American Institute of Chemical Engineers

STUDENT CONTEST PROBLEM

1977

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CONTEST PROBLEM

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AMERICAN INSTITUTE OF CHEMICAL ENGINEERS STUDENT CHAPTERS

Open Only to Undergraduates or Those
Without a Degree in Chemical Engineering

DEADLINE FOR MAILING

Solution must be postmarked not later than midnight, June 1, 1977.

RULES OF THE CONTEST

Solutions will be graded on (a) substantial correctness of results and soundness of conclusions, (b) ingenuity and logic employed, (c) accuracy of computations, and (d) form of presentation. Accuracy of computations is intended to mean primarily freedom from mistakes; extreme precision is not necessary.

It is to be assumed that the statement of the problem contains all the pertinent data except for those readily available in handbooks and similar reference works. The use of textbooks, handbooks, journal articles, and lecture notes is permitted. In cases where there is disagreement in the data reported in the literature, the values given in the statement of the problem have been chosen as being most nearly applicable.

The problem is not to be discussed with any person whatever until June 1, 1977. This is particularly important in cases where neighboring institutions may not begin the problem until after its completion by another chapter. Submission of a solution for the competition implies adherence to the foregoing condition.

A period of not more than thirty consecutive days is allowed for completion of the solution. This period may be selected at the discretion of the individual counselor, but in order to be eligible for an award a solution must be postmarked not later than midnight, June 1, 1977.

The finished report should be submitted to the chapter counselor within the thirty-day period. There should not be any variation in form or content between the solution submitted to the chapter counselor and that sent to the AIChE office. The report should be neat and legible, but no part need be typewritten.

The solution should be accompanied by a letter of transmittal giving only the contestant's name, school address, home address, and student chapter, lightly attached to the report. This letter will be retained for identification by the Secretary of the Institute. The solution itself must bear no reference to the student's name or institution by which it might be identified. In this connection, graph paper bearing the name of the institution should be avoided.

Each counselor should select the best solution or solutions, not to exceed two, from his chapter and send these by registered mail to

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Alkylation Plant Evaluation

A large refinery is operating an alkylation plant constructed during World War II. Expanded over the years, the unit has been made more efficient by minor technological improvements. However, the increased demands on this unit due to the need for lead-free gasoline will require still more investment. Already throughput to the unit has been cut back in an attempt to improve the quality of the product as needed for lead-free gasoline blends. Instead of investing still more money in what is basically old hardware, the company may prefer to construct a whole new unit of a design optimized for the forthcoming clear-octane requirements. The decision will require the economics of an optimized new plant which would produce 10,000 barrels a stream day (332 stream days a year) of debutanized motor alkylate with a clear (lead-free) research octane number of at least 93. Higher octane numbers would, of course, be desirable if equally profitable.

You are to establish the economics of the new plant.

Assume that, in addition to this motor alkylate, 1111.1 barrels a stream day of heavy alkylate, or 10 percent by volume of the total reaction product, will be produced as the major by-product, which will be separated for solvent production.

The alkylation process is described in literature references *1* to *4*, with reference *2* providing the basic chemistry involved. In order to provide management with the desired economic information, a simplified flow scheme, as shown in Figure 1, may be used for the process evaluation. Note that the diagram does not show complete process control instrumentation or charge pumps. Further, design calculations may suggest changes in heat exchange or pump alignment. The following information provides additional assumptions and process particulars which may be used in the development of an optimum plant design.

BASIS FOR ECONOMIC CALCULATIONS

Motor alkylate is used as a blending stock with other gasoline components, and the Economics Department has developed the following product values:

10 RVP MOTOR ALKYLATE BLENDING VALUES
(BASIS: 1981 DOLLARS)

F-1-0 (research octane number)	Value, ¢/gal.
89	48.0
92	48.75
95	49.5
98	50.25

BY-PRODUCTS (BASIS: 1981 DOLLARS)

Propane	26.1
Butanes	29.4
Heavy alkylate	41.0

Feed streams available to the alkylation plant are listed, on the basis of 1981 stream costs or values, on Table 1.

TABLE 1. HYDROCARBON FEED STREAMS AVAILABLE

Composition, % by volume

Component	**Butylene from catalytic cracker**	**Isobutane from gas plant**	**Purchased butylenes**	**Purchased mixed butanes**
Propane	0.3	1.0	2.2	6.1
iso-Butane	23.9	94.2	12.3	48.0
n-Butane	10.3	4.3	2.6	41.6
Butene-1	20.1	—	24.0	
iso-Butene	12.7	—	33.1	
trans-Butene-2	25.2	—	19.3	
cis-Butene-2	7.5	—	6.5	
iso-Pentane		0.5	—	4.3
Availability, bbl./day*	5,000	5,100	4,000	6,000
Cost/value, ¢/gal.†	29.6	28.2	30.7	29.7

* 42 gallons per barrel.
† Basis: 1981 dollars.

Because it is available from other company-operated facilities, sulfuric acid is to be used as the alkylation catalyst. Favorable experience has been obtained by other refineries of the same company using horizontal, internally stirred loop reactors containing heat exchange surfaces. The characteristics of the recommended contactor are given below:

HEAT EXCHANGE CONTACTOR

Net operating volume, gal.	Heat exchange surface, sq. ft.	Power required, hp.	Costs, M$ including drive and settler (1976 dollars)	
			Equipment only	Installed cost
13,000	8,500	400	250	925

[Overall heat transfer coefficient: 60 B.t.u./(hr.)/(sq.ft.)/°F.]

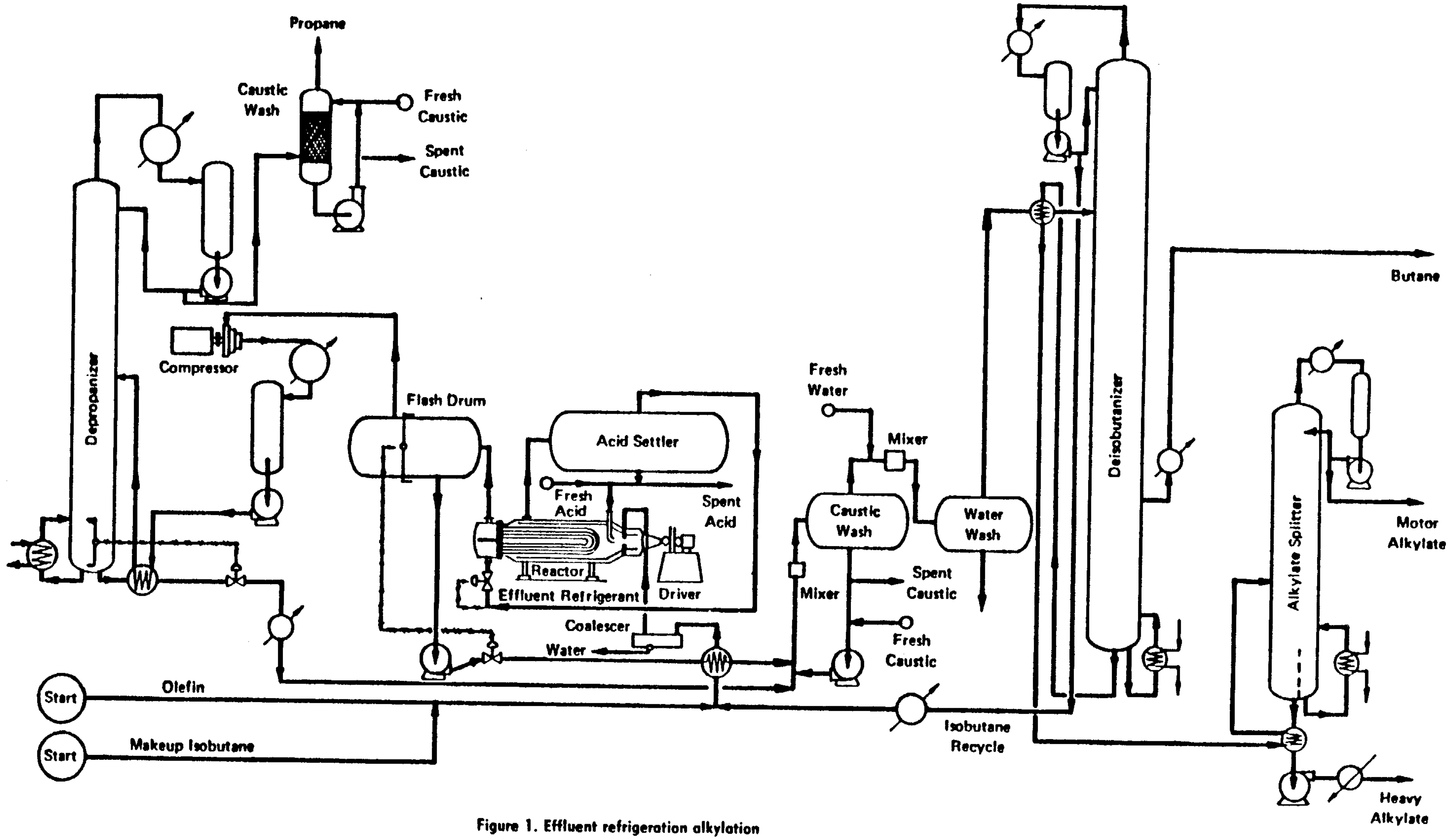


Figure 1. Effluent refrigeration alkylation

Capital cost information for the other plant equipment may be developed from reference 5.

The cost of sulfuric acid exchange, 100% H_2SO_4 exchanged for as low as 85% H_2SO_4, may be assumed to be $38/ton, on the basis of 100% H_2SO_4 (1976 dollars). Fifty percent sodium hydroxide may be purchased for $155/ton (1976 dollars) based on 100% NaOH. Fresh acid makeup costs $48/ton, on the basis of 100% H_2SO_4 (1976 dollars).

Utilities operating costs, which have been developed by the Refinery Economics Department, are listed below. The basis is 1981 dollars:

Circulating cooling water*	3.5¢/1,000 gal.
Purchased electric power	30 mils/kw.-hr.
Heat medium (95,000 bbl./S.D. max. @500°F., 25°API)†	$2.75/million B.t.u. net
Process water	40¢/1,000 gal.
Steam	
650 lb./sq.in. gauge/750°F.	$4.50/1,000 lb.
200 lb./sq.in. gauge/500°F.	$4.20/1,000 lb.
50 lb./sq.in. gauge (credit)	$3.00/1,000 lb.

* Supply 90°F, return 120°F. maximum.

† Specific gravity = 0.9042.

If the project looks attractive, the final design will be completed in 1977. The actual commitment of project capital will occur in January 1978 with the signing of a construction contract for a firm price. Thus capital costs are to be calculated in terms of 1978 Gulf Coast values; however, progress payments will be made to the contractor as follows:

1978—15 percent
1979—55 percent
1980—30 percent

For this evaluation, assume offsites allowances, including tankage, to be 40 percent of the total process capital. Assume a contingency equal to 20 percent of the sum of the process, utilities, and offsites capitals. Because of the high concentration of H_2SO_4 and the relatively low temperatures used, carbon steel may be used for all vessels, pumps, and piping.

A 20-year process life, beginning January 1, 1981, is to be used. Operating costs and raw material and product values are to be frozen at 1981 values. All cash flow monies are to be discounted to January 1, 1978. The Federal tax rate is 50 percent, and a 7 percent investment credit may be taken during the first year of operation. Economic factors being used by the company to allow for inflation are

Year	Equipment and construction costs	Materials and chemicals
1968	0.50	
1970	0.55	
1976	1.00	1.0
1978	1.15	1.20
1981	—	1.45

For ease of computation, the format shown on Table 2 may be used to determine the manufacturing cost. Details for this summary may be obtained from calculations such as those shown on Table 3.

TABLE 2. MANUFACTURING-COST SUMMARY

10,000 bbl./S.D. debutanized motor alkylate

Investment, $mm
- Process unit
- Utilities
- Offsites allowance
  - Subtotal
- Contingency
  - Total

Manufacturing Costs, $MM/yr.
- Operating labor
- Operating materials
- Maintenance labor
- Maintenance materials
- Staff and operations support
- Local taxes and insurance
- Chemicals
- Utilities
- Plant feeds
  - Total

TABLE 3. MANUFACTURING-COST BASIS

Operating-cost basis	
Operating jobs	2 Operators/shift
Manpower including local supervision	5 Men/operating job
Direct labor rate	$24,000/man year
Labor burden	30%
Operating materials	10% Operating labor
Maintenance-cost basis	
Maintenance labor	1.5% Investment
Maintenance materials	1.0% Investment
Staff and operations support	125% Operating labor and materials
Local taxes and insurance	1.5% Investment

TABLE 4. DEPRECIATION SCHEDULE

Basis: Investment 1978-1980
Startup 1/1/81
13-yr. depreciation by sum-of-year's-digits method
No salvage value at end of process life

Year	Ratio	Depreciation factor
1981	13/91	0.143
82	12	0.132
83	11	0.121
84	10	0.110
85	9	0.099
86	8	0.088
87	7	0.077
88	6	0.066
89	5	0.055
90	4	0.044
91	3	0.033
92	2	0.022
93	1/91	0.011

For convenience, Table 4 contains a typical depreciation schedule, and Table 5 lists discount factors. A convenient cash flow format is given on Table 6. Details may be calculated with the use of Table 7.

TABLE 5. DISCOUNT FACTORS

Basis: Assume that all capital is spent uniformly over the year and that income is received uniformly over the year.

Calendar year	Process year	Discounted cash-flow factors 8%	11%	14%	17%	20%
1978	—	0.962	0.950	0.937	0.925	0.914
79	—	0.891	0.855	0.822	0.791	0.762
80	—	0.825	0.771	0.721	0.676	0.635
81	1	0.764	0.694	0.633	0.578	0.529
82	2	0.707	0.626	0.555	0.494	0.441
83	3	0.655	0.564	0.487	0.422	0.367
84	4	0.607	0.508	0.427	0.361	0.306
85	5	0.562	0.457	0.375	0.308	0.255
86	6	0.520	0.412	0.329	0.264	0.213
87	7	0.481	0.371	0.288	0.225	0.177
88	8	0.446	0.334	0.253	0.193	0.148
89	9	0.413	0.301	0.222	0.165	0.123
90	10	0.382	0.271	0.195	0.141	0.103
91	11	0.354	0.245	0.171	0.120	0.085
92	12	0.328	0.220	0.150	0.103	0.071
93	13	0.303	0.198	0.131	0.088	0.059
94	14	0.281	0.179	0.115	0.075	0.049
95	15	0.260	0.161	0.101	0.064	0.041
96	16	0.241	0.145	0.089	0.055	0.034
97	17	0.223	0.131	0.078	0.047	0.029
98	18	0.207	0.118	0.068	0.040	0.024
99	19	0.191	0.106	0.060	0.034	0.020
2000	20	0.177	0.096	0.052	0.029	0.017

TABLE 7. CASH-FLOW BASIS

Incremental Startup Costs, $MM
  Basis: 10% annual manufacturing cost
Working capital, $MM
  Purchased butylenes (1 day)
  Purchased butanes (1 day)
  Chemicals (15 days)
  Operating materials (15 days)
  Spare parts (2% investment)
  Motor alkylate (30 days)
  Heavy alkylate (30 days)
    Total working capital
Revenues, $MM/yr.*
  Propane
  Butanes
  Motor alkylate
  Heavy alkylate
    Total revenue

* Assume only 80% of design revenue received during startup year.

TABLE 6. CASH-FLOW FORMAT

Year	Plant inventory	Working capital	Product revenues	Start up and manufacturing costs	Net revenues	13-yr. Depreciation factor	13-yr. Depreciation	Taxable income	50% Federal tax	7% Inventory tax credit	Income after taxes	Cash flow	__% Discount factor	Discounted cash flow
1978														
79														
1980														
81														
82														
83														
84														
85														
86														
87														
88														
89														
1990														
91														
92														
93														
94														
95														
96														
97														
98														
99														
2000														
TOTALS														

PROCESS NOTES

1. On the basis of the literature references and the operation of other alkylation plants in company facilities, the following range of variables will probably lead to an optimum plant design:

Temperature, °C.	4.5
iC_4 in reactors hydrocarbon effluent, % by volume	75
Olefin space velocity, volume of olefin/(volume of acid) (hr)	0.25-0.45*
Acid consumption, lb. of acid catalyst/gal. of *total* alkylate	0.6
F-1-0 (research octane number clear)—debutanized motor alkylate	93-99

* Maximum olefin space velocity should be limited to 0.45 to ensure sufficient reaction time.

2. A high isobutane-butylene ratio is necessary to maintain isobutane concentration in the acid which will favor primary alkylation reactions and suppress secondary reactions. The data in reference 2 will allow the calculation of the alkylate octane number from this ratio and other process variables. Note that Mrstik's equation of the reference should be 1/F instead of F. This equation plus an octane correlation and other pertinent information for use in these calculations is given correctly in the Appendix.
3. Use reactor effluent refrigeration to maintain temperature control.
4. Olefin space velocity $(SV)_o$ should be used to calculate reaction volume. Use volumetric liquid hourly space velocity and assume that the reactors are half filled with catalyst to calculate reaction volume. See references 2 and 3.
5. Feeds are dried by chilling to remove free water at reaction temperature. A coalescer is shown on the flow sheet (Figure 1).
6. If feed pumps are sized correctly, no interreactor pumps should be required for a multiple reactor system.
7. Purchased mixed butane may be required. Figure 1 does not indicate where it should be charged into the process; the optimum addition point may be chosen on the basis of capital or operating costs or both.
8. For this evaluation it should be assumed that acid life and alkylate quality are independent of acid strength.
9. Acid carry-over out of the acid settlers is assumed to be 100 p.p.m.w. The base is hydrocarbon.
10. The true boiling-point end temperature of the motor alkylate should be 330°F., and the Reid vapor pressure (RVP) at 100°F. of debutanized motor alkylate will be 3.5 lb./sq.in. (reference 6). The yield of heavy alkylate is assumed to be 10 percent by volume of the total alkylate, or 1111.1 bbl./S. D. The isobutane content of the liquid butane side stream is specified as 3 percent of the volume of the butanes. Assume that isopentane in the feed streams leaves in this stream. Table 8 contains typical product compositions.
11. The recycle isobutane purity should be 95 percent by volume.
12. Propane recovery from the depropanizer should be 95 percent by volume, and the purity of the propane product stream should be 97 percent by volume.
13. Sufficient normal butane should be withdrawn in the deisobutanizer bottoms to yield a motor alkylate having a Reid vapor pressure (RVP) at 100°F. of 10 lb./sq.in. Assume that RVP at 100°F. is equivalent to the true vapor pressure and blend on a molar basis. The normal butane octane number is assumed to be 96 research, and the RVP may be assumed to be 52. Assume that the octane numbers of 10 RVP blends may be calculated according to the volume fraction of butane in the motor alkylate.
14. Short-cut distillation routines may be used for fractionator calculations.

TABLE 8. TYPICAL REACTOR-PRODUCT COMPOSITIONS

Debutanized motor alkylate	**% by Volume**
iC_5	4.9
C_6	4.5
C_7	4.2
C_8	83.2
C_9	2.6
C_{10}	0.6
	100.0
Heavy alkylate	
C_{10}	0.8
C_{11}	19.9
C_{12}	76.2
C_{13}	2.5
C_{14+}	0.6
	100.0

HINT: The deisobutanizer may be calculated as two columns in series (references 7 to 9).

Column loads are to be 75 percent of the maximum allowable vapor velocities at the point of highest internal column flows.

15. In order to simplify the calculations, the depropanizer bottoms stream is specified to be returned to the deisobutanizer feed. However, in some plants an additional refrigeration loop is set up, with this stream being returned directly to the reactor input and the size of the deisobutanizer being thereby reduced. (See reference 4).
16. For flash drum calculations, assume an initial flash pressure of 1 lb./sq.in. gauge.

FINAL REPORT FORMAT

1. Cover letter or transmittal document.
2. Introduction

    A concise statement of the problem, covering background and objectives.
3. Summary

    A brief description of the work involved in the evaluation and the conclusions or recommendations.
4. Technical Information

    A description of the proposed process, including a flow sheet detailing flow rates, concentrations, and equipment sizes.

    Calculation summaries of important operating and design parameters, detailing the equations used and the assumptions employed.

    Statements justifying the final conditions chosen for the process variables.

    Summaries of equipment specifications and costs, capital investment, cash flow tabulation, and overall plant profitability as a percentage return on the total investment.
5. Appendix

    Calculations, graphs, an explanation of all the assumptions made, and any details not included elsewhere.

REFERENCES

1. Payne, R. E., "Alkylation—What You Should Know," *Petroleum Refiner*, 37, pp. 316-329 (September 1958).
2. Cupit, C. R., J. E. Gwyn, and E. C. Jernigan, "Special Report—Catalytic Alkylation," *Petroleum Engineer*, 33, pp. 203-215 (December 1961); 34, pp. 207-217 (January 1962).
3. Jernigan, E. C., J. E. Gwyn, and E. L. Claridge, "Optimize Alkylation Processes," *Chemical Engineering Progress*, 61, 11 pp. 48-98 (November 1965).
4. "Effluent Refrigeration Alkylation," *Hydrocarbon Processing*, 53, No. 9, p. 206 (September 1974).
5. Guthrie, K. M., "Process Plant Estimating, Evaluation and Control," Craftsman Book Company of America, Solana Beach, CA (1974); also, *Chemical Engineering*, pp. 114-142 (March 24, 1969), available as Reprint 62 from *Chemical Engineering*.
6. Nelson, W. L., "Petroleum Refinery Engineering," McGraw-Hill, New York (1961).
7. Hengstebeck, R. M., "Distillation Principles and Design Procedures," Reinhold, New York (1961).
8. Henley, E. J., and H. K. Staffin, "Stagewise Process Design," Wiley, New York (1963).
9. Treybal, R. E., "Mass Transfer Operations," McGraw-Hill, New York (1955).

Appendix I

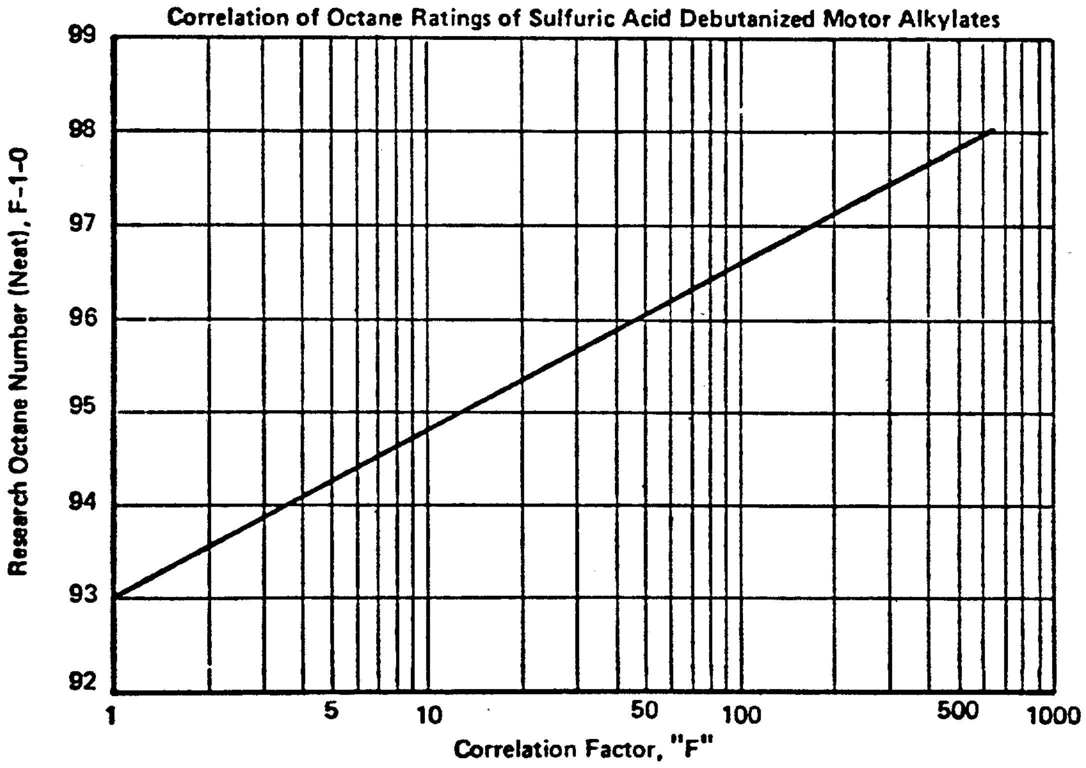
Quality Correlation (Reference 2)

$$\frac{1}{F} = \frac{100\ (SV)_O}{(I)_E \times (I/O)_F}$$

Where: $(I)_E$ = Volume % Isobutane in Reactor Hydrocarbon Effluent

$(I/O)_F$ = External Isobutane-to-Olefin Ratio (Volume)

$(SV)_O$ = Olefin Liquid-Hourly Space Velocity, Volume Olefin/(Volume Acid) (Hour)



Correlation of Octane Ratings of Sulfuric Acid Debutanized Motor Alkylates

Sulfuric Acid Alkylate Yield Data

Isobutane Consumed, Volume/Volume Olefin	1.10	Total Alkylate Yield, Volume/Volume Olefin	1.72
Heat of Reaction, Btu/lb Olefin	615	Acid Consumption, lb Acid/gal Total Alkylate	0.6