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PERFORMANCE OF AN AGITATOR ABSORBER IN REMOVING CO_2 FROM A GAS

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ABSTRACT

The effects of process pressure, carbon dioxide content of the feed gas, solution throughput, and liquid-to-gas ratio on the performance of an agitator absorber at levels of 200-300 p.s.i.g., 10-20 mol-percent, 60-90 gal. /hr., and 16.5-55 gal. /hr. solution per 1000 std. cu. ft. gas/hr., respectively, have been determined. The absorbent used was 40 weight-percent diethanolamine in water; the gas used was inert gas with carbon dioxide added.

The data and results from three sets of sequential factorial experiments are presented. The experiments were designed to test each of the four factors at three levels of operation.

Not for Publication
Presented Before the Division of Gas and Fuel Chemistry
American Chemical Society
New York City Meeting, Sept. 8-13, 1957

"Performance of an Agitator Absorber in Removing CO_2 From a Gas"

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During the last fifteen years, processes for removing carbon dioxide and hydrogen sulfide from industrial gases by scrubbing with various amines have become generally accepted. To date, these processes have employed conventional gas-liquid contactors, packed columns and bubble-cap towers.

It has been shown that the absorptive capacities of the amines increase markedly with increased concentration, but because of the operating difficulties encountered when conventional scrubbers are used to process liquids of even moderate viscosity, the limiting concentration has been about 15 percent amine in water. Thus, for these processes to realize full commercialization, methods of gas-liquid contacting able to tolerate more viscous scrubbing media must be developed.

This paper describes studies of the absorption of carbon dioxide in 40 weight-percent diethanolamine in water utilizing an agitator-type contactor. Figure 1 shows a vertical cross section of the absorber. The action within the absorber is as follows: The lean solution is fed into the vessel through a sparger ring. The liquid is raised in the lift tube by the centrifugal action of the turbine and propelled from the absorber impeller in the form of a fine spray. This spray of liquid droplets moves at a high speed relative to the gas stream, which passes through the spray curtain in upward flow through the absorber. Inasmuch as this is a relatively novel gas-liquid contactor, it is to be expected that its mode of action would be distinctive.

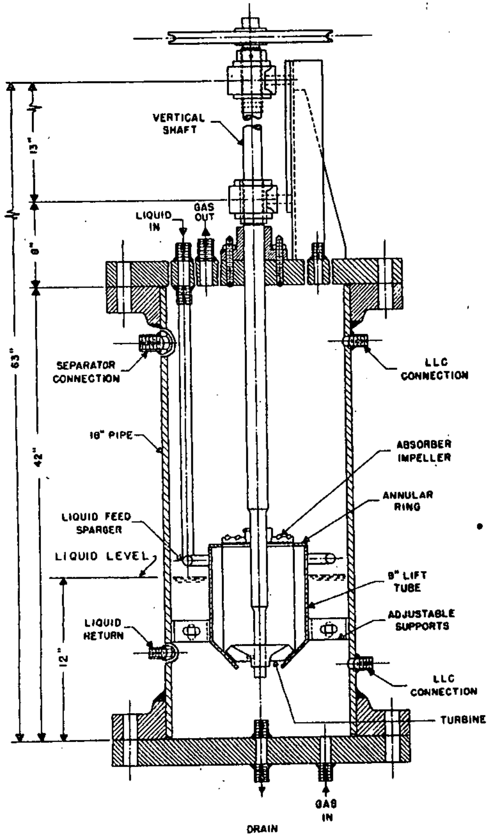
The work described here was undertaken to determine the characteristics of the agitator-absorber with respect to: (1) Process pressure, (2) carbon dioxide content of the feed gas, (3) absorbent solution rate, and (4) liquid-to-gas ratio.

DESCRIPTION OF GAS-PURIFICATION PILOT PLANT

Figure 2 is a flow diagram of the pilot plant. For this study the absorber was installed to operate with existing solution-regeneration facilities.

The Absorber

The absorber is shown in figure 1. The essential internal parts are the annular ring and lift tube and the turbine and impeller. The turbine imparts a centrifugal action to the absorbent solution, which is directed by the annular ring and lift tube onto the impeller, where the spray is formed. The latticed faces of the impeller are beveled to about 38° off horizontal so



THE AGITATOR ABSORBER

Fig. 1. -The agitator absorber

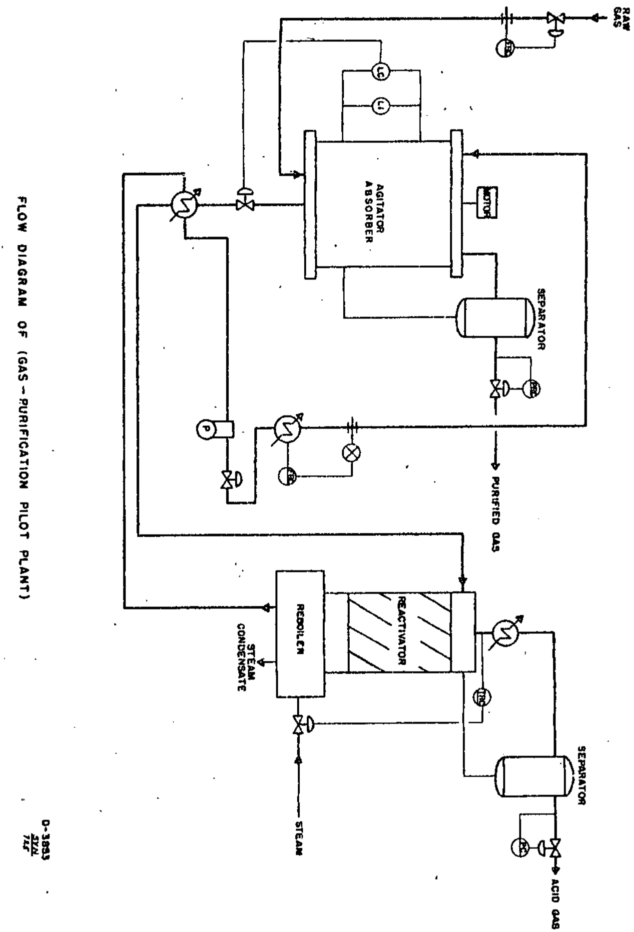


Fig. 2. -Flow diagram of (gas-purification pilot plant)

that the principal portion of the spray is directed toward the walls of the absorber vessel rather than the top. A 1-hp. motor (1,750 r.p.m.) connected to the shaft through sheave pulleys is used to drive the turbine. A constant turbine speed of 750 r.p.m. was used for these tests.

The Reactivator

The reactivator tower is a 17-foot length of 10-inch, schedule 40 pipe, which is packed to a depth of 15 feet with 3/4-inch Raschig rings and direct-connected to the reboiler by 10-inch diameter flanges. The reboiler is 10-feet in length and 16 inches in diameter. It is fitted with a pressure connection, connections for adding makeup condensate and for draining the solution, and a thermocouple connection installed near the end of the tube bundle. Steam for reactivation is controlled by a pressure controller and is measured by weighing the condensate. The entire unit is lagged with 2 inches of magnesia insulation and 1/4 inch of "Insulcote".

Auxiliary Equipment

The solution heat exchanger, solution cooler, and acid-gas cooler are all similar. Each consists of two Griscom-Russell twin G-fin sections connected in series. The heat exchanger and solution cooler each contain four, schedule 40, 3/4-inch, G-fin pipes about 10 feet long. The fin pipes in the acid-gas cooler are about 5 feet long. Thermocouple connections are installed so that all inlet and outlet temperatures can be recorded.

A 1-1/4 by 4-inch triplex, single-acting power pump circulates the solution. The flow of the solution to the absorber is controlled by an air-operated bypass valve.

The gas is stored, before compression, in a wet-type gas holder having a capacity of 1,000 cubic feet. The 2-stage gas compressor can deliver 7,200 standard cubic feet per hour at 350 p.s.i.g.

Solution and Gas Flow

The flow of solution and gas in the pilot plant is typical of most gas-purification systems. Inert gas, varying in CO_2 content from 7 to 10 mol-percent, is taken from the gas holder, compressed to about 350 p.s.i.g., and fed to the absorber.

The carbon dioxide necessary to bring the carbon dioxide content of the unpurified gas to the level of predetermined experimental conditions is added to the suction line of the compressor.

The lean diethanolamine solution enters through the top of the absorber. It is distributed by a sparger ring directly above the liquid level and just below the top of the lift tube and leaves the absorber through a side connection 6 inches from the bottom. The level of solution in the absorber is maintained to a depth of 12 inches (indicated by the broken line in figure 1).

The diethanolamine is forced up into the lift tube by the turbine; baffles in the lift tube eliminate any swirling action. The rising solution contacts the absorber impeller, a deflector designed to give maximum spray commensurate with the dimensions of the absorber vessel. Three distinct spray patterns are formed--(1) the initial spray from the absorber impeller, consisting of small droplets moving at very high velocities, (2) impact spray formed when the initial spray rebounds from the walls of the vessel, and (3) conjunctive spray formed when the initial spray and impact spray collide.

The feed gas enters at the base of the absorber to the right of the lift tube. It bubbles through the diethanolamine, passes through the spray pattern, and leaves the top of the absorber into an entrainment separator as purified gas. It is then returned to the gasholder for feed-gas makeup.

The fouled amine solution leaving the bottom of the absorber is heated by heat exchange with lean amine solution and regenerated in the reactivator with indirect heat from low-pressure steam. The acid gas leaves the top of the reactivator and passes through a cooler where entrained steam is condensed and returned to the column. The acid gas is then returned to the holder for feed-gas makeup.

The reactivated diethanolamine leaves the reactivator, flows through the heat exchanger where it gives up a portion of its heat to the fouled solution leaving the absorber, and is pumped through a water-cooled solution cooler back to the absorber.

EXPERIMENTAL PROCEDURE

The agitator gas-liquid contactor is a novel piece of equipment. To evaluate it in terms of more conventional gas-cleaning apparatus, packed columns and bubble-cap towers, optimum operating conditions for the agitator absorber process must first be found.

Eight obvious factors will affect performance of the absorber: (1) Process pressure, (2) carbon dioxide content of the feed gas, (3) absorbent-solution throughput, (4) liquid-to-gas ratio, (5) concentration of the absorbent solution, (6) feed-gas throughput, (7) the speed of the turbine, and (8) carbon dioxide content of the lean absorbent solution. Although the operational levels of all of these factors are easily controlled within relatively narrow limits, there is no reason to suppose that the efficiency of the process is an additive function of any two of them. Consequently, the complete exploration of the causal relations among these factors would require that the effect of each factor be observed under all combinations of values of the other factors. Such a procedure would require a relatively large number of tests.

To overcome this difficulty, a series of sequential factorial experiments, each concerned with a group of relevant factors, was initiated. Such a procedure allows for maximum flexibility in planning and has the inherent advantage that, as each factorial is developed, the factors involved may be directed toward optimum conditions relevant to all other factors.

Process pressure, carbon dioxide content of the feed gas, absorbent solution throughput, and liquid-to-gas ratio were chosen as the independent variables for the initial experiment; the levels chosen for these factors were 200-300 p.s.i.g., 10-20 mol-percent, 60-90 g.p.h., and 16.4-55 respectively.

Liquid-to-gas ratio in this instance is defined as gallons of solution per 1,000 std. cu.ft. of feed gas per hour. The dependent variable in the process is the total carbon dioxide absorbed, since all other variables for these experiments were predetermined.

As dictated by subsequent operation, a second factorial was designed at new operational levels for the four factors. The purpose of the second set of experiments was to investigate further the interactions among the various factors revealed in the initial set of tests. The block design for each factorial is presented in Appendix 1.

DATA AND RESULTS

Table 1 presents typical operating conditions prevalent throughout the 30 tests performed for this study; table 2 presents the cumulative data from these tests.

Table 1. - Typical operating range for all runs

Gas temperature, °F.	
Before agitator	75-85
After agitator	140-155
Solution temperature, °F.	
Before agitator	100-110
After agitator	140-160
Reboiler pressure, p.s.i.g.	6.5-8
Reboiler temperature, °F.	265-275
Agitator motor	
Ammeter, amps	1.2-1.4
Voltmeter, volts	470 (constant)
Steam pressure, p.s.i.g.	22-30
Steam consumption, lb./gal. amine	0.6-0.8
Turbine speed, r.p.m.	750 (constant)

A statistical analysis of the data from experiment "A" is made and an analysis of the cumulative data from experiments "A" and "B" is presented.

An empirical equation relating the independent variables to the performance of the agitator absorber is developed. The effect of the same variables on the performance of the agitator is presented graphically in chart 1.

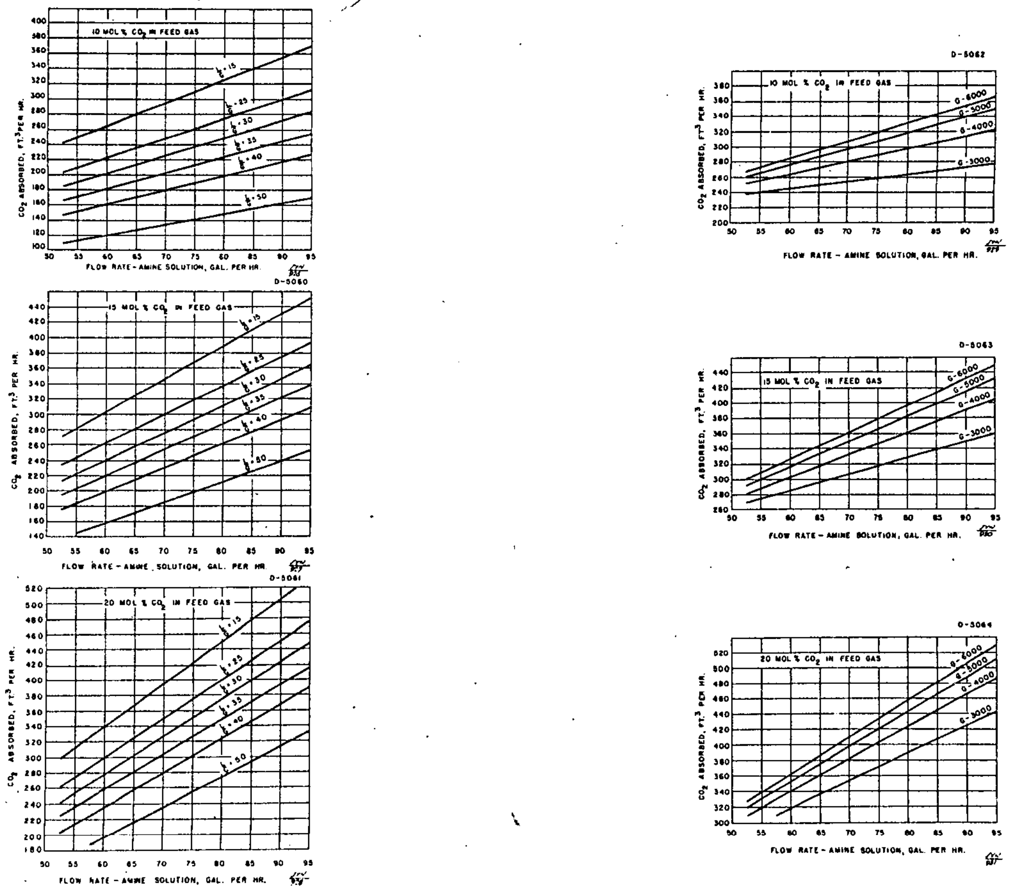


Chart 1. -An expression of the scrubbing capacity of the agitator absorber as a function of solution throughput and CO_2 content of feed gas with L/G ratios and gas rates as parameter.
G = gas rate, std. ft.^{3} per hr. L/G = ratio of solution throughput, gal/hr. to gas rate 1000 std. ft.^{3}/hr.

The following nomenclature is used in these presentations:

- Y = total CO_2 absorbed, cubic feet per hour
- L = L/G = liquid-to-gas ratio, $\frac{\text{gallons per hour solution}}{\text{1,000 std. cu. ft. gas/hr.}}$
- S = solution throughput, gallons/hr.
- C = CO_2 content of feed gas, mol-percent
- P = process pressure, p.s.i.g.
- $D^2/16$ = sum of the squares of the dependent variable accounted for by a given factor, divided by the number of tests involved.
- n = number of tests, contingent to a given calculation.

EVALUATION OF DATA

Table 3 presents an analysis for significance of the 16 runs of experiment "A" in which the factors involved were tested at the high and low levels. This analysis was made using the method of Yates.

The error mean square was determined using data from the runs at which the factors were tested at the median levels. The calculation was made using this relationship:

$$E.M.S. = \frac{\sum Y^2 - \frac{(\sum Y)^2}{n}}{n-1} = 33.2$$

The standard deviation by definition is the square root of the error mean square. In this instance the standard deviation was $\pm$ 6 cu. ft. /hr. of CO_2 absorbed.

The interactions between the carbon dioxide content and solution throughput, and between the carbon dioxide content and liquid-to-gas ratio revealed in the analysis of the data from experiment "A", were evaluated further by solving the normal equations using matrices set up from the cumulative data of experiments "A" and "B". Using the methods of Davies, the coefficients of table 4 were determined and an empirical equation relating the significant factors to the dependent variable was set up.

Table 3. - Factorial analysis - Experiment A

P	C	S	L	Run	Y	Factor	$D^2/16$	Significance
-1	-1	-1	-1	A-11	296	Total	1,211,100	
-1	-1	-1	1	A-4	96	L/G	136,900	0.001
-1	-1	1	-1	A-10	373	S	41,820	0.001
-1	-1	1	1	A-13	132	S L/G	2,601	0.05
-1	1	-1	-1	A-3	350	C	51,984	0.001
-1	1	-1	1	A-14	189	CL	812	nil
-1	1	1	-1	A-19	496	CS	5,625	0.01
-1	1	1	1	A-7	303	CSL	462	nil
1	-1	-1	-1	A-9	260	P	289	nil
1	-1	-1	1	A-15	91	PL	756	nil
1	-1	1	-1	A-16	342	PS	324	nil
1	-1	1	1	A-2	155	PSL	210	nil
1	1	-1	-1	A-18	309	PC	56	nil
1	1	-1	1	A-6	201	PCL	225	nil
1	1	1	-1	A-1	515	PCS	2	nil
1	1	1	1	A-17	294	PCSL	676	nil
0	0	0	0	A-5	263		1,453,842	
0	0	0	0	A-8	270		1,211,100	
0	0	0	0	A-12	271		242,742	
0	0	0	0	A-20	275			

Table 4. - Empirically determined coefficients

Factor	Coefficient
Constant	267.3
C	+57.0
S	+57.125
L/G	-92.5
S L/G	-12.75
CS	+18.75

By substituting these real for the coded factors:

$$P = \frac{P-250}{50}$$

$$C = \frac{C-15.2}{5}$$

$$S = \frac{S-75}{15}$$

$$L = \frac{L/G - 35.7}{19.3}$$

and by affixing the proper coefficients and reducing, equation (1) resulted.

$$(1)\quad Y = 178.3 - 7.35\,C + 1.18\,S - 1.49\,L - 0.044\,SL + 0.25\,CS$$

An analysis for variance was made by solving the inverted matrix set up from the cumulative data of experiments A and B, again using the methods of Davies. This revealed that the empirical equation would account for 98.5 percent of the total sum of squares of the dependent variable.

A further analysis for significance was made using Student's "T" test as presented by Villars. By this calculation, the empirical equation contains only those terms significant at less than the 5 percent level.

The comparison of observed and calculated values for the rate of adsorption of CO_2 in the agitator absorber, included in table 2, was made employing equation (1).

Chart 1 presents graphically the absorbing capacity of the agitator as a function of solution throughput and CO_2 content of feed gas with gas rates and liquid-to-gas ratios as parameters. The data for plotting chart 1 was evolved by solving equation (1).

DISCUSSION OF RESULTS

The dependent variable for these experiments was taken as total carbon dioxide absorbed per hour. The effect of the independent variables--pressure, carbon dioxide content of the feed gas, solution throughput, and liquid-to-gas ratio on the performance of the agitator absorber was determined on that basis.

Significant Effects

The factors of these experiments are tabulated in the fourth column of table 3; the coefficients that give these factors quantitative meaning are tabulated in table 4. Examination of these tables shows that the performance of the agitator absorber will appreciate with higher solution throughput, higher CO_2 content in the feed gas and lower liquid-to-gas ratios. The effect of these factors and of the interactions among them on the performance of the agitator absorber is given explicit quantitative meaning in the correlation afforded by equation (1). Using this equation the performance of the agitator, in terms of cubic feet per hour of carbon dioxide absorbed, can be predicted to an accuracy of plus or minus 13 cubic feet per hour within the range of these tests.

Operating requirements commensurate with feed gas composition may be observed directly by reference to chart 1.

Comparison with Conventional Scrubbers

Using the methods[1] of Coulson and Richardson, the over-all mass-transfer coefficients for the agitator absorber were calculated at three sets of conditions, runs A-1, A-2, and A-12.

Until strict criteria for the choice of agitator volume are resolved, it is not possible to make a generalized comparison of the performance of the agitator absorber with conventional scrubbers on the basis of over-all mass-transfer coefficients. The principle of operation, and hence the flow mechanics in the two systems, are quite different; indeed, the flow mechanics in the agitator are extremely complex. However, it is possible to compare the performance of the two types of equipment for specific operating conditions and to describe the performance of the agitator in terms of a physical tower required to effect the same degree of scrubbing at those operating conditions. This comparison has been made and is presented in table 5. It shows the size towers that would have to be employed in place of the agitator absorber for the specified runs.

Table 5. - Data for comparing agitator absorber to packed tower

Run No.	KgA*	Packing	Cross Tower section, sq. ft.	Packing height, ft.
A-1	0.227	3/4 Raschig rings	0.5	5
A-2	.262	3/4 Raschig rings	.5	6
A-12	.111	3/4 Raschig rings	.5	10

$$*KgA \text{ for agitator absorber} = \frac{\text{lb.-mol of } CO_2 \text{ absorbed}}{(\text{hr.})(\text{atm. } CO_2 \text{ partial pressure})(\text{cu. ft. solution})}$$

Cubic feet of solution is taken as that volume of the absorber actually occupied by solution, irrespective of the spray. For these calculations, that volume was considered to be a cylinder 18 inches in diameter by 12 inches in height. The actual absorber has a cross section of 1.42 sq. ft. and an inside height of 3.5 ft.

FACTORS TO BE INVESTIGATED

It has been shown that the performance of an absorber of centrifugal design is greatly affected by the characteristics of the spray pattern it develops. The spray pattern in turn is almost totally a function of the turbine design and speed, the impeller design, and the viscosity of the absorbent. The viscosity of the absorbent is dependent on the concentration of the diethanolamine and on the heat of absorption developed. Consequently, this factorial will be expanded to include the factors (1) turbine speed, (2) concentration of absorbent, and (3) heat of absorption.

APPENDIX I

THE BLOCK DESIGN FOR FACTORIAL EXPERIMENTS A AND B

Factorial Experiment A

Set I				Set II			
A	B	C	D	A	B	C	D
-1	-1	-1	-1	1	-1	-1	-1
-1	-1	-1	1	1	-1	-1	1
-1	-1	1	-1	1	-1	1	-1
-1	-1	1	1	1	-1	1	1
-1	1	-1	-1	1	1	-1	-1
-1	1	-1	1	1	1	-1	1
-1	1	1	-1	1	1	1	-1
-1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0

Factorial Experiment B

A	B	C	D
0	0	0	1.2
0	0	0	-1.2
0	0	$\sqrt{2}$	0
0	0	$-\sqrt{2}$	0
0	$\sqrt{2}$	0	0
0	$-\sqrt{2}$	0	0
$\sqrt{2}$	0	0	0
$-\sqrt{2}$	0	0	0
0	0	0	0
0	0	0	0

In which:

	LEVELS				
	Factorial A Interactions			Factorial B Curved Effects	
	High	Medium	Low	High	Low
A = pressure, p.s.i.g.	300	250	200	321	179
B = CO_2 content of foul gas, mol-percent	20	15	10	22.4	8
C = solution throughput gal./hr.	90	75	60	96.2	53.8
D = liquid-to-gas ratio, gal./1000 std. cu. ft./hr.	55	35.7	16.4	58.8	12.6

The level designations: 1, -1, 0, $\sqrt{2}$, $-\sqrt{2}$, 1.2 and -1.2 may be defined as the value of the variable in question minus the mean value of that variable divided by the interval for that variable. The interval in turn may be defined as the value of the variable designated as 1 minus the value of that variable designated as 0.

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