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May 19, 1942

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Prof. C. C. Furnas
National Defense Research Committee
1530 P Street NW
Washington, D. C.

Dear Prof. Furnas:

We have obtained additional absorption and desorption data as an aid to the Kellogg group in their design work. These results have included a preliminary study of the heat transfer problem. For these thermal studies a small thermocouple was introduced into the usual 1/2" absorption unit. This thermocouple consisted of a copper tube, 0.050" in outside diameter, down through which the other thermocouple lead wire was passed, and the junction between the copper tube and the wire was soldered at the bottom. This tube was inserted along the axis of the 1/2" tube and it was of such length that it extended 1/2 of the way down into the absorbent, i.e., it was at the geometric center of the absorbent bed.

Heating and cooling runs were carried out with this arrangement under conditions such that no absorption or desorption was taking place. These runs were made to evaluate the heat transfer properties of the absorbent. For these heat transfer studies, 40.7 grams of 10 to 20 mesh deoxygenated absorbent were employed. This material packed to a length of 21-1/2" in the 1/2" tube.

In these heat transfer studies the outside jacket had an inside diameter of 0.95" and the outside diameter of the 1/2" tube was 0.675" (3/8" std. copper pipe), and during cooling a water rate of 1.75 lbs./min. was employed. The results are summarized in Tables I, II, and III. Table I gives results obtained for 2 cooling runs, both with an initial temperature of 85°C. employing cooling water at about 20°C. Table II summarizes results for 2 runs similar to those of Table I with the exception that the initial temperature was 100°C. Table III presents the experimental data obtained from a heating run employing steam as the heating medium.

Preliminary heat transfer calculations have been carried out on the basis of these data employing the Gurney-Lurie plots for cylinders as given in McAdams' "Heat Transmission." In the use of these plots there is a parameter, m, which involves essentially a ratio of the thermal-conductivity of the cylinder bed to the outside heat transfer coefficient and includes a principal dimension of the heat transfer arrangement (in this case the radius). For the heating runs the value of m is of the order of 0.001 for an assumed steam side coefficient of 1,000 (a higher coefficient would give a lower value of m). For the cooling runs the value of m is about 0.005. McAdams gives curves for values of m equal to 0

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TABLE I

Cooling Curves - 85°C. to 20°C.

Cooling Time Minutes	Center Temp. °C.	Water Temp. In °C.	Center Temp. °C.	Water Temp. In °C.
0	84.25	85.0	85.25	85.5
1/2	83.5	19.4	84.5	18.4
1	75.0	17.1	74.5	17.8
1-1/2	63.5	21.0	60.0	23.0
2	52.5	20.0	50.0	19.0
2-1/2	43.5	20.0	42.0	20.0
3	35.0	21.2	35.75	20.0
3-1/2	32.5	20.8	31.25	17.3
4	28.25	18.8	28.0	17.4
4-1/2	27.25	19.0	26.25	16.6
5	25.0	18.6	23.0	23.0
5-1/2	22.75	22.0	—	21.8
6	22.25	24.0	21.5	21.3
6-1/2	—	17.5	—	19.6
7	22.25	21.0	21.5	19.4
8	22.0	20.4	21.5	21.0
9	21.25	21.5	21.5	20.0
10	—	—	—	—

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TABLE II

Cooling Curves - 100°C. to [redacted]

Cooling Time Minutes	Center Temp. °C.	Water Temp. in °C.	Center Temp. °C.	Water Temp. in °C.
0	99.0	100.0	98.5	100.0
0.5	—	—	96.75	22.8
1.0	91.25	21.0	91.75	20.6
1.5	—	—	79.5	20.6
2	63.5	20.0	63.25	20.0
3	43.0	20.0	42.75	19.8
4	31.0	21.0	31.75	20.0
5	25.5	19.7	26.25	20.0
6	23.0	20.3	22.5	20.3
8	20.75	20.0	20.75	19.7
10	20.0	20.0	20.0	19.6

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TABLE III

Heating Curve - 20°C. to 100°C.

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Heating Time - minutes	Center Temperature °C.
0	20.5
0.5	20.75
1.0	35.5
1.5	50.75
2.0	65.5
2.5	75.0
3.0	82.0
3.5	87.25
4.0	90.25
4.5	92.5
5.0	95.0
5.5	96.25
6.0	97.0
7.0	98.0
8.0	98.75

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and then the next closest value is 0.5. As an approximation for these preliminary calculations we used the curve given for m = 0. We are planning to carry out the refined calculations using the equations for the actual values of m to check this assumption.

This use of m = 0 is equivalent to assuming that the external resistance to heat transfer is negligible in comparison to the internal resistance. With this assumption and the center line temperatures as a function of time, it is possible to calculate the thermal conductivity of the absorbent bed. These results are summarized in Tables IV and V. Table IV is for the heating data and the first 2 columns give the center line temperature as a function of the time. The third column gives the observed temperature difference as a fraction of the initial temperature difference. This ratio is one of the ordinates of the heat transfer plots. The next column contains the values read from the plot for the various conditions. These values constitute a dimensionless ratio which includes a factor A (A = k/cp), called the thermal diffusivity, multiplied by the time divided by the radius squared. The last column of the table gives the values of A calculated from this group. These values should be essentially constant due to the fact that they involve only physical properties of the absorbent bed and these properties are ones that do not change greatly with the temperature. It will be noted that the results in the table indicate a reasonably good constancy of A. In fact, we feel that these are very satisfactory considering the type of experiment employed. The average value of A is 0.00285 sq. ft./hr. which leads to a thermal conductivity for the absorption bed of 0.0271 B.t.u./(hour) (sq. ft.)(°F.)/ft.

Table V summarizes a similar analysis for one of the cooling runs for an initial temperature of 85°C. These results show about the same agreement for the constancy of A and give an average value of 0.00274 which is reasonably close to the value obtained from the heating curve. This agreement would be still better if the fact that the value of m was not 0 was taken into account. This correction would be in the direction to bring these two average values of A together.

On the basis of these preliminary calculations, we would recommend that the thermal conductivity of the 10 to 20 mesh granules as packed in a 1/2" tube, i.e., to a bulk density of about 0.6, be taken as about 0.027 B.t.u./(hr.)(sq. ft.)(°F.)/ft. and the heat capacity as 0.25 B.t.u/(lb.)(°F.) since this latter value is used in evaluating k. We plan to "lily-gild" these results and will report on them in a future letter.

In addition, a number of absorption and desorption runs were carried out in which the temperature at the center line was followed during the experiments. Results on a series of absorption runs at 250 lbs./sq. in. ga. and with cooling water at 20°C. are given in Table VI. This table includes the center line temperature as a function of the time, and the overall results presented in this table are summarized in Table VII. The absorption arrangement was the same one described above.

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TABLE IV

Heat Transfer Calculation

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Heating Time Hours, θ	Center temp. °C.	$\frac{100-t}{80}$	$X = \frac{A\theta}{R^2}$	$A = \frac{X(R^2)}{\theta}$
0	20	1.0	0	—
0.0333	65	0.438	0.23	0.00277
0.0417	75	0.313	0.28	0.00282
0.050	82	0.200	0.36	0.00302
0.0583	86.7	0.166	0.40	0.00288
0.0667	90.3	0.1212	0.44	0.00277
0.075	93.0	0.0875	0.52	0.00291
0.0833	94.8	0.065	0.57	0.00287
0.10	97.0	0.375	0.665	0.00279
			Ave. A.	0.00285

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TABLE V

Heat Transfer Calculations

Cooling Time Hours, θ	Center temp. °C.	$\frac{t-20}{65}$	$X = \frac{A\theta}{R^2}$	$A = \frac{XR^2}{\theta}$
0	85	1.0	0	—
0.025	60	0.615	0.16	0.0027
0.0333	52.5	0.50	0.215	0.00269
0.0417	43.5	0.362	0.265	0.00265
0.0500	35.0	0.231	0.34	0.00285
0.0583	32.5	0.192	0.37	0.00267
0.0667	28.25	0.127	0.45	0.00283
0.075	27.25	0.1115	0.47	0.00263
0.0833	25.0	0.077	0.54	0.00283
			Ave. A	0.00274

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The heat transfer characteristics of Table VI are illustrated in Fig. 1. in which the center line temperature is plotted vs. the absorption time in minutes for absorptions made with 4 different rates of exit gas flow. In all cases, there is a very rapid initial temperature rise due to the flow work of the entering gas. At the low rates of flow the temperature then decreases presumably due to the heat capacity of the absorbent bed, after which it rises to a maximum due to the heat of oxygen absorption. As the rate of flow is increased the initial dip due to the heat capacity of the bed is masked by the rapid heat evolution due to the higher rates of absorption. It is likewise noted that the maximum temperature obtained also increases with the flow rate. This is undoubtedly due to the fact that the heat evolution is so rapid that a lower percentage of the heat produced is transferred to the cooling water in the early part of these curves. These rapid rises must mean that the initial rate of absorption increases progressively with the rate of air flow. It will be noted that the maximum temperatures are quite high and that with high flow rates, temperatures of the order of 50°C. would be obtained. We feel that these temperatures are probably about the average for the center of the bed and probably correspond to a relatively low net heat removal by the air due to the fact that the air has already been preheated by the absorption which occurred before this level was reached.

The absorption runs in Table VII indicate that a high percentage oxygen removal and a high saturation are not easily obtained even under these conditions. These results are somewhat lower than we have previously observed with material that was furnished by Professor Calvin. Thus, a previous run on Calvin's material identical with the first run of Table VII gave a weight per cent of oxygen equal to 1.62; the present value is 86% of this. Another run duplicating the fourth run of this table gave a saturation of 2.68 weight per cent O_2 and the present run corresponds to about 76% of the previous value. The reason the comparison is better in the first case than in the second is due to the fact that the rate of oxygen removal is greater and therefore the oxygen concentration factor is more important.

Atmospheric pressure desorption curves have been carried out on an initial temperature of 20°C. with the heating water at 85°C. Results on compounds containing 2.72 and 3.4 weight per cent O_2 are given in Table VIII and these results are plotted in Fig. 2. Table VIII reports the weight per cent desorbed as a function of the time. The final value was determined by using steam to be certain that no residual oxygen was left at the end of the desorption run. Fig. 2 illustrates the per cent desorbed as a function of time for these two runs. It will be noted that in 4 minutes a little less than 80 per cent desorption is obtained, but that in 6 minutes around 92 to 96% desorption is obtained.

A series of three atmospheric pressure desorption runs were also carried out employing atmospheric pressure steam. The sorption bed was originally at 20°C. and 3 different saturations varying from about 2 to 3.6 weight per cent oxygen were employed. The results obtained are given in Figs. 3, 4, and 5, and Table IX. It is to be noted that the desorption

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TABLE VI

Center Temperatures During Absorption

Absorption Pressure - 251 psi

Exit Gas Rate CFH	Absorption Time Minutes	Center Temperature °C.	Cooling Water Temperature °C.	Weight % O_2 Absorbed
0.87	0	18.5	—	0
	0.5	—	—	—
	1.0	27.25	—	—
	1.5	—	18.2	—
	2.0	23.25	19.2	—
	2.5	22.5	19.7	—
	3.0	22.5	19.6	—
	3.5	23.0	19.6	—
	4.0	23.75	20.0	1.96
	4.5	26.5	20.2	—
	5.0	28.0	20.0	—
	5.5	33.0	20.0	—
	6.0	35.0	20.2	—
	6.5	37.0	20.3	—
	7.0	38.25	20.3	—
	7.5	38.0	20.2	—
	8.0	—	—	2.66

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TABLE VI CONT'D.

Center Temperatures During Absorption

Exit Gas Rate CFH	Absorption Time Minutes	Center Temperature °C.	Cooling Water Temperature °C.	Weight % O_2 Absorbed
2.0	0	19.5	20.0	0
	1.0	29.5	20.0	—
	1.5	29.75	19.7	—
	2.0	32.5	20.0	1.40
	2.5	36.25	19.9	—
	3.0	40.0	20.2	—
	3.5	42.25	19.7	—
	4.0	42.25	19.3	—
	4.5	40.5	19.8	—
	5.0	38.0	19.7	2.92
	5.5	35.0	19.9	—
	6.0	32.5	20.0	—
	6.5	29.5	19.6	—
	7.0	27.0	19.6	3.60
3.0	0	20.25	—	0
	1.0	32.5	20.5	—
	2.0	42.25	22.0	—
	2.5	46.0	—	—
	3.0	46.5	—	2.46
4.0	0	19.75	—	0
	1.5	40.25	—	—
	2.0	—	—	2.05

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FIGURE 1

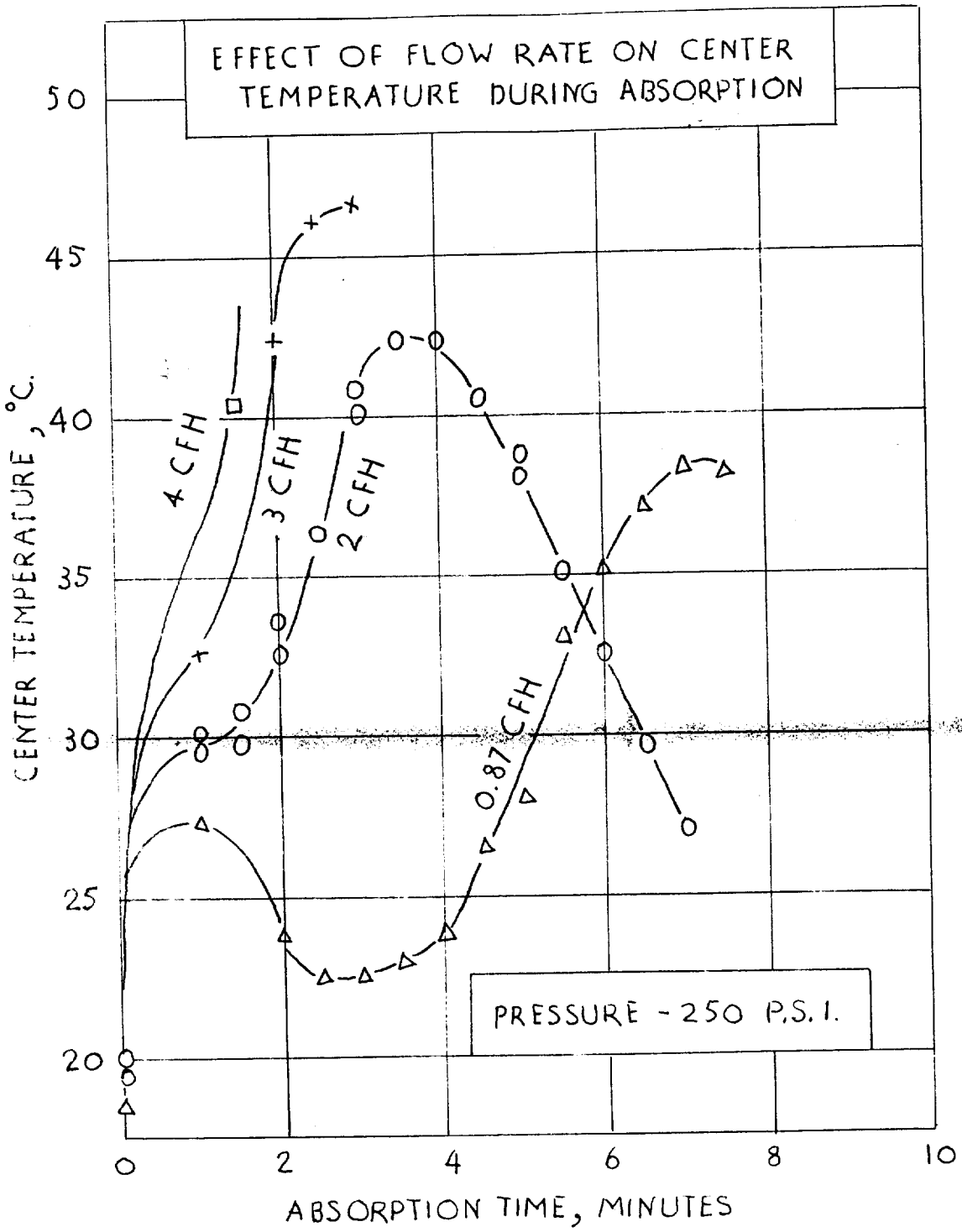

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TABLE VII

Absorption at 250 psi and 20°C.

Exit Gas Rate CFH	Absorption Time Minutes	Weight % O_2 Absorbed	Cumulative Mol % O_2 Removal
0.87	4	1.96	94.9
	8	2.68	80.6
2.0	2	1.40*	66.6
	5	2.92	67.5
	7	3.60	62.5
3.0	3	2.46	62.6
4.0	2	2.05**	58.4

* 1.62 with Calvin compound

**2.68 with Calvin compound (see letter to Furnas 12-4-41)

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rates are slightly lower than those previously reported, probably because of special care in not letting the steam temperature exceed 100°C. at any time. Fig. 3 shows the per cent desorbed as a function of the desorption time and it is noted that the rates are somewhat better than those given in Fig. 2 for a desorption temperature of 85°C. It appears that at 85°C. the desorption time has to be increased 25% to 45% to obtain the same percentage desorbed. Fig. 4 plots the temperature at the center of the bed as a function of the desorption time for these 4 runs together with the heating curve for the solid alone, i.e., 0 per cent saturation. The initial kick in the curve may be due to the lag in the heat wave or to experimental manipulation. It will be noted that the more oxygen that has to be desorbed, the longer the time necessary to reach a given temperature at the center. These same results are plotted in Fig. 5 as the center line temperature vs. the per cent desorbed. All three runs give essentially the same curve and illustrate the fact that the major portion of the desorption is over by the time the temperature has attained 60°C. I believe the inflections in the curve are real and not experimental. The first bend upward would be more or less what would be expected for straight heat transfer. The curve then flattens somewhat due to the fact that desorption is occurring in the region around the thermocouple, then when desorption is essentially complete the curve again turns upward. Our picture is that the major portion of desorption probably occurs at a temperature level between 45 and 65°C. There is therefore a band of this temperature that moves inward as desorption progresses and during the first part of the run the center of the bed is purely being heated without any desorption. The band then reaches the center zone and temperature delays for the desorption.

These results would indicate that 60 to 65°C. is sufficient for desorption and presumably the only reason higher temperatures are necessary is to increase the temperature difference. In other words, improved heat transfer arrangements would allow lower heating fluid temperatures. Likewise, if direct heat transfer to the bed were employed, such as gas recirculation or jiggling operation, the gas temperature could be relatively low.

On the basis of the heat transfer calculations it may be possible to calculate the heat transfer history when desorption is occurring. We are not certain that the unsteady-state heat transfer equations have been integrated for the case in which there is a heat sink. I believe that equations are available for infinite solids but are not sure that they have been worked out for finite cylinders. We are planning to make an attempt to tie the rate of desorption data in with such heat transfer calculations.

Several absorption runs have been carried out at 250 lbs./sq. in. and 35°C. These were made on the usual 1/2" unit and were preceded by a 10-minute cooling period with air in the voids. The results are summarized in Table X for several different rates of exit gas flow and different absorption times. These runs were made at the request of Mr. Roberts and

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TABLE VIII

85°C. Desorption from 20°C.

Desorption Time	Water Temp. °C.	Wt. % Desorbed	Water Temp. °C.	Wt. % Desorbed
0	20.0	0	20.0	0
0.5	80.5	0.22	85.5	0.28
1.0	83.5	0.76	85.5	0.84
1.5	86.0	1.15	85.9	1.27
2.0	85.1	1.45	86.5	1.65
2.5	85.0	1.71	85.0	1.94
3.0	85.0	1.96	85.4	2.18
3.5	85.1	2.11	85.0	2.41
4.0	84.7	2.27	84.8	2.60
4.5	84.7	2.39	85.0	2.75
5.0	85.3	2.49	84.7	2.91
5.5	—	—	85.0	3.02
6.0	85.2	2.63	85.0	3.13
7.0	85.0	2.69	85.5	3.28
8.0	85.5	2.71	85.0	3.36
10.0	85.0	2.72	85.0	3.39
12.0	100.0	2.72	100.0	3.40

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FIGURE 2

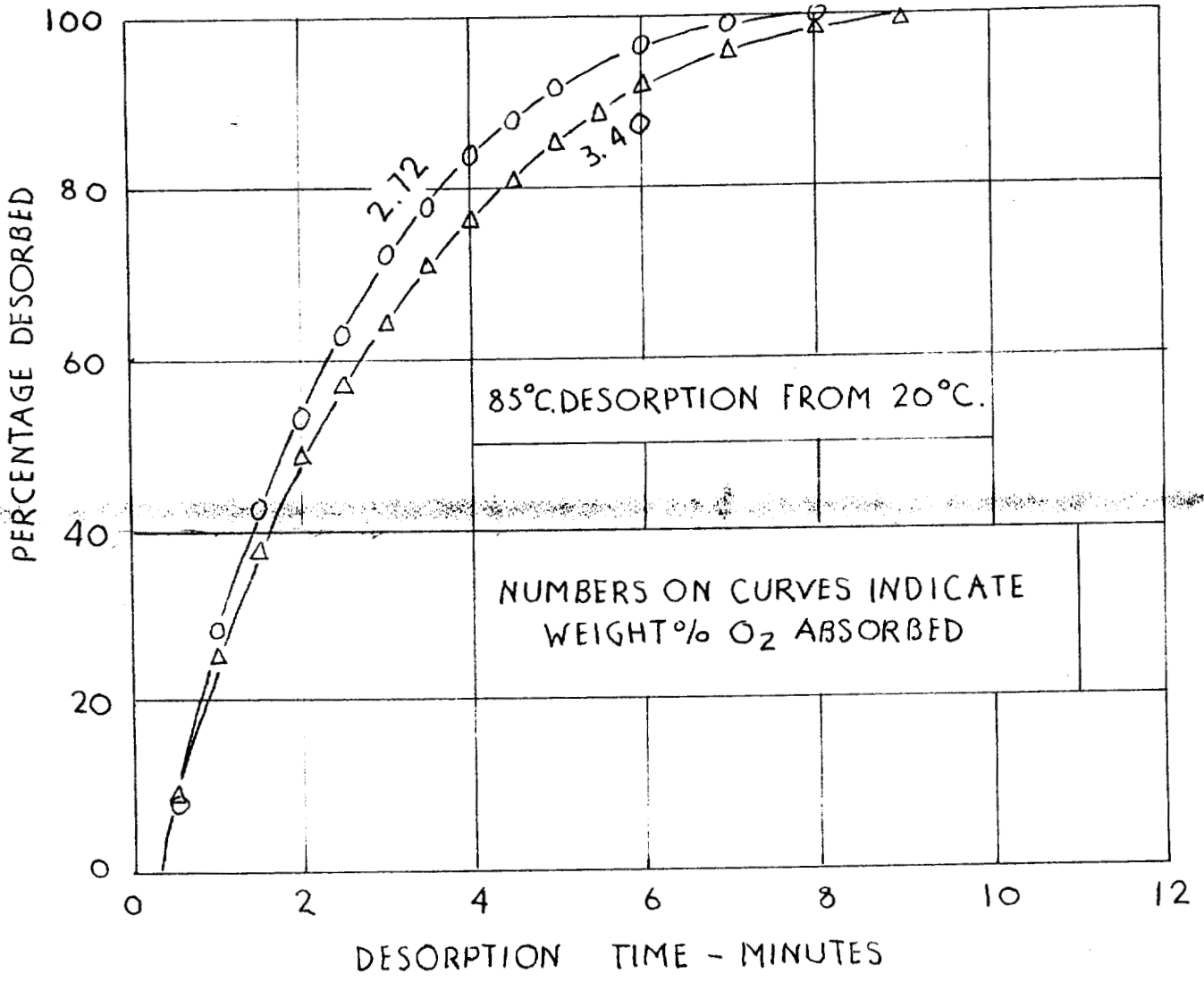

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TABLE IX

100°C. Desorption from 20°C.

Wt. % absorbed	1.96		2.66		3.60	
Desorption Time Minutes	Center Temp. °C.	% Desorbed	Center Temp. °C.	% Desorbed	Center Temp. °C.	% Desorbed
0	21.0	0	22.25	0	20.0	0
0.5	—	20.6	—	15.2	—	13.0
1.0	34.75	42.1	32.5	36.9	29.5	34.6
1.5	46.0	57.1	43.25	53.2	42.75	48.4
2.0	51.25	72.2	49.25	63.8	49.0	59.1
2.5	55.25	82.6	52.75	74.9	53.25	68.7
3.0	61.25	90.5	55.0	80.1	55.0	76.4
3.5	74.5	92.9	57.0	86.6	56.5	83.8
4.0	81.0	95.3	59.25	90.1	58.5	88.9
4.5	85.75	97.6	64.5	94.2	60.75	94.1
5.0	89.0	98.8	74.0	96.5	62.5	96.3
5.5	92.0	99.2	82.0	98.2	68.5	97.6
6.0	94.0	100.0	86.25	99.4	77.25	99.8
7.0			92.25	99.4	88.25	100.0
8.0			95.0	100.0	92.75	

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FIGURE 3

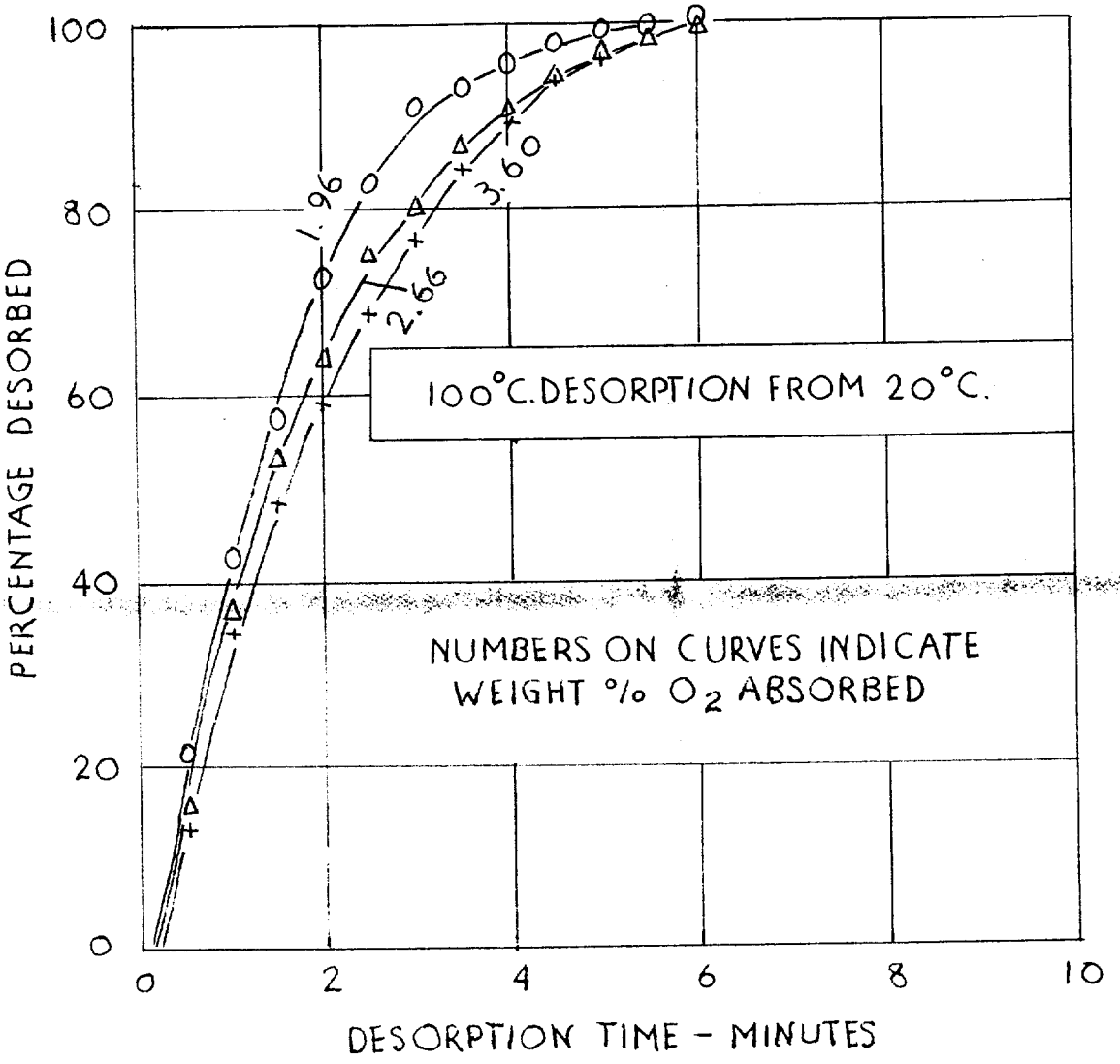

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FIGURE

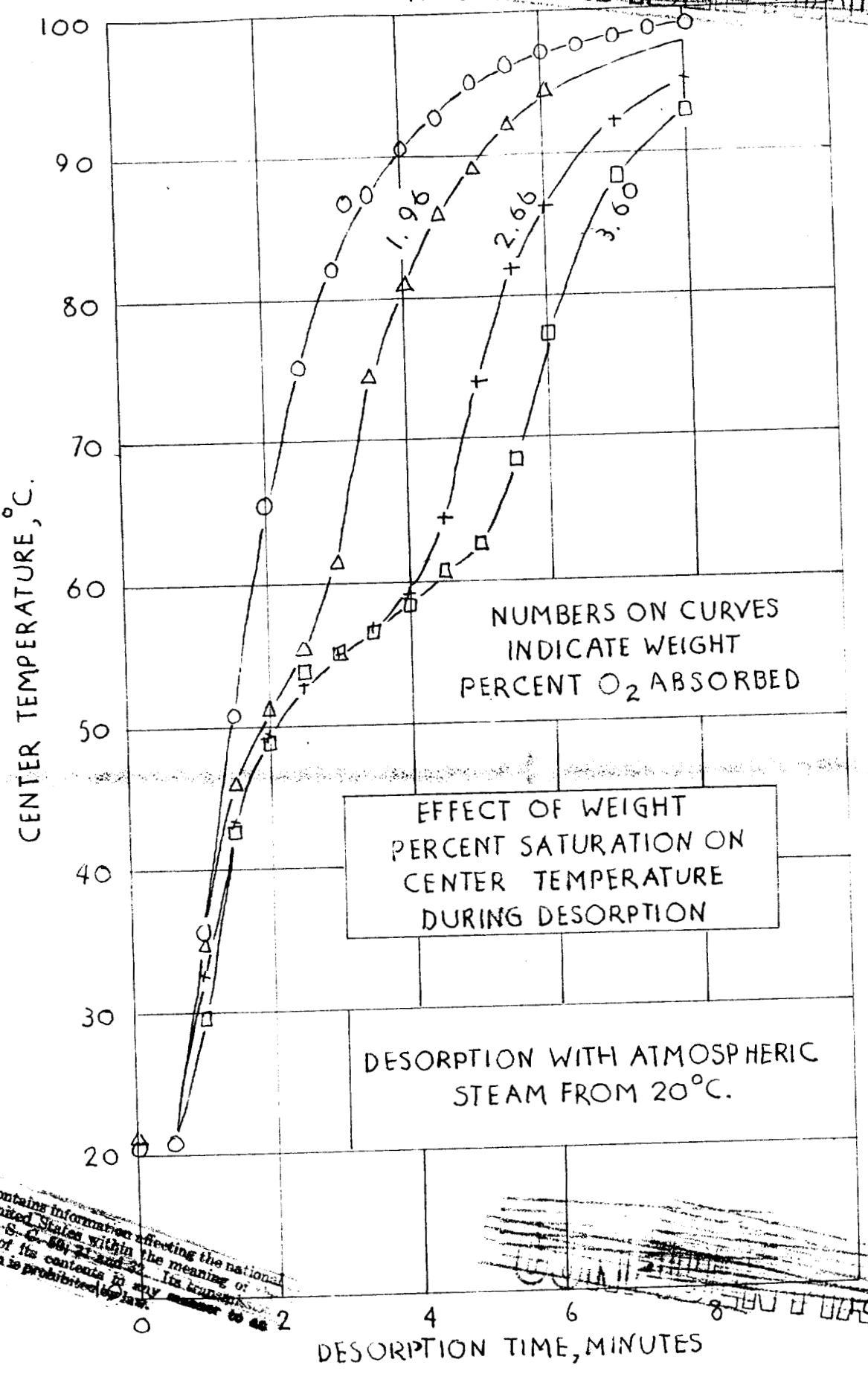

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FIGURE 5

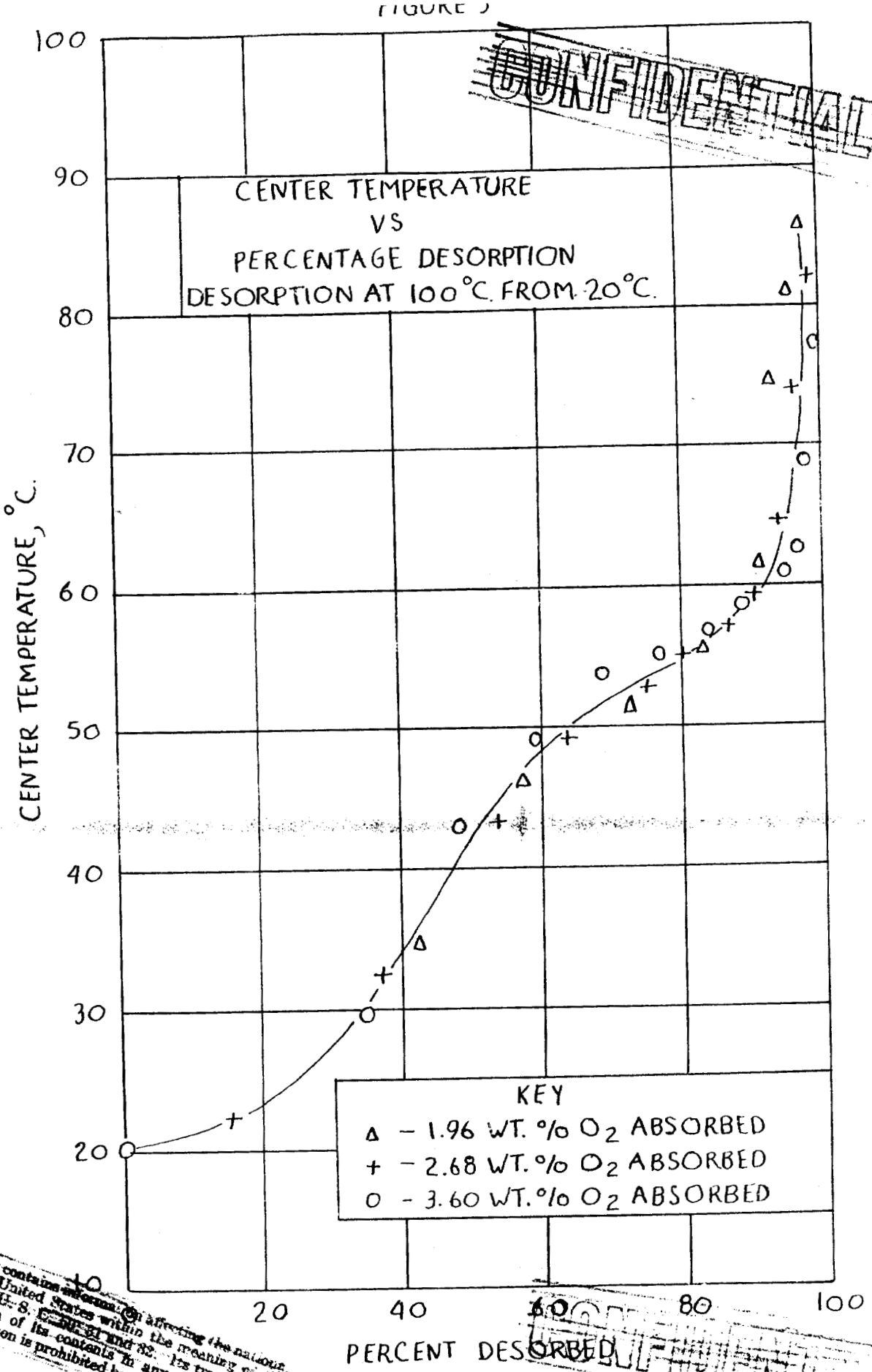

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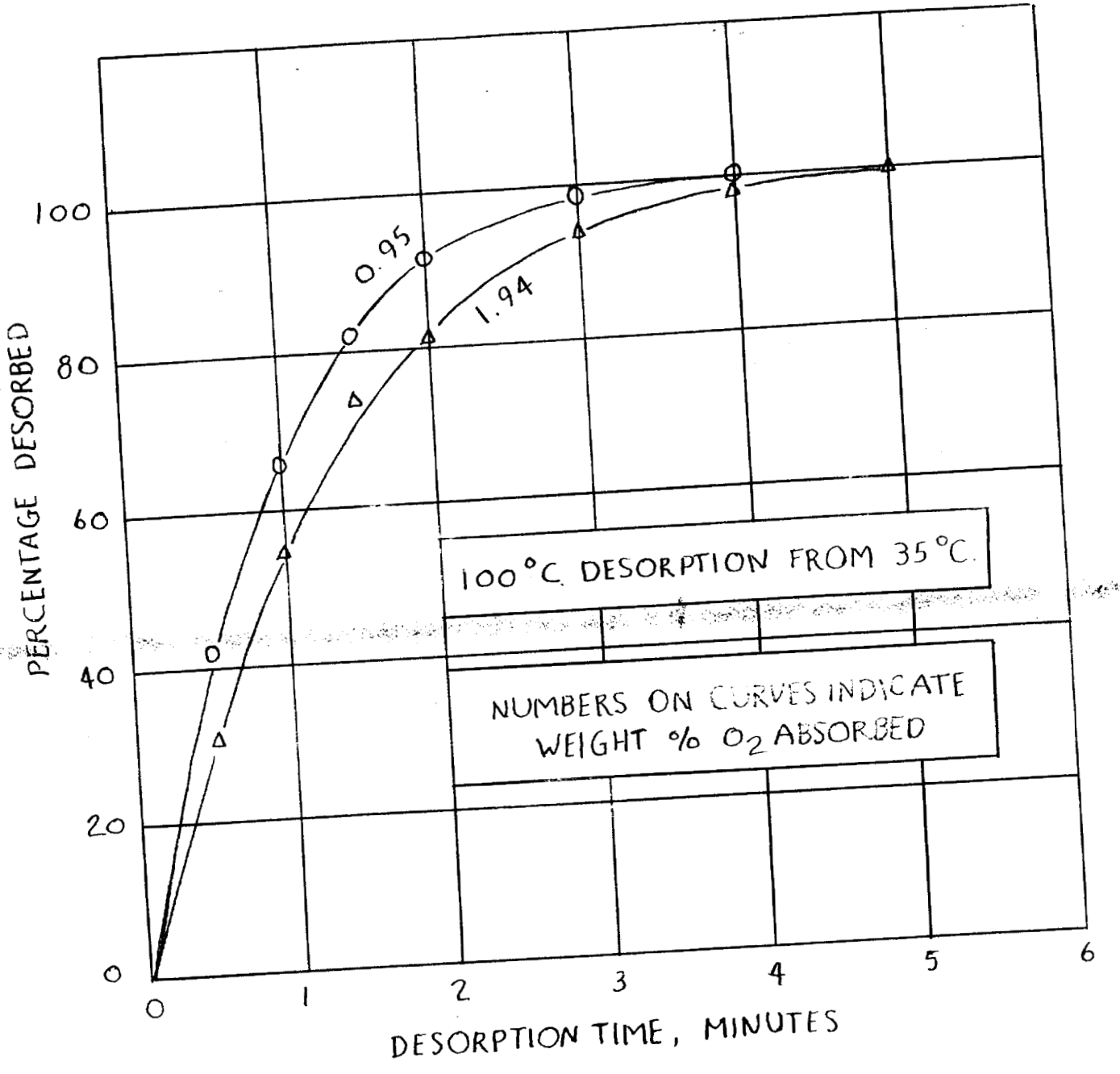
FIGURE 6



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were supposedly directed towards an attempt to obtain an oxygen recovery such that 1,000 cu. ft. could be produced from 6,500 cu. ft. of air. These design conditions correspond to a little over 70 per cent oxygen removal. It will be noted that the data of Table X indicate that such cleanups can be obtained under these operating conditions only with very low flow rates and correspondingly low weight per cent saturations. In addition, these percentage recoveries account for only the air in the voids and the exit gas flow. They would be still lower if voids equivalent to the ends of the apparatus and piping were included.

Desorption curves were carried out at 100°C. from an initial temperature of 35°C. In these runs the center line temperature as well as the per cent desorbed were determined as a function of time. The experimental data obtained on two such runs are given in Table XI and are plotted in Fig. 6.

Yours very truly,

/s/ E. R. Gilliland

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TABLE X

(Cooling Time - 10.0 Minutes with Air in Voids)

250 psi Absorption at 35°C.

Exit Gas Rate CFH	Absorption Time Minutes	Weight % O_2 Absorbed	Cumulative Mol % O_2 Recovery
0	1	0.32	54.5
	2	0.59	86.5
	4	0.68	97.0
0.87	1	0.48	52.0
	2	0.76	59.8
	4	1.39	70.2
	7	2.04	68.1
	10	2.74	68.3
2.0	1	0.52	39.0
	2	0.95	47.2
	4	1.94	55.6
	10	3.80	47.4

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TABLE XI

100°C. Desorption Curves from 35°C.

Wt. % Absorbed	0.95		1.94	
Desorption Time Minutes	Center Temp. °C.	% Desorbed	Center Temp. °C.	% Desorbed
0	34.50	0	35.25	0
0.5	37.25	40.9	40.25	30.5
1.0	45.50	65.5	46.50	54.3
1.5	55.0	81.8	50.75	73.6
2.0	63.25	91.7	54.75	81.6
3.0	80.5	98.2	66.75	94.4
4.0	88.75	100.0	82.25	98.4
5.0	92.75		90.0	100.0
6.0	96.0		95.75	
7.0	97.0		—	
8.0	97.5		—	

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