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QUARTERLY PROGRESS REPORT
THE KEWB PROGRAM
JULY - SEPTEMBER, 1956

ATOMICS INTERNATIONAL

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QUARTERLY PROGRESS REPORT
THE KEWB PROGRAM
JULY - SEPTEMBER, 1956

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ABSTRACT

The reactor test facility for the KEWB program (Kinetic Experiments on Water Boilers) was made critical on July 13, 1956. Preliminary measurements have been made to determine the reactor characteristics. The response of the reactor to forced oscillations has been investigated with the pile oscillator technique and the data are presently being analyzed. Transient behavior of the reactor has been studied with reactivity releases up to 0.7 per cent.

These experiments resulted in self-limited neutron bursts in which the peak reactor power reached 200 kilowatts for the maximum reactivity release of 0.7 per cent. The bursts were limited by an increase in the temperature of the reactor fuel along with a significant assist from the radiolytic gas evolution. Detailed analysis of the data is being conducted to develop quantitative conclusions on the dynamic behavior of the reactor.

I. INTRODUCTION

The program of Kinetic Experiments on Water Boilers—the KEWB program—represents one of the substantial efforts sponsored by the Atomic Energy Commission as a part of the Commission's Reactor Safety Program. The objectives of the KEWB program include the experimental study of the kinetic behavior of homogeneous reactors to develop the knowledge and understanding of the effects of some of the parameters which play dominant roles in the dynamic characteristics and the safety of the reactors. Ultimately it is expected that criteria will be developed to produce homogeneous reactor designs with maximum safety characteristics for all intended applications. This report is the first in a series of periodic progress reports to record and distribute the results of the studies. This first report in the series covers the period of July, August, and September, 1956.

The program objectives and the planning, initial studies and construction in preparation for the experimental work have been reviewed in some detail in a previous publication.¹ However, a brief synopsis is included here for the convenience of the reader.

The approach in this program has been to construct a prototype reactor with the special provisions required for the various experimental studies. Since there are such a large number of parameters which can affect the magnitude of a power excursion, the program has been restricted to the study of those parameters which bear directly on the transient behavior of the reactor. The operating parameters to be investigated include the amount of reactivity released, the rate of reactivity release, the void volume above the fuel solution, the initial solution temperature, the initial core pressure, and the initial power level.

The design and construction of the reactor in a special test facility was undertaken as the first step in the program in October, 1954. The facility is located in the Santa Susana Mountains, at the west end of the San Fernando Valley, about 30 miles from central Los Angeles. Included in this facility are an underground building to house the reactor test cores with reflector, gas handling system and associated equipment; a waste disposal system; a small prefabricated building containing amplifiers and power supplies; and the control building, some 200 feet from the test building. Figures 1 to 3 show the essential features of the test facility installation.

Fig. 1. Plan View of the Reactor Test Building

Fig. 2. View of Completed Underground Test Building

The first test core is a spherical core, 12.3 inches inside diameter, with a wall thickness of about 0.22 inch. This core is patterned after the Los Alamos SUPO² core and is designed for normal operation at 50 kw. The principal features of the core are shown in Fig. 4, while Fig. 5 is a cutaway drawing of the core installed in the graphite reflector.

The reactor was loaded with highly enriched uranium in the form of uranyl sulfate solution and was made critical on July 13, 1956.

II. PROGRESS TO DATE

During the report period, the critical mass of the reactor was established and a preliminary set of measurements was made to determine the reactor characteristics. Included in these tests were: control rod calibration, neutron

distribution in the core, temperature coefficient of reactivity, gas production rate, and power calibration. In addition, data were obtained on the response of the reactor to forced oscillations and to step inputs of reactivity up to approximately 0.7 per cent. All of these tests were conducted with less than one per cent reactivity loading in the reactor and will, therefore, be rechecked after the full loading of four per cent excess is attained. The tests were principally designed to resolve measurement techniques in preparation for the final effort at full reactivity loading, since only the results of the latter measurements are representative of the reactor system to be tested. The major portion of this report is devoted to detailed discussion of the pile oscillator and transient tests.

Fig. 3. View of Site Showing Completed Building and Control and Electrical Building

Fig. 4. Layout of First Reactor Core Vessel to be Subjected to Transient Tests

III. CRITICAL MASS

The KEWB I core was designed to withstand transient pressures resulting from the ignition of hydrogen-oxygen gas mixtures produced during the power excursions. Accordingly, the shell and through-tube thicknesses are considerably greater than that of conventional cores. This additional steel is the primary

Fig. 5. Isometric View of the Reactor

reason for the fact that the critical mass of the unit is several hundred grams higher than that required for otherwise similar reactors. The critical loading at room temperature is 1680 grams of U^{235} in the form of fully enriched uranyl sulfate solution. This determination of the critical mass is obtained with 11.0 liters of fuel solution in the sphere. An additional 0.5 liter of solution will be added in loading the reactor with four per cent excess reactivity. This will result in a fuel solution volume of 11.5 liters and a void volume above the solution of 2.2 liters, which is 16 per cent of the spherical core volume.

IV. CONTROL ROD CALIBRATION

Subcritical multiplication measurements, transcribed to reactivity values, were made during the stepwise withdrawal of a control rod with essentially zero excess reactivity. The effectiveness vs position curve for the rod was then checked by measurements of reactor periods over a portion of the travel of the rod. The calibration curve obtained by these methods, shown in Fig. 6, indicates a total rod worth of about 1.8 per cent reactivity. The reactor has four rods equally spaced on a six-inch diameter circle. It is expected that all rods will have very similar calibration curves, and preliminary indications are that the interaction between the rods is slight.

V. TEMPERATURE COEFFICIENT OF REACTIVITY

The reactor heat is removed by a once-through tap water coolant system. Whenever desired, the water may be diverted through a commercial water heater and an externally-heated line, allowing artificial heating of the core to more than 70° C. The core solution temperature was varied between 35° and 50° C and the reactivity changes noted. The temperature coefficient of reactivity in this range was found to be -0.024 per cent reactivity per degree Centigrade.

VI. ENERGY COEFFICIENT OF GAS PRODUCTION

Based on a power calibration obtained by observing the rate of rise of the core temperature at fixed power and by calculating the heat capacity of the system,

Fig. 6. Control Rod Calibration Curve

a gas production rate of 14 cm^3 at NTP per watt-hour was measured. The gas evolved during one hour of operation at 500 watts was allowed to fill the previously-evacuated atmosphere chamber above the core. The pressure change in this chamber was noted and the gas volume calculated. Temperature corrections were avoided by allowing the plumbing system to return to ambient temperature before recording the higher pressure value.

VII. NEUTRON DISTRIBUTION MEASUREMENTS

Zinc and indium wires were exposed along the axis of the central exposure tube of the core to determine relative neutron distributions. The measured distribution shows a ratio of neutron flux at the center of the sphere to that at the edge of about two. The flux distribution in the core has not yet been fitted to a relation of the expected form of $\frac{\sin kr}{r}$.

VIII. OSCILLATION MEASUREMENTS

Two of the more important constants which determine the kinetic behavior of any reactor system are the effective fraction of delayed neutrons, β , and the prompt neutron lifetime, τ . A convenient means of measuring these constants is available through the use of a pile oscillator mechanism. This technique has been used in the past.^{3,4} The reactor is driven by an oscillating absorber, or other means of reactivity variation, with the net reactivity oscillating about zero so that the power level oscillates about a mean value. Phase lag between the point of average power and the point of zero driving reactivity, and the relative amplitude of the power response curve are measured. The reactivity amplitude is adjusted upward as the oscillation frequency is increased in order to maintain power variations which have conveniently measurable amplitudes. A typical calculated curve is shown in Fig. 7.¹

It will be noted that both constants mentioned above may be determined by extrapolation of intercepts to the graphical coordinates in Fig. 7. However, as will be also noted, the reactivity involved must be used to determine the ordinate value at any given frequency. Since both constants in question are involved in the determination of absolute reactivity, only their ratio can be determined directly.

Fig. 7. Water Boiler Transfer Function

As shown by the calculated curves in Fig. 8, the ratio β/τ is directly measured if the phase lag is plotted against frequency, the ratio being the measured value of the angular frequency at which the phase angle is minus 45 degrees.¹ The ratio of the two constants is nearly as important as the separate values since their use in the kinetic equations most frequently occurs as the ratio.

The oscillation device which is being used in the experiments is somewhat different in design from those which have been used elsewhere. The system includes two cylinders coaxially mounted in the central exposure tube of the reactor along the diameter of the core vessel. Each of the cylinders contains a variable number of cadmium absorbers attached to its surface.

One of the cylinders, the stator, remains stationary while the second cylinder, the rotor, rotates coaxially about the stator. Rectangular pieces of cadmium on the inner surface of the rotor alternately cover and uncover equal-length pieces of cadmium attached to the outer surface of the stator. The cadmium absorbers, or "spots," mounted on the stator are so shaped that their total surface area exposed by the rectangular "shades" describes a sine function when the rotor is moved at constant angular velocity. This characteristic yields a sinusoidal driving function of reactivity. Figure 9 is a photograph of the stator assembly showing the specially shaped cadmium absorbers mounted on the outer surfaces of the cylinder. Figure 10 shows both the stator and the rotor in which the cadmium shades are mounted on the inner surface. It should be noted that the spots on the stator as well as the shades on the rotor are mounted at 90° intervals around the cylinders, so that each revolution of the rotor produces four cycles of oscillation in the reactivity. A plot of the measured reactivity as a function of the rotor position is shown in Fig. 11. A sine curve of equal frequency and amplitude has been included for comparison with the experimental points.

The amount of reactivity controlled by the oscillator is varied by the number of cadmium absorbing spots mounted on the stator. As shown in Fig. 9, nine rows of spots, equispaced along the reactor core diameter, can be included. The variation can be further increased by filling the stator with water. This is necessary to obtain conveniently-measurable amplitudes of power oscillation at the higher frequencies. The maximum variation in reactivity available with the number of rows of absorbers utilized is shown in Fig. 12.

Fig. 8. Water Boiler Power Phase Shift vs Driving Frequency

Fig. 9. Stator of Pile Oscillator

Fig. 10. Rotor and Stator of Pile Oscillator

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Fig. 11. Reactivity vs Angular Position for the Oscillator

Fig. 12. Maximum Available Reactivity vs Number of Cadmium Absorbing Spots Mounted on the Stator

The drive unit for the rotor consists of a hollow drive shaft which extends outside the reflector housing of the reactor and which is rotated by a motor arrangement coupled to it by means of a timing belt and pulleys. Two motor drives are used: a Bodine motor and fixed gear combinations are used at lower speeds, while a 1725-rpm motor coupled to a variable-speed transmission is used to drive the rotor at high velocity. The top speed of the rotor is 3,000 rpm, which yields a reactivity perturbation frequency of 12,000 per minute, since each revolution results in the exposure and concealment of a given absorber "spot" on four separate occasions. The position of the shades is monitored by a phototube-aperture-lightsource arrangement which is keyed to the drive shaft in such a way that a pulse results each time the reactivity passes through a null. The drive system is shown with the aperture and phototube arrangement in Fig. 13.

Fig. 13. Pile Oscillator Assembly Installed in the Central Exposure Tube of the Reactor

The power level of the reactor is monitored with an uncompensated, boron-coated ion chamber powered by batteries. The a-c component of the signal is amplified to a level sufficient to record on an oscillograph having a maximum chart speed of 100 inches/second. Figure 14 shows one of the records which have been obtained. These data were taken with an oscillator frequency of 3.57 perturbations per second ($\omega = 22.4$ rad/sec).

At the low power levels (1.5 to 150 watts) at which the reactor is operated for the pile oscillator measurements, there are delays in the electronic system which affect the data at the higher oscillator frequencies. These delay times are presently being measured, and the corrected data will be presented in a subsequent report. Measurements have been completed at a reactivity loading of one per cent to determine the dependence of the reactor constants upon uranium concentration in the fuel solution.

IX. CONTROL ROD INDUCED TRANSIENTS

A series of power excursions have been induced in the reactor by rapid withdrawal of control rods to a number of different positions. In addition to furnishing data on the dynamic behavior of the reactor, the transients were designed to determine if the radiation levels accompanying normal reactor operation were sufficiently intense to effect recombination of the hydrogen and oxygen gases evolved from the core solution before dilution of these gases was accomplished by the sweep-gas stream.

Most of the transient tests which have been made were restricted to examinations of peak power as a function of reactivity, and included only that reactivity region in which gas production occurs at rates low enough to prohibit expansion pressure from occurring. The gas recombination system was excluded from the system, and a ballast tank was utilized to accommodate the gas produced during the excursions. This allowed examination of the core vessel alone with respect to the gas ignition question. No coolant was circulated through the core, and in most of the excursions the reactor was shut down manually immediately after the peak power had been attained.

The reactivity range investigated included values up to very near prompt criticality, though all measured reactor periods were greater than one-half second.

The power rise in every case was sufficiently slow to be followed accurately with a conventional chart recorder with fast pen-travel provisions (one-half second for full-scale travel). The signal to the recorder is furnished by a boron-lined ion chamber after amplification in a logarithmic amplifier. Period measurements taken from this information channel provided an accurate check on the direct-reading period channels which furnish information to the recording oscillograph.

A typical power trace is shown in Fig. 15. This was obtained with a reactivity release of 0.45 per cent, which gives a reactor period of 4.8 seconds. As is shown in the trace, the power reached a peak of 40 kilowatts, oscillated briefly with decreasing amplitude and then decayed with a negative period of about 80 seconds. The peak power is limited by the core temperature rise with significant assistance from the gas formation. The oscillations which follow the first power peak result from the escape and subsequent regeneration of gas in the core. This periodic behavior is damped and then finally disappears as the sustained high-power operation produces a sufficiently large temperature rise to compensate for the added reactivity. The final power decay rate is determined by the temperature rise and the delayed neutron lifetimes.

Figure 16 is taken from an oscillograph recording of the output from three power channels, a direct-reading period channel, and two thermocouples placed inside the core vessel. Two logarithmic power channels are used to give a complete record of the power as a function of time; these channels overlap one another by about two decades. A period signal is derived from each of these channels, and the reciprocal period may be determined by direct measurement of the trace displacement. The third power channel includes a d-c, linear amplifier system, so that it can be used for an accurate determination of peak power.

The transient recorded in Fig. 16 resulted from a release of 0.71 per cent reactivity, which gives a reactor period of 0.88 second. The power rose to 200 kilowatts before reactor shutdown was accomplished by a combination of temperature rise and gas evolution. The linear power channel shows clearly the shape of the power peak, while the high-range log power channel shows the power trace over approximately five decades of power. The amplification on the low-range log power channel was set sufficiently high that the output saturated before the peak power was reached.

Fig. 14. Oscillogram Taken With the Pile Oscillator Operated at a Frequency of 3.57 Perturbations per Second

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Fig. 15. Power Trace for a Reactivity Release of 0.45 Per Cent

The direct-reading period channel, which is derived from the high-range log power channel, shows the increase in reactor period as the inherent shutdown mechanisms begin to compensate for the reactivity before the peak power level is reached. The indicated peak in the reciprocal period trace and the sharp increase at the beginning of the high-level log power trace are spurious indications which result from the characteristics of the input diode stage of the logarithmic amplifier.

The displacement of the two core thermocouple traces shows clearly that there is a considerable gradient of temperature, until the first gross stirring of the fuel solution occurs as the gas bubbles rise to the surface immediately after the first power peak. The central thermocouple, located near the center of the sphere, shows a peak just after maximum power is reached, while the thermocouple near the edge of the sphere continues to rise during the bubble-induced convection period.

These thermocouples are iron-constantan units enclosed in a stainless steel sheath, and provided with MgO insulation. The sheath is 0.040 inch in outer diameter, and the element wires are 0.010 inch in diameter. The junction is formed by removing some of the MgO from an open end of the sheath and closing the tip of the sheath by cold-welding while simultaneously making the couple itself. The resulting blade at the end of the sheath is less than 0.010 inch thick. The blade is then gold plated (0.003 inch) for corrosion resistance.

All of the transient experiments were conducted by withdrawing the control rods to equal elevations. The rod travel times will not permit reactivities greater than about 0.9 per cent to be added, even when the rods are withdrawn as a group, since shutdown begins to occur before they have reached their final position. As additional fuel is loaded into the reactor this limitation will be somewhat relieved, but the specially designed fast reactivity introduction devices will be installed for the initiation of the faster transients.

Parameters affecting shutdown behavior have been investigated under the following conditions:

1. Stable periods ranging from 36 seconds to 0.8 second.
2. Reactivity releases of 0.2 to 0.7 per cent.
3. Initial pressure in the 39-liter closed gas system communicating with the solution surface ranging from 40 to 65 cm Hg.

4. Gas-filled void space above the solution and within the spherical core fixed at 2.6 liters (11.1 liters of enriched uranyl sulfate solution in a 13.7 liter sphere).
5. Initial solution temperature fixed approximately at 30° C.
6. Reactivity insertion essentially step input.

The results of the power excursions are given in Table I along with earlier water boiler transient data taken with the reactors at Livermore, California,⁵ and at the Los Alamos Scientific Laboratory.⁶ The data are plotted in Fig. 17 with the peak power shown as a function of reactivity input. Figure 18 shows the product of peak power times stable reactor period as a function of reactivity step.

Detailed analysis of the data reported here is being conducted. As more data are obtained, a continuing analysis will permit development of pertinent conclusions on the kinetic behavior of the water boiler reactor.

It is to be noted that excellent agreement has been obtained between the present data and the earlier data^{5,6} obtained for reactivity releases up to 0.4 per cent. The additional information reported here represents the first examination of water boiler transient behavior resulting from reactivity releases greater than 0.4 per cent.

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TABLE I

WATER BOILER TRANSIENTS

Reactor	Run No.	Initial Conditions			Reactivity (per cent)	Reactor Period (seconds)	Peak Power (kilowatts)
		Pressure (cm Hg)	Temperature (°C)	Power (kw)			
KEWB (1956)	1	62	29	Negligible	0.17	36	3.5
	2	54	36		0.24	20	8
	3	57	34		0.35	9.2	20
	4	52	32		0.45	4.8	40
	5	45	28		0.53	3.0	52
	7	44	38		0.58	2.2	57
	8	Uncertain	Uncertain		0.58	2.2	80
	9				0.51	3.4	44
	10				0.60	1.85	83
	11				0.67	1.13	136
	12				0.67	1.13	154
	13	43			0.71	0.88	205
Livermore (1954, Ref. 5)	1	76	28	Negligible	0.13	57	3.1
	2		24		0.18	34	5.8
	3		21		0.27	16	15.8
SUPO (1954, Ref. 6)	1	59	30	1	0.42	5.9	32
	2		77	1	0.42	5.9	23
	4		82	10	0.42	5.9	35

Fig. 17. Peak Power vs Reactivity Release for KEWB Power Excursions

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Fig. 18. Product of Peak Power Times Reactor Period vs Reactivity Release

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REFERENCES

1. M. E. Remley, J. W. Flora, D. L. Hetrick and L. P. Inglis, "Program Review of the Water Boiler Reactor Kinetic Experiments," NAA-SR-1525, March 15, 1956.
2. L. D. P. King, "Los Alamos Homogeneous Reactor - SUPO Model," LA-1301, February 7, 1952.
3. J. M. Harrer, R. E. Boyer, and Darwin Krucoff, Nucleonics, 10, No. 8, 32 (August, 1952).
4. A. M. Weinberg and H. C. Schweinler, Phys. Rev. 74, 851 (1948).
5. J. W. Flora, J. W. Shortall, and W. E. Drummond, "Temperature Effect on Reactivity of the C.R. & D. Water Boiler," LRL-148, June, 1954.
6. P. R. Kasten, "Reactor Dynamics of the Los Alamos Water Boiler," Chem. Eng. Progress Symp., Series No. 11, Nuclear Eng., 50, Part I (1954).