrons will be determined by a pile oscillator technique. Energy coefficient of gas production will be determined as a function of both power level and temperature, although it is not expected to vary significantly with these parameters. Overall heat transfer coefficients will be evaluated in a series of oscillation experiments, so that post-burst behavior in an appreciable number of the tests can be predicted reliably.

To initiate the transients, reactivity will be added to the test reactor by withdrawal of poison from the core. Two mechanisms will be utilized in order that the time scale of withdrawal may be varied over a wide range, i. e., about 0.040 to 3.0 seconds. The shortest time scale is intended as an approximation to a step increase in reactivity, while the extended time scales will yield information related to ramp rates involved in more typical accidents.

The amount of reactivity to be released in the first test model will be determined by either of two criteria, whichever proves limiting: (1) that amount of reactivity normally provided for 50-kw operation, or (2) that amount which is capable of destroying the integrity of the core container of the test model. If the first criterion proves to be limiting, the maximum reactivity released will be about 4 per cent. Half this amount is required to reach 80° C solution temperature at a 50-kw equilibrium power level, and the remainder is a realistic requirement for experimental flexibility, e. g., absorbing samples installed in or near the core; reflector removal for beam production, margin of control, etc. The second, or destructive criterion cannot be estimated

at the present with the degree of confidence desired. Therefore the kinetic phase of the program will start with the introductions of small (e. g. , 0.2 to 0.3 per cent) amounts of reactivity. The amounts will then be increased stepwise in small enough steps that the results of each succeeding transient can be predicted from the preceding results with sufficient accuracy to guarantee that no rupture will occur in the system.

Since destructive testing has not been included in the current program, a considerable "ruggedization" of the reactor core vessel has been effected to prevent a rupture of the system. Present calculations indicate that, with the ruggedized core design, the tests involving reactivity releases of up to 4 per cent can be accomplished.

III. EXPERIMENTAL FACILITY

The experimental site is located at the North American Aviation Field Test Station, which is situated in the Santa Susana Mountains near the west end of the San Fernando Valley. A plot plan of the KEWB experimental facility is given in Fig. 1.

A. REACTOR TEST BUILDING

The Reactor Test Building, a plan of which is shown in Fig. 2, is an underground concrete structure. This building houses the reactor test core, the control rod, gas handling and fuel storage systems, and the necessary detection instruments. The building is 15 ft by 26 ft by 10 ft high with outside walls and floor of reinforced concrete, 8-inches thick. The roof is a slab of reinforced concrete, one-foot thick. Six feet of earth fill covers the building for shielding purposes. The interior is divided into three gas-tight rooms: the reactor room (12 ft by 15 ft), the gas and fuel handling room (6-1/2 ft by 7-1/2 ft), and the valve gallery (6-1/2 ft by 7-1/2 ft). Concrete shielding walls, two-feet thick, separate the three rooms. A ventilation system is provided for emergency use and can be used to purge the atmosphere in any or all of the rooms. The exhausted air is discharged from a disposal stack.

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Fig. 1. Plot Plan of the KEWB Experimental Facility

B. CONTROL AND ELECTRICAL BUILDINGS

A 12 ft by 20 ft prefabricated sheet-steel building, located 200 feet from the reactor test building, serves as the control station. All recording instruments necessary to operate the reactor in a normal fashion, plus the transient instrumentation, are located in this building. To reduce the effects of cable loss, the preamplifier circuits and some power supplies are located in a small shelter, called the electrical building, located within a few feet of the test building.

C. WASTE DISPOSAL

The waste disposal system for the facility consists of three underground tanks and a 60-foot exhaust stack with a 2000-cfm blower system. The stack and blower are the means by which gas withdrawn from the reactor system may be released to the atmosphere after sufficient decay to insure tolerance-level discharge. A 300-gallon tank, initially at vacuum, is used to collect gas directly from the reactor system. This low-pressure source provides not only the necessary temporary storage capacity, but also, in conjunction with an automatic pressure regulator located between it and the reactor, insures that the reactor atmosphere is at the desired negative pressure. The collection tank is evacuated when required, and the vacuum pump exhaust is fed to the stack blower intake. The system is so interlocked that discharge of excessive activity or blower motor failure will automatically interrupt the active gas flow.

A second storage tank, 1,000-gallon capacity, is buried below floor level of the test building and will retain all liquid waste from the facility. This tank is equipped with pumpout connections, so its service may be renewed if and when occasion demands.

The third underground tank is also of 1,000-gallon capacity and will retain the reactor cooling water so that it may be checked for activity before release to ground drainage. The reactor is cooled by a "once-through" tap water system. Calculation of induced activity based on chemical analysis of well samples from the vicinity of the site indicate less than drinking tolerance activity levels will be present upon discharge from the core. However, the possibility of migration of fuel solution into the cooling water in the case of a breach of one or more of the coils has required the holdup precaution. This tank, as well as the waste-liquid storage tank, is equipped with level alarm

Fig. 2. Plan View of the Underground Reactor Test Building

to indicate impending overflow. The capacity of 1000 gallons allows reactor operation at 50 kw for about one hour.

The experimental facility is shown in Fig. 3 and 4, which are two views of the installation. Figure 3 shows the underground reactor test building with the entrance ramp in the center and the electrical building at the right. The complete facility is shown in Fig. 4 with the control building in the right foreground and the test building and electrical building in the center background.

IV. REACTOR DESCRIPTION

All existing low power homogeneous reactors,²⁻⁶ of the type frequently referred to as water boilers, have three common characteristics: (1) small core vessels of less than 20-liters capacity, (2) graphite reflector, and (3) a plumbing system external to the reflector for processing of the gases evolved from the core during operation. However, design details which affect transient characteristics vary considerably between both existing and proposed models. For this reason the first model to be tested for kinetic behavior is a replica of a particular reactor design - one on which safety information is required in connection with licensing at a specific location. The rated power level of this first test model is representative of the maximum of current water boiler designs, viz. 50 kilowatts. Also representative is the core geometry, which is spherical. This geometry, by merit of most favorable neutron economy, has proved to be the most popular configuration.

In all respects except biological shielding and experimental facilities the first test reactor is a near duplicate of the proposed 50-kw unit. Control, cooling and gas recombination systems are direct reproductions, while the core has been modified in order to assure a reasonable amount of latitude and safety during the investigations and to provide for special pressure and temperature measurements without alteration of transient behavior.

Figure 5 shows the essential features of the core vessel. The sphere is 12.5 inches I. D. with a minimum wall thickness of 0.220 inch. Ten lengths of stainless steel tubing, 1/4 inch O. D. by 0.028 inch wall, each 9 feet long, provide sufficient cooling capacity to maintain the fuel solution at 80° C when the reactor is operating at 50 kw. The inlet and outlet lines are manifolded

Fig. 3. View of the Underground Reactor Test Building
(The Electrical Building is Shown on the Right)

Fig. 4. View of the Complete Experimental Facility
(The Control Building is Shown in the Right Foreground with the
Test Building and Electrical Building in the Center Background)

Fig. 5. Layout of the First Reactor Core Vessel to be Subjected to Transient Tests

along one side of the sphere, and the coils are essentially horizontal. A 2-1/4 inch O.D. tube is re-entrant in the sphere along a horizontal diameter. This central exposure tube will accommodate the poison rod to be used as the mechanism for introducing the reactivity increments. Four additional re-entrant tubes, equally spaced about the vertical diameter, provide passages for the control and safety rods. These rods are normal sintered B_4C rods contained in thimbles. They are positioned by conventional rack and pinion drives and fall freely when released by electromagnets attaching them to their individual racks. These rods control a total of about 8 per cent reactivity.

A vertical effluent line is attached to the top of the core. This tube, 2 inches in diameter and 18 inches long, leads to a deflection dome which facilitates gas-liquid separation in the event of expulsion of fuel solution from the core. The solution is temporarily retained in an annular reservoir, while the hydrogen-oxygen gases are allowed to pass through an entrainment filter before being swept to the recombiner. Drainage from the holdup reservoir to the core is accomplished by gravity feed thru a 3/16-inch hole at the bottom of the 2-liter reservoir. Above the entrainment filter the vessel is brought to a dome configuration and gas sweep lines entering at this location conduct the evolved hydrogen and oxygen from the core vessel to the recombiner and return the condensate to the core.

The reflector consists of AGOT-grade graphite bars stacked to form a 56-inch cube, which rests on a concrete pedestal and is completely enclosed by a gas-tight reinforced sheet-aluminum container. This container is capable of withstanding an internal pressure of 2 psig and will serve to confine liquid and gas released by the core if rupture of that container should occur. A cutaway view of the reactor installation is shown in Fig. 6.

A. GAS AND FUEL HANDLING SYSTEMS

The plumbing associated with the test reactor is located in a metal-lined gas-tight room adjacent to the reactor room but separated from it by two feet of concrete. (See Fig. 2.) The gas-recombination system and all vessels and piping necessary for manipulations and storage of fuel are located in alcoves in the metal-lined room. Operations involving equipment in this room, which include the transporting of fuel to and from the core, fuel concentration and dilution, decontamination of all lines and vessels, measurement of gas production from the core, etc., are conducted remotely through a concrete shielding wall which is two-feet thick.

The gas handling system provides for circulation of 7 cfm of gas through the core vessel. The sweep gas dilutes hydrogen and oxygen produced in the core and conducts the mixture through a platinized-alumina catalyst bed, where the gases are recombined, and returns the condensate to the core. An aspirator provides the driving pressure for sweep-gas flow, and phase separation takes place in a 30-liter reservoir which also serves as the housing for an entrainment filter and the catalyst bed. A tap-water heat exchanger at the inlet to the

Fig. 6. Perspective Cutaway of the Test Reactor Installation

canned-rotor aspirator pump removes the heat of recombination from the system. The working liquid for the aspirator is distilled water and is maintained at constant volume in the reservoir by action of an overflow weir.

The fuel handling system consists primarily of three vessels with inter-connecting piping. A 3-liter bowl is used to introduce the initial charges of uranium into the system and to contain fuel solution during concentration by vacuum distillation. The contents of this vessel drain by gravity into a 20-liter cylindrical reservoir, 6 inches in diameter, which serves as the main storage tank for fuel solution in the reactor system. A distillation condenser is mounted above the 3-liter vessel, and will be used to trap water vapor during concentration of the fuel solution contained in the 3-liter vessel.

B. INSTRUMENTATION

The instrumentation system is composed of two major portions. One portion comprises those instruments, controls, and actuators which provide working control of the reactor. These enable the operator to operate the reactor in a conventional manner. This group of instruments is designated as the "operational" instrumentation. The second portion comprises those instruments, controls, actuators, and recording devices which enable the operator to initiate a reactivity release and record the dynamic behavior of the reactor following the release. This group is designated as the "transient" instrumentation.

1. Operational Instrumentation - A block diagram of the nuclear instruments for normal reactor operation is shown in Fig. 7. Two pulse-counting channels are provided for pre-startup and low power level indication. The detectors are BF_3 chambers placed on top of the gas-tight container which enclose the reflector. One channel is connected through a pulse amplifier to a linear count rate meter with range switching for accurate determination of power level in the low range. The other channel is similarly connected to a four-decade logarithmic count rate meter for wide-range monitoring at low levels. Two ionization chamber channels are also provided. One furnishes input current to an electrometer capable of measuring and displaying currents from 10^{-10} to 10^{-4} ampere. The electrometer output is also used as the input current to a combined servo-amplifier and level recorder. The servo-amplifier output is used to control the position of one of the control rods so as to hold the

Fig. 7. Block Diagram of the Reactor Operation Instrumentation

reactor power level constant at a desired value. The second ionization chamber provides a current to a logarithmic amplifier whose output is displayed on a level recorder covering six decades without scale switching. Thus this channel provides wide-range monitoring of power level at high values.

Four automatic safety trips are provided during normal reactor operation. As shown in Fig. 7, the output of the linear count rate meter is fed to a meter relay so that an excessive counting rate will actuate the scram circuit. Likewise, the current into the electrometer is passed through a meter relay to the scram circuit, and the amplified output from the electrometer is also fed to a second meter relay and then to the scram circuit. A voltage proportional to the period of the reactor is taken from the output of the logarithmic amplifier and used to actuate the scram circuit through the period meter relay if the reactor period should become short.

2. Transient Instrumentation - Block diagrams of the instrumentation for recording the dynamic behavior of the reactor following a reactivity release are shown in Fig. 8 and 9.

Fig. 8. Block Diagram of Instrumentation for Transient Neutron Levels

Power level information is furnished by three channels operating from ion chambers. Two of these chambers are connected to logarithmic amplifiers with a range of about six decades. The outputs of these amplifiers are linear with respect to the logarithm of the input current from the ion chambers, thus enabling six decades of neutron level to be recorded on a single galvanometer trace. The third chamber is connected to a current amplifier directly and is intended to measure the power level on a linear scale during an excursion. The use of a linear channel for this purpose gives a more accurate recording of the power level near, and including, the peak value.

A group of about 24 strain gages is mounted at various points on the outside surfaces of the reactor core, the overflow chamber, and the ballast tank in the gas handling system. These gages will be calibrated in position prior to actual reactor operation by the application of hydrostatic pressure to the system, so that the relationship of gage output to pressure at the gage locations will be known. Each active strain gage constitutes one leg of a four-leg Wheatstone bridge. The bridge is energized by a three-kilocycle voltage from a carrier amplifier; the output is amplified and demodulated by the carrier amplifier, and then fed to a galvanometer in a recording oscillograph. A device termed a "carrier amplifier-multiplier" is used to enable each channel of a four-channel carrier amplifier to select one strain gage from a group of six gages assigned to that channel for recording during an excursion and to read each other gage in the group after the excursion without the necessity of rebalancing the channel controls between readings. Thus both elastic and permanent deformation of the reactor and ballast chamber may be accurately measured.

Pressure pickups are provided to measure both the initial static pressure in the sphere, the reaction and impact pressures during expulsion of fuel solution and the pressure surges from inflammation of hydrogen-oxygen. The pickups intended to measure reaction pressure and explosion pressure are used in conjunction with a 20-kilocycle four-channel carrier amplifier. The outputs of the amplifier are recorded on galvanometers, whose frequency response is essentially flat to 3000 cycles per second. The pickups intended to measure static pressure and also to monitor the pressure drop across the aspirator pump are used in conjunction with a 3-kilocycle carrier amplifier, and the output is displayed on meters located in the control room. Temperature measurements in the fuel solution are made by iron-constantan thermocouples

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Fig. 9. Block Diagram of Instrumentation for Supplementary Transient Data

in stainless steel sheaths with compressed MgO insulation. The wires are 0.010 inch in diameter, and the tips are bare except for a thin layer of platinum sputtered on for chemical protection. The stainless steel sheath is brought through the sphere wall by welding it to both ends of a hole through a stainless steel cap screw which is screwed into a boss-type fitting in the sphere. The output is taken directly to a galvanometer of fairly high sensitivity. Tests have shown this to be a reliable method of obtaining fast response temperature information in the fuel solution.

- LEGEND:
—□— PRESSURE PICK-UPS:	—●— THERMOCOUPLES:
1 - 0-25 PSIA	1 - CORE FUEL TEMPERATURE
2 - 0-100 PSIG	2 - CORE FUEL TEMPERATURE
3 - 0-100 PSIG	3 - CATALYST BED TEMPERATURE
4 - 0-1000 PSIG	4 - BALLAST CHAMBER TEMPERATURE
5 - 0-1000 PSIG	
6 - 0-25 PSIA	X STRAIN GAGES AT VARIOUS POINTS
7 - 0-25 PSIA	
8 - 0-1000 PSIG	

Fig. 10. Locations of Detectors for Supplementary Data

The locations of the strain gages, pressure pickups, and thermocouples are shown with respect to the major parts of the reactor system in Fig. 10. Microphones are located on the core and recombiner assembly as an aid in detecting equipment malfunction and to give aural perception of the reactor and gas handling system behavior during an excursion. The microphone outputs are amplified and presented over a speaker in the control room and recorded on magnetic tape for further study. It is expected that comparative estimates of the violence of the excursions can be made from these recordings and that a useful, qualitative picture of the hydrodynamic behavior of the fuel will be obtained.

V. THEORETICAL CONSIDERATIONS

Concurrent with the planning of the facility and the experimental program, a series of theoretical studies of the transient behavior of water boiler reactors has been in progress. The main objectives have been the following:

1. To facilitate specification of adequate transient instrumentation.
2. To indicate the relative importance of the various parameters.
3. To predict the dependence of peak power, pressure, etc., on the more important parameters, especially in the neighborhood of potentially damaging situations.

Additional analysis has been concerned with the possibility of measuring the reactor constants during the static phase of operation by observing both free and forced power oscillations of small amplitude.⁷

The theoretical model employed consists of the usual space-independent reactor kinetic equations, coupled with linear representations for heat production and transfer and for the production and diffusion of radiolytic decomposition gas. Some of the pertinent numerical values used are as follows:

Prompt neutron generation time.	120 microsec
Reciprocal heat capacity of core	0.017 °C/kw-sec
Reciprocal relaxation time for heat flow	0.018 sec ⁻¹
Radiolytic gas production rate (STP)	4.16 cm ³ /kw-sec
Reciprocal residence time for gas bubbles	0.5 sec ⁻¹

Temperature coefficient of reactivity . . . $-2.4 \times 10^{-4}/^{\circ}\text{C}$
Gas coefficient of reactivity. $-7 \times 10^{-6}/\text{cm}^3$

These coefficients are typical measured values for a water boiler, except for the bubble residence time and the gas coefficient of reactivity. The bubble residence time was arbitrarily chosen as two seconds for preliminary computations, and the value for the gas reactivity coefficient is the smallest of several values which may be derived from computation and from rather uncertain experimental evidence.

The results of the transient studies indicate that the range of introduced reactivity steps may be qualitatively divided into four regions. These are characterized by the type of shutdown mechanism which predominates and by the manner in which the time scale for the energy burst influences the shutdown mechanism.

The first range is approximately from zero to 0.4 per cent reactivity, corresponding to stable periods greater than ten seconds. In this range the shutdown is caused primarily by temperature rise, because the transient is proceeding slowly enough that the radiolytic gas produced in the core solution escapes without contributing to the reactivity. Transient behavior in this range has previously been investigated.^{8, 9}

The second range is from 0.4 to 1.0 per cent, corresponding to periods between 10 and 0.05 seconds. This covers the range in which the time scale of the energy release is comparable to the average residence time of gas bubbles in the solution, so that gas production will begin to play a significant role in the shutdown.

The third range is from 1.0 to 2.0 per cent, with periods from 50 to 10 milliseconds. Here the time scale for the transient is very short compared to the bubble residence time, and most of the gas generated will contribute to shutdown. Since the energy coefficient of reactivity for gas production is an order of magnitude larger than that for temperature effects, the severity of these excursions is much less than would be anticipated from consideration of temperature alone.

Subsequent to the burst which lasts for a small fraction of a second, the loss of negative reactivity by bubbling will cause a new power rise; however, this second surge is similar to the effect of introducing reactivity at a

relatively slow "ramp" rate. In fact, this return of reactivity may be compared with a "power demand" situation in which the rate of reactivity introduction decreases as the transient proceeds. The rate, which is initially of the order of one dollar per second, is sufficiently great that some overshoot will occur, but in contrast with the initial burst the result is a very mild transient for which the time scale is several seconds or more.

It is during this slow transient that sufficient energy must be generated that the loss of negative reactivity by bubbling may be compensated by temperature. The importance of radiolytic gas is thus twofold: the peak power in a fast burst is greatly limited, and the eventual release of energy needed to attain an equilibrium prescribed by the temperature-reactivity relation is greatly slowed. Because of this change in time scale, the total energy release is practically halved by the gas production and only a small fraction of this energy is produced in an intense burst.

The result of an analogue computation typical of this range of reactivity inputs is shown in Fig. 11. On the basis of temperature alone, the predicted peak power for this case would be about 70 megawatts, instead of the 8 megawatts shown. Events subsequent to the first burst are shown by the use of an expanded vertical scale and a compressed time scale. The second power peak, this time only 150 kilowatts, is associated with the slow return of reactivity as radiolytic gas escapes from the solution. Note that during the events shown here, the times are small compared to the characteristic time for heat transfer, so that the process is still essentially adiabatic. Not shown is the asymptotic approach to a final equilibrium power of 52 kilowatts, prescribed by the amount of the initial reactivity step and the operating power coefficients of reactivity for temperature and gas production.

The fourth range is from 2.0 to 4.0 per cent, with periods from 10 to 4 milliseconds. This range is characterized by the appearance of inertial pressure, which arises because the mixture of core solution and radiolytic gas bubbles cannot expand rapidly enough to keep up with the rapidly rising rate of energy production. (This phenomenon is analogous to transient thermal stresses in a metal which is heated so rapidly that expansion cannot keep up with the temperature rise.)

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Fig. 11. Analogue Computation for a Two-Dollar Step Increase in Reactivity

Figure 12 shows the results of analogue computations both with and without correction for the inertial pressure effect. Here the peak power in the fast burst is plotted as a function of reactor period and reactivity step. The relative change in peak power is nearly proportional to the reciprocal period squared, as was originally suggested by Dr. Manson Benedict.¹⁰

Fig. 12. Peak Power vs Reactivity Step from Analogue Computations

In the simple case of an open-ended cylindrical core, for which the inertial pressure computation was performed, the peak inertial pressure is 6 atmospheres at the largest reactivity step now contemplated (4.0 per cent). If the radiolytic gas were not present, this effect would be negligibly small; the inertial pressure arises primarily because the presence of gas bubbles greatly increases the compressibility of the solution without materially affecting its density. This in turn implies a significant decrease in the speed of sound.

During each of the stepwise numerical computations which were performed, the minimum speed of sound was noted and the time required for sound to traverse the reactor core diameter was calculated. Comparison of this time interval with the reactor period in each case shows that the time for sound traverse is consistently somewhat less than the period, but the two times are not greatly different in any of the cases considered.

Therefore, in order to estimate the likelihood of shock waves in the core solution, another approach is necessary. The maximum fluid displacement velocity was calculated for the 4-millisecond transient, and it turned out to be ten times smaller than the minimum speed of sound in this case. Hence, the computation indicates that shock waves will probably not be encountered, but the range of reactivity steps in which inertial effects are important must be explored very cautiously. This is especially important for the first test core, which is spherical instead of cylindrical, so that as the solution level rises it encounters a reduced free surface area and a consequent enhancement of inertial effects.

Several other phenomena are important in determining the energy release. When the core vessel has a limited expansion volume, with a small diameter relief tube, there will be a pressure surge beginning when the vessel is filled, whereupon subsequent expansion encounters a resistance to transient flow in the relief tube. This effect becomes important at different reactivities, depending upon the amount of expansion volume initially available. In the spherical core, all transients will be first investigated with the largest practical void volume; studies of the effect of reduced void volume will proceed carefully, using the results of theoretical calculations as a guide. For example, the case shown in Fig. 11 is modified by this effect as follows:

Initial Void Volume (liters)	Peak Power (Megawatts)	Peak Pressure (Atmospheres)
0.5	16	6.5
1.0	8.5	1.7
1.5	8	0.35
∞	8	0

For reactivity steps greater than about 2 per cent, the situation is complicated by inertial pressure. The dependence of peak pressure on initial void volume is qualitatively the same, but the calculation is less reliable. Results of calculations for 3.0 per cent reactivity and a one-liter void show 78 atmospheres peak pressure arising from the combination of inertial effects and limited void space.

Fortunately, the temperature coefficient of reactivity remains more or less unaffected by these phenomena, and the worst case is that in which gas production contributes nothing to the shutdown. The power surge is still temperature-limited, and it appears that the peak power would be larger by an order of magnitude. It is expected that subsequent tests to be performed with a cylindrical core having essentially unlimited expansion space will show that this configuration has much advantage in intrinsic safety over the sphere (e. g. Los Alamos Water Boiler) and the closed cylinder (e. g. North Carolina State College Water Boiler), particularly if provision is made for holding up overflow in a reservoir outside the region of significant statistical weight.

The spherical core has an additional disadvantage in that the reduction in reactivity caused by gas bubbles in an under-full sphere is partially offset by the reduced neutron leakage from the more nearly spherical geometry. The effect is not large and is essentially independent of solution height, because both the density effect on reactivity and the geometrical effect on leakage are approximately proportional to the total volume of gas bubbles.

The onset of boiling is another phenomenon of importance in determining the energy release. Here the important parameter is initial temperature, which may be varied either by initiating a transient at various equilibrium power levels or by passing hot water through the cooling coils when the reactor

is shut down. If the boiling point is reached some time after the initial gas-limited burst (i. e., during the relatively slow second power surge), the effect of boiling will be a sudden shutdown by steam formation. On the other hand, if 100° C is reached during a pressure surge caused by inertial effects or by limited void space, the results indicate that no boiling can occur because the pressure-temperature curve during the surge will be rising more rapidly than the equilibrium vaporization curve. Boiling will then contribute only to minimizing the tail on the power-time curve after peak pressure has been reached.

Initial power level is an important parameter for small reactivity steps, as evidenced by the fact that the peak power in a small transient starting from "zero power" may be much less than the nominal operating power level of the reactor. For fast transients, the initial power level is important only as it affects the initial temperature and hence the time at which boiling begins. The peak power in a fast transient is essentially unaffected by the starting concentration of delayed neutron emitters, which is the only other parameter influenced by the initial power level. It should also be noted that the initial solution level will depend on the power because of the presence of an equilibrium gas-bubble concentration. This will become important at small values of the initial void volume.

The rate of input of reactivity is important in those cases where the shutdown mechanisms begin to act significantly before the full amount of available reactivity is inserted. This will occur for faster transients and for higher initial power levels. For a given amount of available reactivity, the step input yields the transient with the highest peak power, while at the other extreme there is a range of low rates of reactivity input for which there will be no power over-shoot at all but rather a slow transition to a new equilibrium power. On the other hand, the energy release varies only a factor of two from one extreme to the other. Since peak power is much more indicative of potentially hazardous situations, and since it will vary greatly with the reactivity rate, this rate is an important parameter for experimental investigation. Because the step input represents the limiting case for transients with a given total reactivity available, most of the computations to date are concerned with step inputs.

Other parameters of lesser importance may be noted. For example, the energy coefficient of reactivity for radiolytic gas will be inversely proportional to the initial absolute pressure over the solution. Also, the prompt neutron

generation time, to which the peak power is approximately inversely proportional, will depend on the type of reflector, the fuel concentration, the thickness of the core shell, and the positions of safety and control rods. Finally, the details of the holdup and return of expelled solution will influence the power-time history.

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