2706

OAK RIDGE NATIONAL LABORATORY
Operated By
CARBIDE AND CARBON CHEMICALS COMPANY

UCC

POST OFFICE BOX P
OAK RIDGE, TENNESSEE

ORNL
CENTRAL FILES NUMBER

CF-53-7-221

DATE: July 23, 1953

COPY NO.

SUBJECT: PRELIMINARY BOILING EXPERIMENTS IN THE
SUPO MODEL OF THE WATER BOILER

This document contains 19 pages.
This is copy 28 of 33. Series A.

TO: R. N. Lyon

FROM: D. G. Thomas

Photostat Price \$ 4-80
Microfilm Price \$ 2-20

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

1 5686

65 - 1

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

PRELIMINARY BOILING EXPERIMENTS IN THE
SUPO MODEL OF THE WATER BOILER

SUMMARY

It has been demonstrated that it is possible to operate a homogeneous reactor (Supo model of the Water Boiler) under boiling conditions and that under the particular conditions encountered, a boiling homogeneous reactor is not inherently unstable.

The solution density change on going from non-boiling to boiling conditions has been calculated using the two-group two-region method. The maximum density change found was 0.8% corresponding to a total nuclear power of 5.4 KW. For small reactivity additions the relationship

$$\frac{\Delta k}{k} = 0.3 \frac{\Delta d}{d}$$

is good to $\pm 10\%$. Average bubble rise rates of 10 ft/sec were calculated assuming that 1 KW of heat was dissipated in uniform volume boiling. This suggests that the onset of vapor evolution in the solution increased the rate of circulation and thereby the rate of surface evaporation. Disengagement velocities from the free surface of the water boiler were found to be 30-50 lbs. of vapor/(hr.)(sq. ft.).

2.

INTRODUCTION

On November 13 and 14, 1951, R. J. Goldstein, P. R. Kasten, R. N. Lyon and P. C. Zmola of ORNL visited L.D.P. King of Los Alamos Scientific Laboratory, and with his cooperation and aid, boiled the Supo model of the Water Boiler⁽¹⁾. This was accomplished by stopping the water flow through the internal cooling tubes, the heat generated being removed with a reflux condenser. The purpose of the experiment was to determine whether a boiling reactor was capable of stable operation. The smooth operation of the reactor during the boiling runs demonstrated that, for the particular conditions encountered, a boiling homogeneous reactor is not inherently unstable. The purpose of this memorandum is to describe briefly the qualitative results and to analyze the data obtained during the experiments.

EXPERIMENTAL RESULTS

Tests were made under three slightly different operating conditions. During the first series of tests there was 880 grams total of U^{235} in the sphere in 12.9 - 13.0 liters of solution. In the second series of tests there was the same amount of uranium but 246 cc less water in the system. The final series of tests were made after 5 grams of U^{235} had been added to the sphere solution. The nominal solution level was 5 cm below the top of the sphere. For the first two series of tests the following procedure was used. The water flow through the

(1) L.D.P. King, "The Los Alamos Homogeneous Reactor, Supo Model"
Report LA-1301 or AECD-3287, February 7, 1952.

~~_____~~
internal cooling coil was stopped and the power level was increased until the solution temperature was within 2°C of the boiling point. The just non-boiling condition was maintained for 10-15 minutes after the steady state non-boiling readings were obtained. The control rod was withdrawn in a stepwise fashion with 10-20 minute intervals between changes in rod position. In the final test the same procedure was followed except that there was no non-boiling run.

The onset of boiling was assumed to correspond to the approximately five fold increase in fluctuations of the power meters. A portion of the chart from The Leeds-Northrup recorder is shown in Figure 1. The chart speed was too slow to allow power fluctuations to be followed, nevertheless it does give a qualitative indication of the change in fluctuations in going from non-boiling to boiling conditions. At the start of the first afternoon's test, the average power fluctuations during boiling were $\pm 20\%$ at a nuclear power level of 5.19 KW. After 2 1/2 hours of operation at 5 KW or greater the average power fluctuations had decreased to $\pm 10\%$. One possible explanation is that in the early tests the cooling coils and steel sphere had not heated up and there was volume boiling of the solution. Whereas in the later tests the cooling coils and steel sphere were in temperature equilibrium and could have been heated enough by gammas and neutrons to allow surface boiling. With the large surfaces available, this would allow more uniform vapor evolution and thus less fluctuations.

It should be pointed out that in the first series of tests the average power passed through a maximum as the control rod was withdrawn. This was not observed in other tests.

Slow Feed

The data obtained during these experiments are given in Table 1.

For a bare, spherical homogeneous reactor, the effect of a small change of reactivity on the density can be expressed by

$$\frac{\Delta k}{k} = 2 \left(\frac{k-1}{k} \right) \frac{\Delta d}{d} \quad (1)$$

However since the Supo model of the Water Boiler had an essentially infinite graphite reflector, this equation would not be expected to apply. Therefore two group theory for a spherical homogeneous core and infinite reflector⁽²⁾ was used to determine the effect of small reactivity changes on the density of the core. Since the model geometry selected did not account for absorption in the core tank, control rods, thimbles, and cooling coils, leakage out the glory hole and condenser passage ways as well as the unsymmetrical shape the thermal constants were adjusted using a fictitious $\sum_{as}$ for the stainless steel. The non-boiling test just below the boiling point was used to evaluate the fictitious $\sum_{as}$.

The problem was essentially that of solving the following transcendental equation⁽³⁾:

$$= \begin{bmatrix} D_{1c} \frac{X'}{X} - D_{1r} \frac{Z_1'}{Z_1} \\ D_{1c} \frac{Y'}{Y} - D_{1r} \frac{Z_1'}{Z_1} \end{bmatrix} \begin{bmatrix} S_2 D_{2c} \frac{Y'}{Y} - S_3 D_{2r} \frac{Z_1'}{Z_1} - (S_2 - S_3) D_{2r} \frac{Z_2'}{Z_2} \\ S_1 D_{2c} \frac{X'}{X} - S_3 D_{2r} \frac{Z_1'}{Z_1} - (S_1 - S_3) D_{2r} \frac{Z_2'}{Z_2} \end{bmatrix} \quad (2)$$

(2) S. Glasstone, M. C. Edlund, "The Elements of Nuclear Reactor Theory," D. Van Nostrand (1952)

(3) Nomenclature is tabulated at the end of the report.

15
TABLE 1

EXPERIMENTAL DATA

Date	Barometer, mm. Hg.	Duration of Test, min.	NE Rod Position	Sphere Temp., °C	Sphere Condition	Pressure Drop, Cm H ₂ O		Circulating Air Flow, liters min
						Condenser	Catalyst Bed	
Nov. 13 - AM ⁽¹⁾	-	-	610	92.0	Non Boiling	5.4	1.5	-
Nov. 13 - PM	-	15	650	93.6	Boiling	6.3	1.0	78
Nov. 13 - PM	-	15	630	93.0	Boiling	5.8	1.2	85
Nov. 13 - PM	-	15	676	93.0	Boiling	6.8	0.6	61
Nov. 13 - PM	-	20	712	93.0	Boiling	7.2	0.4	46.5
Nov. 13 - PM	-	15	759	92.9	Boiling	7.4	0.2	30
Nov. 14 - AM ⁽²⁾	589.5	15	610	91.8	Non Boiling	5.0	1.8	99
Nov. 14 - AM	589.5	10	700 ⁽³⁾	92.4	Non Boiling	5.4	1.6	96
Nov. 14 - AM	589.5	20	802	92.7	Boiling	6.1	1.2	81
Nov. 14 - AM	589.5	15	948	92.8	Boiling	7.0	0.5	57
Nov. 14 - PM ⁽⁴⁾	587.9	15	728	92.3	Boiling	5.7	1.4	82
Nov. 14 - PM	587.9	20	975	92.3	Boiling	7.2	0.3	40

(1) 880 Gm 25 total, 12.9-13.0 liters in system

(2) 3 dumps since Nov. 13 runs. Total of 246 cc less water in system.

(3) This corresponds to 610 on the Nov. 13 tests, or a loss in reactivity equivalent to 5.48 grams of 25.

(4) Added 5 grams 25

Table 1 continued

16

TABLE 1 (Continued)
EXPERIMENTAL DATA

Date	Neutron Rate Meter	Condenser Power			Power				
		Temp., °C		Water Flow Rate, Gallons minute	Power, KW	KW Meter†	Auto. cont. Power KW*	Internal Counter	
		Condenser Inlet	Condenser Outlet					Counts min.**	Power KW
Nov. 13 - AM ⁽¹⁾	-	7.0	19.5	0.80	2.64	-	3.60	18.7	3.95
Nov. 13 - PM	-	6.5	24.75	0.83	3.92	4.8 ± 0.3	4.6 ± 0.4	24.6	5.19
Nov. 13 - PM	-	6.5	23.77	0.83	3.79	4.55 ± 0.5	4.3 ± 0.4	22.87	4.83
Nov. 13 - PM	-	6.5	26.10	0.83	4.27	5.3 ± 0.5	5.0 ± 0.5	26.36	5.56
Nov. 13 - PM	-	6.5	26.70	0.83	4.43	5.2 ± 0.2	4.9 ± 0.1	26.12	5.51
Nov. 13 - PM	-	6.5	26.40	0.83	4.36	5.0 ± 0.2	4.8 ± 0.3	25.48	5.38
Nov. 14 - AM ⁽²⁾	-	6.0	15.6	0.81	2.08	2.6 ± 0.0	2.5 ± 0.0	13.28	2.80
Nov. 14 - AM	-	6.4	20.4	0.82	3.03	3.7 ± 0.2	3.6 ± 0.1	18.85	3.98
Nov. 14 - AM	± 4	6.4	24.3	0.83	3.95	4.7 ± 0.1	4.5 ± 0.2	23.70	5.01
Nov. 14 - AM	± 3	6.3	27.7	0.82	4.63	5.5 ± 0.4	5.3 ± 0.5	27.85	5.88
Nov. 14 - PM ⁽⁴⁾	± 4	5.2	23.2	0.84	3.99	4.9 ± 0.2	4.5 ± 0.3	23.7	5.01
Nov. 14 - PM	± 6	5.6	26.9	0.82	4.63	5.6 ± 0.4	5.4 ± 0.4	28.12	5.93

† Values given are average values with the ± limits indicating the maximum fluctuation in the meter reading.

** Power in KW = (counts/min)/4.74

* Meter off 6%; True Power = Power Reading 1.06

17

The fast and slow constants which were assumed initially are given in Table 2.

The specific procedure followed was to determine a reproduction constant for the system. Using Equation 3 the fictitious $\sum_{as}$ for the stainless steel

$$k = \epsilon pf\eta = \frac{\gamma \gamma \sigma_{a25}}{\gamma \sigma_{a25} + (1 - \gamma) \sigma_{a28} + 2 \sigma_{aN} + \beta_{H_2O} \times \sigma_{aH_2O} + \frac{\sum_{as}}{Nu}} \quad (3)$$

was determined then a new value for L^2 was calculated and Equation 1 solved again for the reproductive constant. This process was repeated until successive values of k agreed to within 1%.

In order to determine the density-reactivity relationship, it was assumed that all additions of reactivity caused boiling and therefore solution density changes. New solution constants were evaluated from the following relationship.

$$L^2 = L_0^2 \frac{d_0}{d}^2 \quad (4)$$

$$\zeta = \zeta_0 \frac{d_0}{d}^2 \quad (5)$$

$$D = D_0 \frac{d_0}{d} \quad (6)$$

The new reproduction constant corresponding to the reactivity change on boiling was computed from Equation 3, and the density ratio solved for by iteration.

The value of the reproduction constant for the first non-boiling test changed by less than 1% on the third approximation, therefore the solution density was calculated for that k and for various reactivity changes. For comparison purposes the density change was also calculated for one point for the first approximation of the reproduction constant.

659

18

TABLE 2

NUMERICAL CONSTANTS USED FOR CALCULATIONS

ζ_c	= 35.93	Uranium	88.7% U^{235}
L_{2c}^2	= 1.701	Sphere Radius	15.24 cm
D_{1c}	= 1.185	$\sigma_a(U^{235})$	645 barns
D_{2c}	= 0.1843	$\sigma_a(U^{238})$	2.8 barns
ζ_r	= 350	$\sigma_a(N)$	1.8 barns
L_{2r}^2	= 2700	$\sigma_a(H_2O)$	0.66 barns
D_{1r}	= 0.9766	$p \epsilon \approx 1$	
D_{2r}	= 0.903		

19

The results of the density change calculations for the first series of tests are given in Table 3. The results are plotted in Figure 2 as density ratio against equivalent grams U^{235} added as control rod was withdrawn. There is a very nearly linear relationship between reactivity addition and density change, the curve being fitted to within $\pm 10\%$ by the expression

$$\frac{\Delta k}{k} = 0.30 \frac{\Delta d}{d} \quad (7)$$

using the values from the third approximation given in Table 3. Equation (1) gives a numerical constant of 0.57 for the bare sphere case compared to the empirical value of 0.30 obtained above for a reflected system. The value given in Equation 7 seems quite reasonable since in a reflected system the density change must occur in a much smaller volume than in that for an equivalent sphere.

The average solution density decreased by only a maximum of 0.8% for the maximum reactivity addition. However the average power fluctuations during the boiling runs were $\pm 15-20\%$ according to the Leeds and Northrup recorder and $\pm 5-10\%$ according to the power meters. If the power fluctuations were due to density fluctuations alone then the vapor generated in volume boiling must have escaped from the system in surges. For example, if only 1 KW of power was generated by volume boiling, then for the calculated maximum average density change (0.8%), the average escape velocity was about 10 ft./sec. With this low residence time, the possibility exists that the onset of vapor evolution in the solution caused sufficient circulation to decrease the effective film thickness at the free surface, thereby allowing increased surface evaporation.

20

TABLE 3

RESULTS OF DENSITY CALCULATIONS

Date	Sphere Condition	NE Rod Position	Control Rod Equivalent, Grams 25	Nuclear Power, KW	Condenser Power, KW	Calculated Reproduction Constant	Calculated $\delta k, \%$	Exptl. $\delta k, \%$	Calculated Solution Density Ratio d_o/d
<u>1st Approx.</u>									
Nov. 13 - AM	Non Boiling	610	11.85	3.95	2.64	1.4824	-	-	1.00
Nov. 13 - PM	Boiling	676	7.47	5.56	4.27	1.4844	0.20	0.15	-
Nov. 13 - PM	Boiling	759	4.43	5.38	4.36	1.4858	0.34	0.25	1.00589
<u>2nd Approx.</u>									
Nov. 13 - AM	Non Boiling	610	11.85	3.95	2.64	1.412	-	-	-
<u>3rd Approx.</u>									
Nov. 13 - AM	Non Boiling	610	11.85	3.95	2.64	1.4021	-	-	0.9998
Nov. 13 - PM	Boiling	630	10.30	4.83	3.79	1.4028	0.07	0.052	1.0016*
Nov. 13 - PM	Boiling	650	8.94	5.19	3.92	1.4035	0.14	0.097	1.0033*
Nov. 13 - PM	Boiling	676	7.47	5.56	4.27	1.4042	0.21	0.15	1.0048
Nov. 13 - PM	Boiling	712	5.93	5.51	4.43	1.4050	0.29	0.197	1.0065*
Nov. 13 - PM	Boiling	759	4.43	5.38	4.36	1.4057	0.36	0.25	1.0079

*Interpolated

Figure 2. Effect of Reactivity Addition on The Density of the Fuel Solution as the SUPO Model of the Water Boiler was Boiled.

A brief examination of the literature showed that there seemed to be a limiting disengagement velocity for the vapors from the surface of a boiling liquid above which serious entrainment was observed⁽⁴⁾⁽⁵⁾. The values quoted ranged between 10 and 50 lbs./ (hr)(sq. ft.). Since the solution level in the water boiler was not known accurately, it was not possible to calculate the disengagement velocities accurately. In order to estimate values, two cases were assumed. In the first case the just non-boiling solution level was assumed to be at the usual operating level of 5 cm below the top of the sphere, it was also assumed that there was no holdup in the condenser. Thus the only change in solution level was due to volume boiling of the core solutions as given in Table 3. In the second case, it was assumed that the solution was 5 cm below the top of the sphere at 20°C and expanded as it was heated up to just below the boiling point. Again it was assumed that there was no liquid holdup in the condenser. In both cases the heat removed in the condenser was used to calculate the pounds of steam evaporated per hour. The results of the two calculations are given in Table 4. These data are plotted in Figure 3 as disengagement velocity against equivalent grams U^{235} in the sphere. For comparison purposes the condenser power and nuclear power curves are also included on this graph.

(4) D. E. Pierce, Ind. Eng. Chem. 45, 81A, February, (1953)

(5) Chemical Engineers Handbook, John H. Perry, Editor-in-Chief,
McGraw-Hill Book Company, Inc., New York, New York,
3rd Edition (1950) p514

23

TABLE 4

**STEAM DISENGAGEMENT VELOCITY FROM
FREE SURFACE OF WATER BOILER**

Sphere Condition	NE Rod Position	Internal Counter Power, KW	Condenser Power, KW	Disengagement Velocity lb./(hr)(sq. ft.)	
				Case I	Case II
Non Boiling	610	3.95	2.64	21.4	28.1
Boiling	630	4.83	3.79	31.1	41.2
Boiling	676	5.56	4.27	35.6	48.0
Boiling	712	5.51	4.43	27.1	51.0
Boiling	759	5.38	4.36	37.0	51.1

Case I Solution level 5 cm below top of sphere at just non-boiling, no condensate hold up in condenser.

Case II Solution level 5 cm below top of sphere at 20°C, no condensate hold up in condenser.

65

15

Figure 3. Effect of Reactivity Addition to SUPO Model of Water Boiler on the Power and Disengagement Velocity

25

The first case gives disengagement velocities for boiling conditions of from 31.1 to 37.1 lbs./ (hr.) (sq. ft.) and there appears to be a slight decrease in the disengagement velocity for the greatest amount of reactivity added corresponding to the observed decrease in nuclear power. The second case gives disengagement velocities for boiling conditions of from 41.2 to 51.1 lbs./ (hr.) (sq. ft.) and no decrease in the disengagement velocity even for the greatest amount of reactivity added. This is due to the increased dependence of solution area on solution volume as the solution level is raised.

DISCUSSION

In the critical non-boiling calculation, the value of k decreased from 1.48 to 1.40 on going from the first approximation to the third approximation. For the maximum reactivity addition the ratio of the densities (d_0/d) increased from 1.006 to 1.008 in going from the first to the third approximation. Thus, a rather large change in the assumed k had only a slight effect on the density ratio. This indicates that, despite any uncertainties in k introduced by the method of calculation, the calculated density ratio gives a good estimate of the true value.

Comparison of the Δk given by the two approximations shows agreement to within 6%. Further, a comparison of the calculated Δk with values given by direct calibration⁽⁵⁾ shows that the calculated Δk figures are consistently

(5) L.D.P. King, Private Communication to P. C. Zmola (Jan. 12, 1952) gave a figure of 3.0 grams equivalent of U^{235} equal to 0.1% in k for conditions near the boiling point for the Supo model of the Water Boiler.

about 40% too high. This indicates that the reliability of the calculated method is good since it predicts the trend of reactivity variation correctly, although the magnitude of the reproduction constant may not be given exactly.

Several reasons may be advanced for the decrease of nuclear power with reactivity addition observed in the first series of tests. It was suggested⁽⁶⁾ that the apparent loss of reactivity was due to the removal of water from the cooling coils by steam pressure. This was checked by King in another series of tests in which the cooling coils were maintained under a constant head of about 5 ft. of water. He indicated that more reasonable results were obtained. Another possibility is that at the higher nuclear power the condenser became overloaded with condensate and so did not drain free. This also would cause water removal from the system, and consequent loss of moderation. Finally the results of Figure 3 indicate that there might have been saturation in the (lbs. of steam evaporated)/(hr.)(sq. ft.). It is probable that a combination of all three effects was responsible for the observed effect.

D G Thomas

D. G. Thomas

/tks

(6) L.D.P. King, Private communication, (loc. cit.)

NOMENCLATURE

D_{1c}	Fast diffusion coefficient in the core
D_{2c}	Slow diffusion coefficient in the core
D_{1r}	Fast diffusion coefficient in the reflector
D_{2r}	Slow diffusion coefficient in the reflector
d	Solution density
f	Thermal utilization, $\sum_a(25)/\sum_a(\text{all})$
k	Reproduction constant = $\epsilon p f \eta$
L_{2c}	Diffusion length in the core
L_{2r}	Diffusion length in the reflector
N	Number of atoms per cu. cm.
p	Resonance escape probability
S_1	Coupling coefficient $(D_{1c}/\tau_c D_{2c}) / (1/L_{2c}^2) + \mu^2$
S_2	Coupling coefficient $(D_{1c}/\tau_c D_{2c}) / (1/L_{2c}^2) - \nu^2$
S_3	Coupling coefficient $(D_{1r}/\tau_r D_{2r}) / (1/L_{2r}^2) - (1/\tau_r)$
X	$(\sin \mu r)/r$
X'	First derivative of X with respect to r , evaluated at core reflector interface
Y	$(\sinh \nu r)/r$
Y'	First derivative of Y with respect to r , evaluated at core-reflector interface
Z_1	$(e^{-r/(\tau_r)^{1/2}})/r$
Z_1'	First derivative of Z_1 with respect to r , evaluated at core-reflector interface
Z_2	$(e^{-r/L_{2r}})/r$
Z_2'	First derivative of Z_2 with respect to r , evaluated at core-reflector interface

~~_____~~ 28
 $\beta(X)$ Molecules (X)/atoms total uranium

γ Fraction of U^{235} in fuel = 0.887

Δ increment

ϵ Fast effect

η Neutrons emitted per capture in U^{235} = 2.12

$$\mu^2 = \frac{1}{2} \left[- \left(\frac{1}{\zeta_c} + \frac{1}{L_{2c}^2} \right) + \sqrt{\left(\frac{1}{\zeta_c} + \frac{1}{L_{2c}^2} \right)^2 + \frac{4(k-1)}{\zeta_c L_{2c}^2}} \right]$$

$$-\nu^2 = \frac{1}{2} \left[- \left(\frac{1}{\zeta_c} + \frac{1}{L_{2c}^2} \right) - \sqrt{\left(\frac{1}{\zeta_c} + \frac{1}{L_{2c}^2} \right)^2 + \frac{4(k-1)}{\zeta_c L_{2c}^2}} \right]$$

Σ_a Macroscopic absorption cross section

σ_a Microscopic absorption cross section

ζ_c Fermi age of core region

ζ_r Fermi age of reflector region