ECONOMICS OF KNOCK RATINGS OF OTTO-CYCLE ENGINE FUELS

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Any general consideration of the economics of the antidetonation properties of Otto-cycle engine fuels must include both automotive and aircraft fuels. While, as shown by table 1, in terms of absolute quantities consumed automotive fuels overshadow aviation fuels by a ratio of over 200 to 1, the latter are of increasing significance to the fuel manufacturer and of great importance in their economic bearing on modern transportation. In addition, development of high-octane blending agents for aviation fuels may profoundly influence automotive fuels. Owing to inherent differences in the requirements and the economic factors influencing the respective development of automotive and aircraft fuels, these two classes of fuels are necessarily discussed separately.

I. AUTOMOTIVE FUELS

The basis for the current octane ratings of automotive fuels is primarily with respect to performance, as indicated by the public's demand for rapid acceleration, freedom from gear shifting, etc. The demand has been met by the car manufacturers by increases in compression ratios, increases in engine speeds, better carburetion, and many relatively minor improvements. Supercharging of automobile engines has not come into widespread use, but its general adoption lies probably in the near future. All of these design factors could be directed toward fuel economy and lower specific engine weight per horsepower, but neither is in demand at present.

For these general reasons octane numbers of automotive fuels have been relatively stable over the past several years, as shown by table 2, but there is a trend upwards in the case of the premium-grade fuels. Regular-grade fuels have been artificially maintained at approximately 70 C.F.R.M. rating by the license provisions covering the use of tetraethyl lead in these fuels. If the contemplated change from the present C.F.R. motor test method results in raising the true or effective octane level, it may be expected that regular-grade fuels will immediately rise in octane number. In general, a gradual elevation in octane rating of automotive fuels may be anticipated, with this gradual evolution susceptible to more sudden changes, not all of which can be forecast accurately. As will be discussed later, it is reasonable to suppose that, owing to the large potential supply of high-octane blending agents at present being developed for aviation

TABLE 1

Consumption of automotive fuels in the United States

YEAR	PREMIUM GRADE	REGULAR GRADE	THIRD GRADE AND MISCELLANEOUS	TOTAL
	gallons	*gallons*	*gallons*	*gallons*
1936	780,000,000	12,555,000,000	5,665,000,000	19,000,000,000
1935	619,000,000	11,399,000,000	5,232,000,000	17,250,000,000

Consumption of aviation gasoline in the United States (8)

YEAR	CONSUMPTION BY COMMERCIAL AIRLINES	CONSUMPTION BY GOVERNMENT SERVICES	MISCELLANEOUS	TOTAL CONSUMPTION
	gallons	*gallons*	*gallons*	*gallons*
1936	47,508,565		10,451,496	81,024,315*
1935	33,260,609	29,319,412	11,104,259	73,684,280
1934	25,136,274	23,647,113	9,630,869	58,414,256
1933	26,326,796	21,835,526	8,861,104	57,023,426
1932	23,686,948	20,077,884	10,293,599	54,058,431
1931	19,157,382		11,658,009	30,815,391
1930	14,549,477		13,981,331	28,530,808
1929	6,285,374		14,235,243	20,520,617
1928	2,134,690		7,764,702	9,899,392
1927	1,174,098		3,882,351	5,056,449
1926	863,617		2,246,028	

* Including estimated consumption by U. S. Government services.

TABLE 2

Average octane ratings of United States motor fuels (11)

YEAR (JAN. 1)	OCTANE NUMBER (C.F.R.M.)		
	Premium grade	Regular grade	Third grade
1934	75	69	53
1935	75	69	52
1936	76	69	51
1937	77	70	54

fuels, some of this material may spill over into the automotive fuel market, thus creating new automotive fuels which will induce the development of engines capable of realizing their potentialities.

With the octane demand for automotive fuels relatively stable for the moment in the 70 to 80 C.F.R.M. range, economic discussion will be directed toward the cheapest methods of producing these fuels. Present automotive fuels (excluding third-grade gasolines) are blends of straight-run, reformed, cracked, and natural gasolines, with an increasing use of the newer polymer gasolines for further octane appreciation. The use of tetraethyl lead to bring the finished blend to the final octane number is nearly universal. Yearly quantities of motor fuel stocks segregated as to method of manufacture are given in table 3, in which it will be noted that in 1936 the volume of cracked gasoline exceeded that of straight-run for the first time.

With the majority of crudes, gasolines from gas oil or combination reduced crude cracking can be brought to octane levels where they present no difficult octane problems, at least in the manufacture of regular-grade gasoline. Eliminating for the moment the use of polymer gasoline, the problem then reduces to the optimum economic utilization of the straight-run material boiling in the gasoline range to permit its inclusion in the final blend. The octane number of straight-run distillates may be raised by two principal methods: (*1*) naphtha reforming of all or a portion of the straight-run distillate, blending the reformed and virgin fractions, and leading to the required octane number, or (*2*) the use of tetraethyl lead alone.

TABLE 3

Quantities, in barrels, of motor fuel stocks manufactured (9)

1 barrel = 42 U. S. gallons

FUELS	1935	1936
Cracked	207,537,000	239,620,000
Straight-run	219,280,000	231,287,000
Natural	39,333,000	42,041,000
Benzol	1,871,000	2,537,000
Total	468,021,000	515,485,000

Any economic comparison of the two general methods must compare the use of tetraethyl lead alone with the optimum combination of reforming plus ethylization. The optimum combination of reforming and ethylization involves an economic balance to determine the percentage of the virgin straight-run gasoline to be reformed and the octane number and corresponding yield to be attained by the reforming operation to give the greatest return for the original raw material.

The assumptions used in these evaluations were as follows: (*1*) 70-octane finished gasoline has a transfer value of 6 cents per gallon. (*2*) Fuel (liquid or gas) valuation is 80 cents per 6,000,000 B.t.u. (L. H. V.). *(3)* Evaporation and sweetening losses shall be held negligible. *(4)* The octane and leading characteristics of a gasoline, whether sweetened or unsweetened, shall be considered identical. *(5)* Reforming cost shall be assumed as 0.2 cent per gallon, charged to the reformer. Fixed charges and royalty costs shall be omitted from consideration. *(6)* Sweetening cost shall be assumed as 0.05 cent per gallon of gasoline sweetened. *(7)* Virgin 100° to 400°F. base stock shall require no other treatment than sweetening before leading. *(8)* No limitation of allowable tetraethyl lead concentration in gasoline shall be considered as bearing upon the relative economics of ethylizing and reforming. *(9)* Tetraethyl lead cost shall be set at 0.26 cent per cubic centimeter, and costs of blending and mixing with ethyl fluid shall be neglected. *(10)* No differential evaluation due to varying vapor pressure or boiling range characteristic of finished gasoline shall be made, and yields of reformed gasoline shall be based on 100 per cent butane recovery. (This is a simplifying assumption and is usually of minor importance.) *(11)* The evaluation of base stocks shall not take into account lead credit or debit due to overall changes in lead consumption resulting from blending with extraneous refinery gasolines. Evaluations shall be based on the assumption that the lead requirements of a blend of gasoline can be estimated with sufficient accuracy from a weighted average of the lead requirements of the components raised to the same octane number, where such lead requirements are small. *(12)* Evaluations are to be distinguished from the ultimate values, which allow for corrections involving the factors of casinghead price, refinery butane balance, and lead susceptibility of the total gasoline produced in the refinery.

The primary basis for comparative appraisal is a statement of the relation between raw charging stock value, finished gasoline value, leading and sweetening costs when ethylizing the virgin straight-run to the required octane. This relation is given by equation 1:

$$D = G - S - L \tag{1}$$

where D = raw charging stock value (400° end point virgin gasoline) in cents per gallon, based on total ethylization,

G = finished gasoline value in cents per gallon (70 C.F.R.M. or any other arbitrarily selected octane number on any fixed octane scale),

S = sweetening cost, in cents per gallon sweetened, and

L = leading cost of sweetened gasoline, in cents per gallon leaded.

The above calculation involved in evaluating the charge, D, in terms of total ethylizing requires only ethylizing data and octane characteristics of the 400°F. end point virgin naphtha and the basic transfer value of finished gasoline of the required octane (assumed in the illustrations cited as 6 cents per gallon).

The evaluation of 400°F. end point virgin gasoline in terms of optimum reforming plus ethylizing is the next step in the analysis. Assuming a basis of 1 gallon of 100–400°F. boiling range virgin charging stock, let:

C = charging stock value, in cents per gallon (100–400°F. virgin gasoline),

C_r = value of heavy naphtha to reformer, in cents per gallon,

C_v = value of raw virgin light naphtha, in cents per gallon,

G = gasoline value, in cents per gallon (70 C.F.R.M. sweetened gasoline or any other arbitrarily selected octane number on any fixed octane scale),

F = fuel value, in cents per gallon,

P = processing cost, in cents per gallon, charged to reforming,

L_v = leading cost of light virgin gasoline (to arbitrarily selected overall octane number), in cents per gallon leaded,

L_r = leading cost of reformed gasoline (to arbitrarily selected overall octane number), in cents per gallon leaded,

S = sweetening cost, in cents per gallon sweetened,

X = feed to reforming, per cent by volume of 100–400°F. charge, and

Y = yield from reforming (100 per cent C_4 recovery), per cent by volume of charge to reforming. Then

$$C_r = \frac{Y}{100}(G - S) + \left(\frac{100 - Y}{100}\right)F - P - \frac{Y}{100}L_r \qquad (2)$$

and

$$C_v = G - S - L_v \qquad (3)$$

but

$$C = \frac{X}{100}C_r + \frac{100 - X}{100}C_v \qquad (4)$$

and

$$C = \frac{X}{100}\left[\frac{Y}{100}(G - S) + \left(\frac{100 - Y}{100}\right)F - P - \frac{Y}{100}L_r\right] + \frac{100 - X}{100}(G - S - L_v) \qquad (5)$$

The above relationship of equation 5 allows for no correction factor for treating losses, since it is designed primarily for use with reforming set-ups including clay treating and stabilization. Stock losses from treating and treating costs, as well, can be evaluated and included under the processing cost (P) to make the equation generally applicable.

TABLE 4

Comparison of values of 400° end point virgin naphtha; total ethylizing versus ethylizing and reforming

Optimum values and operating conditions

	SOURCE		
	Pennsylvania	Mid-Continent	East Texas
Light virgin naphtha:			
Volume per cent of 400° end point base naphtha	39.6	48.0	77.0
C.F.R.M. octane number	63.6	63.4	63.3
Heavy naphtha:			
Volume per cent of 400° end point base naphtha	60.4	52.0	25.0
C.F.R.M. octane number	29.2	32.2	29.6
Reformer yield, volume per cent of heavy naphtha	84.8	85.7	86.8
C.F.R.M. octane number of reformed gasoline	65.0	65.4	63.5
Total gasoline:			
Yield, volume per cent of 400° end point base naphtha	90.8	92.5	97.0
C.F.R.M. octane number* unleaded	64.5	64.2	63.3
Cc. of lead per gallon to 70.0 octane number†	0.67	0.65	0.59
Cc. of lead per gallon to 70.0 octane number, straight leading without reforming	5.2	3.0	1.6
Value of 400° end point base naphtha:			
Value when leading only, in cents per gallon	4.597	5.170	5.534
Value when leading and reforming, in cents per gallon	5.300	5.386	5.638

* Weighted average of octane numbers of light virgin naphtha and reformed naphtha.

† Weighted average of lead required for light virgin and reformed naphthas.

Equation 5 indicates a method for computing the values of charging stock in terms of ultimate gasoline value for any overall octane requirement and fuel evaluation for any combination of reforming and leading. It will be noted that certain basic data are necessary for the solution of these equations, including leading and octane characteristics of various percentages of light and heavy naphthas, and correlations covering the reforming yields for the heavy naphthas considered when reformed to various octanes. A detailed presentation of all these data is beyond the scope of this paper, but the data on which the final results of figure 1 are based are summarized in table 4.

Figure 1 shows the results of applying an economic balance to determine the optimum combination of reforming and ethylizing for three typical

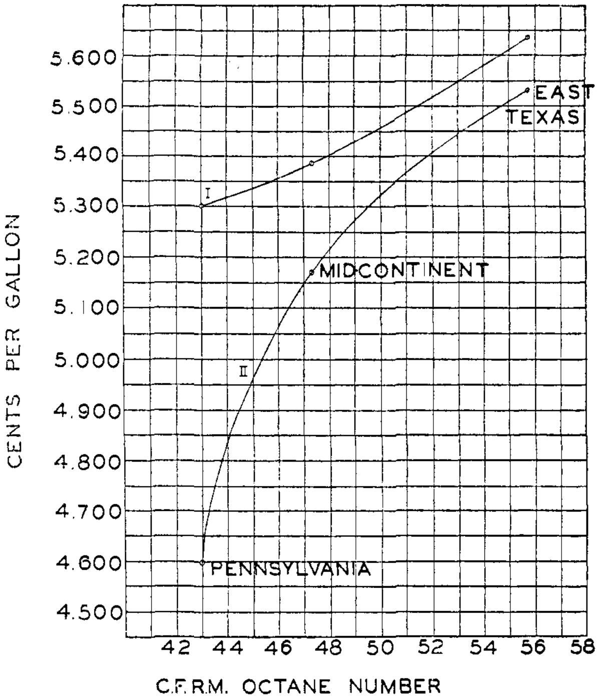

FIG. 1. Comparison of values of 400° end point virgin naphtha for leading only and for optimum reforming plus leading. Conditions: gasoline = 6 cents per gallon; fuel = 80 cents per barrel; lead = 0.26 cent per cubic centimeter; reforming cost = 0.2 cent per gallon charged. Value of 400° end point virgin naphtha, in cents per gallon, is plotted against C.F.R.M. octane number of 400° end point virgin naphtha. Curve I, optimum ethylizing and reforming to 70 C.F.R.M. Curve II, ethylizing only to 70 C.F.R.M.

400°F. end point straight-run gasolines as a comparison with the use of tetraethyl lead alone. Examining figure 1, it will be noted that the differential between the use of lead alone and the optimum combination of reforming and leading decreases with increase in octane of the original 400°F. end point base stock. It must be emphasized that the absolute values as shown in figure 1 are based on assumptions as noted, and that any specific case must be subjected to a more extended analysis, taking into account all local conditions.

The economics of the manufacture of premium-grade automotive fuel are not as susceptible to general analysis, owing to the fact that the quantity of premium-grade gasoline produced by most refiners is small compared with that of regular-grade gasoline, and therefore selected stocks of higher than overall average octane are utilized. Polymer gasolines are finding increasing use in premium-grade blends. Table 5 illustrates the blending

TABLE 5

Ethylizing characteristics of refinery gasoline blended with thermal polymer gasoline

	OCTANE NUMBER BY C.F.R.M. METHOD	TETRAETHYL LEAD TO 70 C.F.R.M.	TETRAETHYL LEAD TO 78 C.F.R.M.
		cc.	*cc.*
Base stock (refinery blend)	67.0	0.37	3.56
Polymer gasoline	77.0		
Blend of 70 per cent base and 30 per cent polymer	71.0		1.15

TABLE 6

Thermal polymer gasoline as blending agent in preparation of premium automotive fuel

Basis: 70 gallons of base stock

	TETRAETHYL LEAD REQUIRED TO 78 C.F.R.M.
	cc.
70 gallons of base at 3.56 cc. per gallon	249
70 gallons of base and 30 gallons of polymer gasoline = 100 gallons of blend at 1.15 cc. per gallon	115
Tetraethyl lead equivalent per gallon of polymer	134

Premium value of polymer gasoline over 78-octane fuel based on tetraethyl lead at 0.26 cent per cubic centimeter = (134 ÷ 30) cc. × 0.26 cent = 4.46 cc. × 0.26 cent = 1.16 cents per gallon

and leading characteristics of thermal polymer gasoline, when used as a blending agent in preparing premium-grade gasoline from a base stock of initially high octane number. From the data of table 5 the calculations of table 6 may be made, assuming that the total premium-grade fuel sold will be increased by the amount of polymer gasoline in the blend.

II. AVIATION FUELS

In comparison with the 70 to 80 C.F.R.M. octane range of automotive fuels, the present working range of fuel octane ratings used in commercial air transport work is 80 to 90 C.F.R.M. Appreciable quantities of 100-octane fuel are being used for military and special purposes, and widespread commercial use of 90- to 100-octane fuels appears to lie in the immediate future. While no accurate data are available to indicate overall octane trends in aviation fuels, table 7 shows the proportions of the fuels of different octane ratings upon which the U. S. Army Air Corps has requested bids over a period of seven years. In the year ending July 1, 1937 the Army purchased 3,000,000 gallons of 100-octane fuel, and the 1937–38 purchases will show a substantial increase in the proportion of 100-octane fuel. The octane trend in the fuel purchases of commercial airlines has shown a similar upward swing. As the major United States airlines are at present operating nearly identical equipment, it is not surprising that the fuels used should fall in a narrow range with respect to octane requirements.

TABLE 7

Distribution of U. S. Army fuel purchases with respect to octane number (1)

YEAR	OCTANE NUMBER*				AVERAGE OCTANE NUMBER
	58–65	87	92	100	
	per cent	*per cent*	*per cent*	*per cent*	
1930	56.4	43.6			70.6
1931	31.6	68.4			77.7
1932	16.6	83.4			82.2
1933	6.5	50.2	43.3		87.3
1934	5.3		94.7		90.2
1935	3.9		91.7	4.4	91.3
1936	3.5		77.5	19.0	92.6

* Army method.

The newest type engines in the United States land transport service are for the most part using 87 to 90 C.F.R.M. octane fuel for both takeoff and cruising for the best overall economy. The immediate predecessors of these engines, which are still in service and far from obsolete, have been found to give good operating results on 87-octane fuel for takeoff and 80-octane fuel for cruising. Economic studies are being conducted by the various operators, balancing overall fuel and engine maintenance costs against the price differentials for the fuels of higher octane number. One large airline reports a definite economic justification for the use of 90-octane fuel throughout in its newest equipment as against 87-octane fuel. It may be concluded, therefore, that, compared with the relative stability of octane requirements for automotive fuels, aircraft fuels are in a state of change, with the choice of octane number determined by economics, based on the use of present equipment. The engine manufacturers are now ready to offer engines which will be capable of taking full advantage of fuels up to 100-octane number or higher. The rapidity with which the new engines and fuels will be generally adopted is again entirely a question of economics.

Briefly examining current specifications for aircraft fuels, it will be noted that requirements other than octane number dictate largely the source of supply of the current fuels, and, to a large extent, the chemical constitution of these fuels. Table 8 summarizes typical specifications of large purchasers of aviation fuels in the United States. In general, these specifications tend to exclude, except in small blended concentrations, other than paraffinic types of gasoline. The present situation, owing to the maximum permissible tetraethyl lead concentrations, is that 87-octane grades can only be manufactured from carefully selected crudes. Therefore current demands dictate increasing use of the high-octane blending agents, if the octane trend is to continue upward.

Economic discussion of aviation fuels must attempt to answer the following questions: (*1*) What are the potential increased earning powers of fuels of higher octane number? (*2*) Will outlets other than 100+-octane aviation fuels absorb a portion of the high-octane blending agents? (*3*) What are the potential supplies of the high-octane blending agents?

The first question has been the subject of much technical discussion over the past several years. It is beyond the province of this paper to present the technical details involved in the evaluation of octane numbers in terms of engine performance and fuel saving. The major conclusions of these studies will be summarized briefly, following which their economic significance will be dealt with.

Klein (7), Buc and Aldrin (3), Du Bois and Cronstedt (4), Young (10), and others have presented the various relations between results obtainable with higher supercharge, higher compression ratios, and combinations of the two together with their relations to fuel consumption and the octane ratings of fuels. In general it may be stated that, for high maximum power output, high supercharge without very high compression ratio is desirable, whereas for maximum economy under cruising conditions high compression ratio is necessary.

Barnard (2) has shown that present land transport designs are standardized at a total gross loading of approximately 13 lb. per brake horsepower available for takeoff. Disposable load (fuel, oil, crew, payload) for current designs, regardless of ship size, is approximately 34.5 per cent of the gross load or 4.5 lb. per brake horsepower available for takeoff. Higher loadings are permissible for sea operations, owing to the greater space available for takeoff. For example, the Trans-Pacific flying boats are reported to be designed for a disposable load per brake horsepower maximum of 6.7. It follows, therefore, that any increase in brake horsepower maximum (without appreciable increase in engine weight) will permit taking off with higher loads. The other means toward economy is by obtaining lower specific cruising fuel consumption. Barnard (2) has shown that a close balance exists between the economics obtainable by increasing boost (increasing takeoff horsepower) and decreasing specific fuel consumptions by increased compression ratios. Either route requires higher octane numbers. For commercial airline work a compromise is made between the two in engine design.

With a given engine design and fuel, current practice is to operate on a rich mixture for takeoff to obtain maximum power without detonation. At the conclusion of the takeoff period the throttles are partially closed and the mixture leaned to obtain cruising power output. The extent to which the mixture can be leaned down safely under cruising conditions, and hence the specific cruising fuel consumption obtainable in actual operation, is only determined, for a given engine and fuel, by operating experience. Until recently mixture control was entirely based on the pilot's judgment, and, with the many details requiring his attention, the tendency was to operate on a cruising mixture which was safely on the rich side. One gauge of mixture control was formerly R.P.M., which is now no longer possible in actual service with constant-speed propellers. Another criterion of detonation during this recent period of development was cylinder head temperature. With the newer engines of higher specific output better cooling is required, which has resulted in invalidating the previous relationship between cylinder head temperature and harmful conditions in the cylinder. It is reported that with engines of the latest design pistons will be ruined, owing to detonating conditions, before abnormal cylinder head temperatures are indicated. Fortunately, instrumentation for mixture control has improved so that the mixture may be controlled to the known safe value either by automatic mixture control or manually, checked by exhaust gas analysis.

As a result of better engines, better fuels, and newer control devices, rapid strides have been made in lowering the specific cruising fuel consumption obtained in practice. Whereas a year and a half ago cruising fuel consumptions in commercial operation of the order of 0.55 lb. per brake horsepower hour were considered excellent, the same operators report that they are today realizing specific consumptions of 0.46 to 0.48 lb. per brake horsepower hour in their newest equipment and with present fuels of 87 to 90 octane number. The specific fuel consumption which may be anticipated in actual practice for fuels on the order of 100 octane number is a subject of some uncertainty. Tests (10) have been reported indicating that under carefully controlled conditions specific consumptions as low as 0.35 lb. per brake horsepower hour have been obtained.

TABLE 8

*Aviation gasoline specifications of typical U. S. consumers**

SPECIFICATIONS	U. S. ARMY AIR CORPS: Grade: 100 Spec. 2-92 Date of last revision: 6-20-35		U. S. ARMY AIR CORPS: Grade: 92 Spec. 2-95 Date of last revision: 6-19-35		PRATT AND WHITNEY GRADE: 506, 507, 511 DATE OF LAST REVISION: 9-8-33		WRIGHT AERONAUTICAL GRADE: 5801 E, 5802 E, 5803 E, 5804, AND 5805 A DATE OF LAST REVISION: MAY, 1937		AMERICAN AIRLINES GRADE: 720, 800, 801, 802, 872, 873, AND 933 DATE OF LAST REVISION: 1-24-36		UNITED AIRLINES GRADE: WINTER ANTIKNOCK DATE OF LAST REVISION: 7-1-36		PAN-AMERICAN AIRWAYS GRADE: PAA 87 OCTANE DATE OF LAST REVISION: 4-24-35		EASTERN AIRLINES GRADE: SAME AS WRIGHT WITH EXCEPTIONS		T. W. A. GRADE: 73, 80, 87, AND 90 DATE OF LAST REVISION 7-10-36	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Octane number	Not less than C.P. isoöctane		Not less than 72 parts isooctane and 28 of *n*-heptane plus 3 cc. of T.E.L.			73, 80, 87		73, 80, 87, 90, 95	First two digits of grade numbers			74, 80, 83, 87		87				73, 80, 87, 90
Type of knock engine	C.F.R.		C.F.R.		C.F.R.		C.F.R.		C.F.R.		C.F.R.		C.F.R.				C.F.R.	
Knock test method	2-94 (Army)		2-94 (Army)		C.F.R.M.		C.F.R.M.		C.F.R.M.		C.F.R.M.		C.F.R.M.				C.F.R.M.	
$Pb(Et)_4$ permitted, ml. per gallon	3.0		6.0		73, 80-2	87.3	1, 2, 3 3.75 4.00		Last digit grade Nos.		80-2	83-87.3	2.5		80-1.5 87-3.0		73-none 80-1.5 87-3.0 90-4.0	
Corrosion—copper dish	Must pass		Must pass		Must pass		Must pass		Must pass		Must pass		Must pass				Must pass	
Gum (Accel.—4 hr., 100°C., 100 # O_2)	10 mg.		10 mg.		10 mg.		10 mg.		10 mg.		10 mg.		10 mg.				10 mg.	
Color	Blue		Blue				W. W. before dye		Leaded—blue	Unleaded plus 25								
Acid heat °F					20		20 (b)		20		20						20	
Sulfur, per cent	0.10		0.10		0.10		0.10		0.10		0.10		0.10				0.10	
Reid vapor pressure, lb. per square inch	7.0		7.0		7.5		7.0		7.0		7.5		6.5				7.0	
Freezing point, °F	−76		−76		−76		−76		−76		−76		−76				−76	
Distillation characteristics:											(f)							
5% condensed, °F					150				150		140							
10% evaporated, °F. (a)	167		167				167						167					167

10% condensed, °F.					158				167		150							
50% evaporated, °F. (a)	212		212				212	1.76					212		221			221
50% condensed, °F.					195				212		195							
90% evaporated, °F. (a)	275		275				275						275		347			347
90% condensed, °F.					231				266		231							
96% condensed, °F.					252				311		252							
Distillation loss					2.0		2.0		2.0		2.0						2.0	
Distillation residue	2.0		2.0				1.0		2.0		2.0						2.0	
Recovery						96				96		96						
Sum 10, 50, 90% evaporated																564		564
Sum 10, 50% evaporated		307		307				307		307					Not required			
Reaction 10% bottoms							Neutral				Neutral							
Aromatic HC's permitted	Yes		Yes		Yes		Yes		Yes				(g)				Yes	
Water tolerance		(c)		(c)														
Heat of combustion		(d)		(d)				(e)										
Odor		(h)		(h)														

* Compiled by Central Aviation Department, Standard Oil Development Company.

(a) The per cent evaporated shall be found by adding the distillation loss to the amount collected in the receiver at each specification point.

(b) Subject to nitrating test: The difference between the initial and final temperatures (maximum) shall not exceed 40°F. 20 cc. of nitrating acid (75 per cent concentrated sulfuric and 25 per cent concentrated nitric acid by volume) is added to 50 cc. of the sample. This addition is made in a beaker drop by drop for the first few drops; if the reaction is not violent the balance of the acid may be added without this precaution. The mixture is then constantly stirred with a thermometer until the temperature drops and the maximum temperature is recorded as the final temperature. The initial temperature is that of the nitrating acid before it is added to the sample. The temperature of the gasoline before the acid addition is made shall not vary more than 1°F, plus or minus from that of the nitrating acid.

(c) Water tolerance: 80 ml. of fuel shaken with 20 ml. of water; on settling balance of water must neither increase nor decrease more than 2 ml.

(d) The product of heat of combustion (high value) in B.T.U. per pound by specific gravity shall not be less than 13,700.

(e) For 95 grade the heat of combustion or lower calorific value shall be not less than 20,500 B.T.U. per pound as determined in an oxygen bomb calorimeter.

(f) Summer grade identical with winter grade except for 15 per cent point, which is 150° max.

(g) Note: The gasoline shall be a straight-run product.

(h) The odor of the fuel shall not be nauseating or irritating. No substances of dangerous toxicity under usual handling shall be present.

On the other hand, it is reported that difficulty has been encountered when attempting to operate the newest engines with 100-octane fuel at 0.39 lb. per brake horsepower hour, and it is indicated that engine manufacturers will hesitate to guarantee 100-octane fuel engines for specific fuel consumption less than approximately 0.43 lb. per brake horsepower hour. Relative values for cruising specific fuel consumptions of 0.47 lb. per brake horsepower hour for 87-octane fuel and 0.40 lb. per brake horsepower hour for 100-octane fuel and engines have therefore been assumed in subsequent illustrations with the feeling that adequate credit is being given to the higher octane fuel.

Barnard (2) recently demonstrated the increased potential earnings obtainable by the use of the higher octane fuels, basing his calculations on data available on engine and fuel performance. While this analysis provided a stimulus to both the engine and the fuel manufacturers, it is felt that it fell short of indicating the probable economic value of the higher octane fuels to the commercial users of these fuels for the following reasons: (*1*) Increased earning power was computed on the basis of a fixed quantity of fuel. The same quantity of fuel of a higher octane number corresponds to a greater power development and hence an expanded operation. (*2*) Increased earning power as a function of fuel octane number was based on 100 per cent load factor, a condition never realized in practice, at least for land transport work in this country. (*3*) It was assumed that all of the potential increased payload due to the use of higher octane fuels could be realized and could be credited to the fuel with no overhead, profit, obsolescence or increased maintenance chargeable against the increased gross revenue. (*4*) No allowance was made for takeoff or reserve fuel.

The following illustration will attempt to show the effect of these factors on octane economic evaluation for a moderately long non-stop land transport operation in the United States. The trip chosen for the purposes of this study is one similar to the New York to Chicago non-stop flight conducted by several commercial airlines. While the figures used must be considered as approximate only, they are believed to be of the correct order of magnitude and that modifications of the basic premises will result in minor changes.

Table 9 summarizes the premises upon which subsequent calculations are based. In table 10 the minimum incremental value of 100-octane number fuel over 87-octane number fuel is calculated, based on lowered fuel consumption only. The maximum incremental value of 100-octane fuel versus 87-octane fuel is calculated in table 11 by assuming that all of the fuel weight saved can be replaced with revenue-producing payload.

To investigate the influence of load factor on the earning power of the higher octane fuel, it is necessary to examine the effect of load distribution, i.e., for any given load factor the percentage of flights which go out fully loaded. Any given load factor (average percentage of full payload carried) can be attained with various distributions between full and partial loads.

Referring to figure 2, for illustration, if we assume a load factor of 75 per cent, this may be obtained with a distribution such that 40 per cent of the trips carry full load and 60 per cent partial load, the partially loaded flights averaging 58.3 per cent of full payload. Operation using 87-octane

TABLE 9

Premises for calculation of octane fuel valuations

Gross weight ship			24,000 lb.
Empty weight ship			15,600 lb.
Disposable load			8,400 lb.
Fuel (87-octane grade):	*Gallons*	*Pounds*	
Warm-up, taxiing and takeoff	25	150	
Climb, cruise and descent	415	2,490	
Reserve	100	600	
Total fuel	540	3,240	
Oil	43	322	
Crew (3)		500	
		4,062	4,062 lb.
Payload			4,338 lb.
Specific cruising fuel consumptions:			
87-octane fuel, 0.47 lb. per brake horsepower hour			
100-octane fuel, 0.40 lb. per brake horsepower hour			
Cost of 87-octane fuel (in plane tanks), per gallon			$0.13
Gross revenue: $0.0002875 per lb. mile ($5.75 per passenger mile with passenger plus baggage at 200 lb. average). To smooth the relationships payload and revenue are computed on a poundage basis.			
Mileage (non-stop)			720 mi.

fuel and engines based on this load factor and load distribution is defined by the solid line of figure 2.

With a given service between two points it is reasonable to postulate that increased revenue due to ability to carry added payload will only be realized during periods of peak demand, when present operations go out fully loaded and potential payload must be refused or extra ships (with partial payloads) operated. During the remainder of the period under consideration it is also reasonable to assume that the actual payloads

TABLE 10

Calculation of minimum incremental value of 100-octane over 87-octane fuel

Assumptions: (*1*) Fuel consumption for warm-up, taxiing, and takeoff is constant at 25 gallons (150 lb.) irrespective of octane number. (*2*) Reserve fuel will be actually used on one-third of the flights. (*3*) The increased value per gallon of 100-octane fuel will be based on lowered consumption only.

87-octane fuel load	3240 lb.
Takeoff, etc	150 lb.
Fuel for cruising and reserve	3090 lb.
100-octane fuel for cruising and reserve: $(0.40 \div 0.47) \times 3090$	2630 lb.
Takeoff, etc	150 lb.
100-octane fuel load	2780 lb.
Average fuel consumption of 87-octane fuel: $3240 - \frac{2}{3}(600) = 2840$ lb	473.3 gal.
Average fuel consumption of 100-octane fuel: $2780 - \frac{2}{3}(600) \times \frac{0.40}{0.47} = 2440$ lb	406.6 gal.
Total average cost of 87-octane fuel per trip: 473.3 × \$0.13 =	\$61.53
On the basis of equal fuel costs the minimum value, per gallon, of 100-octane fuel = \$61.53/406.6	\$0.1513
Minimum incremental value, in cents per gallon	2.13

TABLE 11

Calculation of maximum incremental value of 100-octane versus 87-octane fuel

Assumptions: (*1*) Fuel consumption for warm-up, taxiing and takeoff is constant at 25 gallons (150 lb.) irrespective of octane. (*2*) Reserve fuel will be actually used on one-third of flights. (*3*) Ships go out fully loaded, i.e., 100 per cent load factor. (*4*) The fuel is credited with all of the increased gross revenue obtained by using the higher octane fuel.

Total load of 87-octane fuel	3240 lb.
Total load of 100-octane fuel	2780 lb.
Weight saving useful for payload	460 lb.
Increased gross revenue (100 per cent load factor): 460 × 720 × \$0.0002875	\$95.22
If the increased gross revenue is all credited to the fuel, the maximum value of the 100-octane fuel is 61.53 + 95.22	\$156.75
Average consumption of 100-octane fuel	406.6 gal.
Maximum value of 100-octane fuel per gallon = 156.75/406.6	\$0.3855
Assumed price of 87-octane fuel	0.130
Maximum differential price per gallon	\$0.2555

realized will be identical, regardless of the fact that the ships used have an increased potential payload-carrying capacity. (These premises will furnish a picture of the increased earning power of the new fuels and engines in the period immediately following their adoption. Over a period of years, based on an expanding traffic, the probable ultimate increased earning power will be greater. It is the writer's belief, however, that economic justification must be based on present traffic demands and equip-

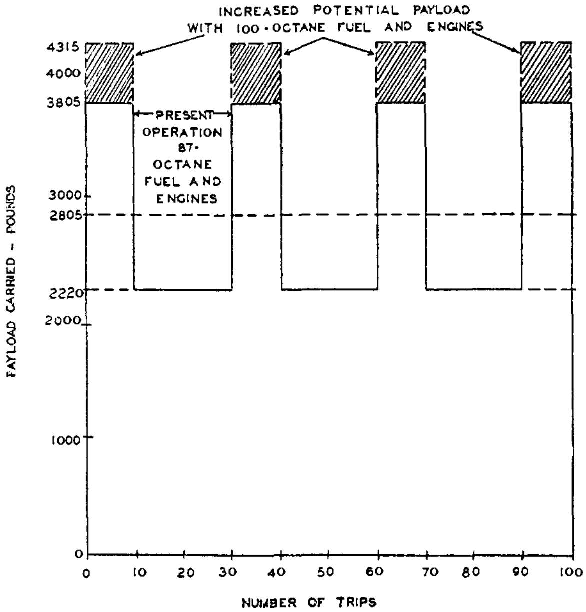

FIG. 2. Influence of load distribution on potential payloads, using 100-octane fuel and engines. Basis: 75 per cent load factor; 40 per cent of flights fully loaded; 60 per cent partially loaded. 4315 lb. maximum payload using 100-octane fuel and engines; 3805 lb. maximum payload present operation; 2805 lb. average payload present operation (75 per cent of 3805 lb.); 2220 lb. average payload partially loaded flights (58.3 per cent of 3805 lb.).

ment. On the other hand, the installation of new engines in present ships will not impose an obsolescence charge against the new fuel and motors based on the present rate of engine replacement.)

The shaded areas in figure 2 represent the potential increased payloads which can be realized in whole or in part for the assumed load factor and distribution by the use of 100-octane fuel and engines.

The calculations of tables 10 and 11 have shown, respectively, the minimum and maximum increased values per gallon of 100-octane fuel

TABLE 12

Calculation of effect of load distribution on increased earnings with 100-octane fuel and engines

Basis: payload capacity 87-octane fuel and engines 4338 lb.; payload capacity 100-octane fuel and engines 4798 lb.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
			87-OCTANE FUEL AND ENGINES				100-OCTANE FUEL AND ENGINES							
NUMBER OF FLIGHTS FULLY LOADED	NUMBER OF FLIGHTS PARTIALLY LOADED	PER CENT OF FULL PAYLOAD ON PARTIALLY LOADED FLIGHTS	Payload carried on fully loaded flights	Payload carried on partially loaded flights	Total average payload per 100 trips	Gross revenue for 100 trips	Payload carried on fully loaded flights	Payload carried on partially loaded flights	Total average payload per 100 trips	Gross revenue for 100 trips	INCREASED REVENUE WITH 100-OCTANE FUEL AND ENGINES OVER PRESENT	MAXIMUM VALUE OF 100-OCTANE FUEL, 40,660 GALLONS	MAXIMUM VALUE OF 100-OCTANE FUEL	INCREASED VALUE OF 100-OCTANE FUEL OVER 87-OCTANE
75 per cent load factor														
		per cent	*lb.*	*lb.*	*lb.*	*dollars*	*lb.*	*lb.*	*lb.*	*dollars*	*dollars*	*dollars*	*cents per gallon*	*cents per gallon*
0	100	75	0	325350	325350	67347	0	325350	325350	67347	0	6153	15.13	2.13
20	80	68.8	86760	238590	325350	67347	95960	238590	334550	69252	1905	8058	19.82	6.82
40	60	58.3	173520	151830	325350	67347	191920	151830	343750	71156	3809	9962	24.50	11.50
60	40	37.5	260280	65070	325350	67347	287880	65070	352950	73061	5714	11867	29.18	16.18
75	25	0	325350	0	325350	67347	359850	0	359850	74489	7142	13295	32.69	19.69
50 per cent load factor														
0	100	50	0	216900	216900	44898	0	216900	216900	44898	0	6153	15.13	2.13
20	80	37.5	86760	130140	216900	44898	95960	130140	226100	46803	1905	8058	19.82	6.82
40	60	16.7	173520	43380	216900	44898	191920	43380	235300	48707	3809	9962	24.50	11.50
50	50	0	216900	0	216900	44898	239900	0	239900	49659	4761	10914	26.84	13.84

* Sample calculations: Columns 1 and 2, basic premises. Column 3: for 75 per cent load factor, 20 flights out of 100 fully loaded. Let X = per cent of full payload on partially loaded flights. $20 + 80X/100 = 75$. $X = 68.8$ per cent. Column 4: column 1 × 4338 lb. Column 5: 4338 lb. × (column 3/100) × column 2. Column 6: column 4 + column 5. Column 7: 720 miles × $0.0002875 × column 6. Column 8: column 1 × 4798 lb. Column 9: same as column 5. Column 10: column 8 + column 9. Column 11: 720 miles × $0.0002875 × column 10. Column 12: column 11 − column 7. Column 13: cost of 87-octane fuel for 100 trips ($61.53 × 100) + column 12. Column 14: column 13 ÷ 40,660 gallons. Column 15: column 14 − 13 cents.

over 87-octane fuel for the given set of premises. The probable answer lies somewhere between the two. Table 12 shows a calculation of increased earnings for 100-octane fuel based on 75 and 50 per cent load factors but with various distributions between fully and partially loaded flights, and assuming that all the increased payload capacity under peak demand conditions can be realized. While the results of table 12 can be computed much more simply, this sample calculation is given in detail to avoid confusion as to the method employed.

Figure 3 summarizes the results of all calculations illustrated by table 12. Curve I of figure 3 defines the maximum incremental value,

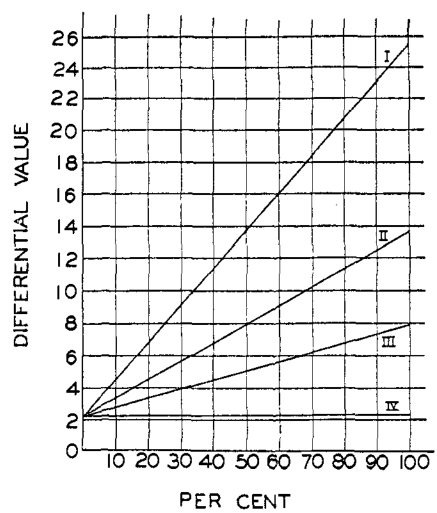

FIG. 3. Influence of load distribution on incremental value of 100-octane fuels. Differential value of 100-octane fuel over 87-octane fuel, in cents per gallon, plotted against per cent of flights fully loaded. Curve I, assuming all of potential increased payload credited to fuel; curve II, 50 per cent of potential increased payload credited to fuel; curve III, 25 per cent of potential increased payload credited to fuel; curve IV, no increased payload credited to fuel.

for any load factor and load distribution, of 100-octane fuel and engines over 87-octane fuel. If we take, for example, a 75 per cent load factor, obtained with a distribution of 75 per cent of the flights fully loaded and 25 per cent with zero load, an incremental value of 19.7 cents per gallon is read from figure 3, which represents the maximum differential value obtainable for 100-octane fuel with an overall load factor of 75 per cent. If, with a load factor of 75 per cent, only 40 per cent of the flights are fully loaded, the incremental value is depreciated to 11.5 cents per gallon. If 0 per cent of the flights are fully loaded and 75 per cent partially loaded, an incremental value of 2.1 cents per gallon is obtained, corresponding to the reduced fuel consumption only. A 100 per cent load factor obviously means 100 per cent of flights fully loaded.

Curve I of figure 3 assumes that all of the increased potential payload-carrying capacity can be sold during periods of peak demand. It is believed to be a fair approximation to assume that an average of only 50 per cent of the increased payload capacity can be realized. On this basis the curve designated as II becomes the reference curve.

Figure 3, as discussed so far, really refers to probable increased gross earning per gallon of fuel. The net increased earning power per gallon for the higher octane fuel will be less than the increased gross earning by the amount of the fixed charges against this increased revenue. The increased revenue per gallon which can be credited to the fuel for higher price justification will therefore probably approximate 25 per cent of the total increased potential revenue earned by the use of the fuel. For the

TABLE 13

Approximate estimated increased earning power per gallon of 100-octane fuel over 87-octane for a 720-mile land transport operation

PER CENT OF FLIGHTS FULLY LOADED	CENTS PER GALLON DIFFERENTIAL
0	2.1
20	3.3
40	4.4
60	5.5
80	6.7
100	7.9

type of operation and on the basis of the premises used in this illustration, it would appear that differential net earning powers approximately as shown in table 13 could be postulated for 100-octane over 87-octane fuel for the various load distributions with probable differential earning powers falling in the range of 3 to 6 cents per gallon as shown by curve III, figure 3.

Curve IV defines the minimum incremental value of the higher octane fuel based on lower fuel consumption only and independent of load distribution.

It should be emphasized that the illustration here used is based on a long non-stop land operation. For shorter range operations the incremental value of higher octane fuel will be less, approaching the minimum incremental value of approximately 2 cents per gallon. On the other hand, the long range sea operations will show greater increased earnings for any increase in payload, but, again, the load factor and load distribution will reduce the premium which can be paid for the higher octane fuel.

III. ECONOMICS OF THE USE OF HIGH-OCTANE BLENDING AGENTS

The high-octane blending agents now available commercially as typified by isoöctane (2,2,4-trimethylpentane) and its isomers, and isopropyl ether, can be utilized in various ways as dictated by economic considerations: (*1*) as blending agents with aviation base stock for the manufacture of 100+-octane aviation gasoline; (*2*) as blending agents in the manufacture of 87-octane aviation gasoline; and (*3*) as blending agents in the manufacture of motor fuels, either 70-octane regular grade or ethyl grade.

The manufacture of 100+-octane aviation fuels with a tetraethyl lead maximum imposed by specifications makes the use of high-octane blending agents necessary. It has been demonstrated earlier that 100-octane fuels can probably command a price differential over 87-octane fuels in the range

TABLE 14

Octane numbers and tetraethyl lead response of isopropyl ether and isoöctane blends with aviation base (3)

BLENDING AGENT	VOLUME PER CENT ADDED	A.S.T.M. OCTANE NUMBERS: CLEAR	A.S.T.M. OCTANE NUMBERS: 1 cc. of tetraethyl lead per gallon	A.S.T.M. OCTANE NUMBERS: 3 cc. of tetraethyl lead per gallon
Isopropyl ether	0	73.5	82.0	87.5
	10	76.3	84.1	89.3
	25	80.5	88.6	94.0
	40	85.0		97.5
Isoöctane	0	73.5	82.0	87.5
	10	76.0	84.0	89.0
	25	79.4	86.8	91.4
	40	83.0		94.2
	50	85.5	93.0	96.0

of 3 to 6 cents per gallon if used in the longer range land transport work in the United States. Considering that the blended fuels will probably not contain over 50 per cent of total blending agent, a price differential of this order should assure the manufacturers of sufficient "spread." The writers estimate the approximate manufacturing cost of any of the blending agents mentioned as falling in the range of 7 to 9 cents per gallon (including plant depreciation at 20 per cent per year and charging stock debited against the operation at 15 cents per million B.t.u. with corresponding fuel oil credits for by-products).

Table 14 gives published C.F.R.M. octane numbers of isopropyl ether and isoöctane blends together with leading characteristics.

Assuming an 87-octane aviation gasoline (containing 3 cc. of tetraethyl lead per gallon) and further assuming that a blend of this aviation gasoline with 40 per cent of an hypothetical blending agent will furnish 100-octane gasoline (the blend also containing 3 cc. of tetraethyl lead per gallon), the relation between the values of 87-octane aviation gasoline and the blending agent is calculated in table 15.

Aviation gasoline of 87 octane number is being prepared from selected straight-run light naphthas without exceeding lead tolerances imposed by specifications. The economic value of the high-octane blending agents in the preparation of 87-octane gasoline can be based on: (*1*) the lead replacement value using the present selected base stocks, and (*2*) the upgrading of straight-run naphthas of lower octane than the present selected base stocks. Examining the first possibility, and using blending and leading

TABLE 15

Value of high-octane blending agents in manufacturing 100-octane aviation gasoline

Basis: aviation gasoline of 87.5 C.F.R.M. octane number containing 3 cc. of tetraethyl lead per gallon

Assumed blend: 60 per cent of 87.5-octane aviation gasoline and 40 per cent of blending agent. Assume that the blend with 3 cc. of tetraethyl lead per gallon will have 100 octane number. Let A = value of 87.5-octane base in cents per gallon, B = value of blending agent in cents per gallon, and P = premium value of 100-octane over 87-octane in cents per gallon:

$$0.6A + 0.4B = A + P$$

$$B - A = \frac{P}{0.40} \quad \text{(equation 6)}$$

Value of P *cents*	Value of $B - A$ *cents*
2	5
4	10
6	15
8	20

data as given by Buc and Aldrin (3), the calculations of table 16 may be made.

If the high-octane blending agents were used in the manufacture of 87-octane fuels, a much lower premium based on lead saving would be obtained for the blending agent than when used in the manufacture of 100+-octane. (This illustration assumes that the 87-octane unleaded isoöctane blend would give the same performance as an 87-octane fuel containing lead. Evidence indicates that a leaded fuel would rate higher in performance on a full scale engine test.)

The use of high-octane blending agents in upgrading low-octane straight-run naphthas, thereby making them available for use in 87-octane aviation blends, is illustrated in table 17.

TABLE 16

Value of high-octane blending agents on lead replacement basis in making 87-octane aviation gasoline

Octane number of aviation gasoline base plus 3 cc. of tetraethyl lead	87.5
Lead required, cc. per gallon, to raise 25 per cent isoöctane blend to 87.5-octane aviation gasoline	1.05
Basis—gallons of 87.5-octane aviation gasoline	75
Aviation base stock, 75 gallons at 3 cc. of tetraethyl lead per gallon	225 cc.
Blend: 100 gallons (75 gallons of aviation base + 25 gallons of isoöctane) at 1.05 cc. of tetraethyl lead per gallon	105 cc.
Tetraethyl lead equivalent of 25 gallons of isoöctane	120 cc.
Cc. of tetraethyl lead per gallon of isoöctane	4.8
Cents per gallon differential value of isoöctane over 87.5-octane aviation gasoline, based on tetraethyl lead saving, equals 4.8 × 0.26 cent	1.25

TABLE 17

Value of high-octane blending agents in upgrading low-octane naphtha to furnish aviation base

Assume a straight-run naphtha of 65 octane number. This material will be upgraded by the use of a 100-octane blending value blending agent to match a 73.5-octane aviation base stock. The aviation base and the blend can each be brought to 87 octane by the use of 3 cc. of tetraethyl lead per gallon.

Preparation of blend: Let X = percentage of 65-octane naphtha in blend

$$65\frac{X}{100} + \left(1 - \frac{X}{100}\right)100 = 73.5$$

$$X = 75.7 \text{ per cent of 65-octane straight-run naphtha}$$

Let A = value of 87-octane aviation base in cents per gallon, B = value of blending agent in cents per gallon, and N = value of 65-octane naphtha in cents per gallon:

$$0.757N + 0.243B = A - 3 \times 0.26$$

$$B = 4.11A - 3.11N - 3.21$$

$$B - A = 3.11(A - N) - 3.21 \qquad \text{(equation 7)}$$

Values of $A - N$ *cents*	Values of $B - A$ *cents*
3	6
6	15

For differential values of 87-octane aviation over 65-octane straight-run naphtha of 3 or 6 cents per gallon, the corresponding premium values of the blending agent over 87-octane aviation become approximately 6 and

15 cents per gallon, respectively; hence this use of the high-octane blending agents would appear to offer economic possibilities.

The few data available on the blending and leading characteristics of the high-octane blending agents are for the most part confined to blends with straight-run naphthas suitable for aviation base stocks or with the various standard reference fuels. The octane blending and leading characteristics of several of the high-octane blending agents may be summarized as follows: (*1*) 2,2,4-trimethylpentane has an octane blending value of 92 to 100, with the lower blending values corresponding to the lower concentrations of the blending agent. The octane level of the blend appears to have little influence. The lead susceptibility of the blend is approximately that of the base stock, at least for the lower concentrations. (*2*) The other trimethylpentanes have octane blending values slightly lower than those of the 2,2,4 compound. The clear octane num-

TABLE 18

Use of high-octane blending agent (assumed blending value 100) in automotive fuel blend

Base stock: refinery blend as given in table 5

(A) Lead replacement value for 70 C.F.R.M. blend:

Let X = per cent of base stock in blend

$$67.0\,\frac{X}{100} + 100\,\frac{(100 - X)}{100} = 70.0$$

X = 91.0 per cent base stock

91 gallons of base at 0.37 cc. of tetraethyl lead per gallon	33.6 cc.
100 gallons of blend (91 gallons of base + 9 gallons of blending agent)	0.0 cc.
Tetraethyl lead equivalent to 9 gallons of blending agent	33.6 cc.
Cents per gallon premium value of blending agent over 70-octane = (33.6 ÷ 9) × 0.26	0.97

(B) Lead replacement value for 78 C.F.R.M. blend:

Let X = per cent base stock in blend

$$67.0\,\frac{X}{100} + 100\,\frac{(100 - X)}{100} = 78.0$$

X = 66.7 per cent base stock

66.7 gallons of base at 3.56 cc. of tetraethyl lead per gallon	238 cc.
100.0 gallons of blend (66.7 gallons of base + 33.3 gallons of blending agent)	0 cc.
Tetraethyl lead equivalent to 33.3 gallons of blending agent	238 cc.
Cents per gallon premium value of blending agent over 78-octane = (238 ÷ 33.3) × 0.26	1.85

ber approximates 95 as compared with 100 for C. P. isoöctane. (*3*) The dibutylenes or dimers before hydrogenation to the isoöctanes have octane blending values which are a function of concentration in the blend and octane level of the blend. Egloff (5) cites blending values varying from 152 (5 per cent concentration) to 95 (75 per cent concentration) when blended with A-3 Reference Fuel (43.6 octane number). (*4*) Isopropyl

TABLE 19

Use of high-octane blending agent (assumed blending value 130) in automotive fuel blend

Base stock: refinery blend as given in table 5

(A) Lead replacement value for 70 C.F.R.M. blend:

Let X = per cent of base stock in blend

$$67.0 \frac{X}{100} + \frac{(100 - X)}{100} 130 = 70.0$$

$$X = 95.2 \text{ per cent base stock}$$

95.2 gallons of base at 0.37 cc. of tetraethyl lead per gallon	35.2 cc.
100.0 gallons of blend (95.2 gallons of base + 4.8 gallons of blending agent)	0 cc.
Tetraethyl lead equivalent to 4.8 gallons of blend	35.2 cc.
Cents per gallon premium value of blending agent over 70-octane = (35.2 ÷ 4.8) × 0.26	1.91

(B) Lead replacement value for 78 C.F.R.M. blend:

Let X = per cent of base stock in blend

$$67.0 \frac{X}{100} + \frac{(100 - X)}{100} 130 = 78.0$$

$$X = 82.5 \text{ per cent base stock}$$

82.5 gallons of base stock at 3.56 cc. of tetraethyl lead per gallon	293.7 cc.
100.0 gallons of blend (82.5 gallons of base + 17.5 gallons of blending agent)	0.0 cc.
Tetraethyl lead equivalent to 17.5 gallons of blending agent	293.7 cc.
Cents per gallon premium value of blending agent over 78-octane = (293.7 ÷ 17.5) × 0.26	4.36

ether has a blending value somewhat over 100 with concentration and octane level of the blend having little influence.

Based on these approximate data, the economics of the use of the high-octane blending agents are illustrated by tables 18 and 19.

From tables 18 and 19 it appears that the high-octane blending agents have low economic value when used for 70-octane automotive blends. In the manufacture of premium automotive blends the blending value of the dibutylenes appears to give these materials an attractive economic value for the following reasons: Selective polymerization plants will produce good yields of dibutylenes based on the olefins charged. To manufacture the isoöctanes hydrogenation is a costly further step in the process. Hence excess polymerization capacity over that required for the aviation blending agent may be installed, and the excess dimer produced may be blended in premium-grade motor fuel, thus permitting the processing of the aviation gasoline requirements only through the hydrogenation stage and realizing an attractive premium on the balance of the high-octane polymer.

IV. POTENTIAL SUPPLIES OF HIGH-OCTANE BLENDING AGENTS

The U. S. consumption of aviation gasoline, as given in table 1, has been estimated as approximately 81,000,000 gallons for 1936. (The figures of table 1, while prepared from all available statistical data, may be somewhat on the low side.) Based on the rate of increase for the past several years, the 1937 consumption will be in excess of 100,000,000 gallons. The world consumption of aviation gasoline for 1936 has been estimated by others at 252,000,000 gallons (6).

A survey of present available material for the manufacture of technical isoöctane (2,2,4-trimethylpentane) indicates a potential U. S. supply of 155,000,000 gallons per year (3). The potential supply of isomeric trimethylpentanes having octane ratings only slightly below that of 2,2,4-trimethylpentane must be appreciably greater than that of this compound, as the first step in their manufacture is the selective polymerization of isobutene and normal butene, resulting in "dimer" yields of 150 to 200 per cent of the isobutene content of the charge. Supplies of propylene for the manufacture of isopropyl ether have been estimated as sufficient for the U. S. manufacture of 340,000,000 gallons per year of technical isopropyl ether (diisopropyl ether) (3). It should be noted that any of these materials is at present only used in blended concentrations up to approximately 50 per cent.

From these figures it is evident that the potential quantities of several high-octane blending agents are far in excess of probable requirements for aviation gasoline; hence these materials may spill over into the motor fuel market for use in motor fuel blends if economic justification can be shown.

Other materials than the particular blending agents cited may be expected to influence aviation gasoline economics and octane ratings. The increased use of certain of these may be contingent upon revision of present specifications, particularly a clarification of fuel ratings in the region above 87 octane number with respect to actual engine performance.

V. CONCLUSIONS

1. Automotive fuels have been relatively stable in octane ratings for several years, with certain factors indicating a more rapid rise in octane number.

2. One of the major economic problems in the manufacture of automotive fuels is the most economical use of the straight-run naphtha fraction of the crude. With low-octane virgin naphthas the optimum balance is partial reforming and partial ethylizing, with the differential between partial reforming and total ethylizing decreasing with increased octane number of the virgin naphtha.

3. Aviation fuels are in a state of change with respect to octane numbers. The industry is ready to use 100+-octane fuels provided these are made available at a price structure permitting their economic justification by the users and as soon as engine manufacturers offer engines.

4. Based on certain premises it is the writers' belief that net increased earning powers of 100 effective octane aviation fuel over 87-octane fuel of 3 to 6 cents per gallon can be justified for a portion of the land transport work in the U. S. If all commercial U. S. land transport operations are included, the differential earning power will fall in the range of 2 to 6 cents per gallon.

5. It appears that the high-octane blending agents cannot be economically used in blends with aviation base stocks (of 73 to 74 C.F.R.M.) for the manufacture of 87-octane aviation gasoline. The high-octane blending agents can be used economically in upgrading low-octane naphthas for use in 87-octane aviation gasolines.

6. The use of the high-octane blending agents in automotive fuels would appear to be limited to those showing high blending values and in the manufacture of premium-grade automotive fuels. It is suggested that excess dibutylenes may be absorbed in premium-grade automotive fuel.

The suggestions and criticisms of D. P. Barnard of the Standard Oil Company (Indiana), A. L. Beall of the Wright Aeronautical Corporation, and William Littlewood of American Airlines are gratefully acknowledged.

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DISCUSSION

J. EDWARD KLINE (Research Laboratories of the Standard Oil Company, Whiting, Indiana): This paper parallels Barnard's (Barnard: S. A. E. Journal (Trans.) **41,** No. 3, 415 (1937)) in its economic evaluation of octane number increases in aviation fuel. Both papers justify a definite premium for higher octane fuels, but they differ considerably, first as to the basis employed and second, as to quantitative values cited for differential value determinations.

Barnard presents an evaluation expressed in terms of maximum increase in ultimate gross earning capacity per unit increase in octane number, 2.2 cents per octane number per gallon representing an average value, which he offers to substantiate his conclusion that the aviation industry must prepare for an increasing utilization and the petroleum industry for an increasing production of higher octane aviation fuels. These incremental values are computed for revenue increases attributable either to the higher compression ratio or greater supercharge made possible by octane number improvement in the 72 to 100 octane range for flights of various duration. While it is more complete than the present paper in these respects, and while ample evidence is submitted to justify the conclusion mentioned above, Barnard's paper does not satisfactorily indicate either the immediate or the probable ultimate value of the higher octane fuels to their commerical users, because quantitative determinations are based on 100 per cent load factor and on equipment designed to take the fullest possible advantage of octane improvements, and because revenue increases are given in terms of gross rather than of net earning capacity.

The economic evaluation given in the present paper is confined to a single illustration of the immediate increase in net earning capacity of 100-octane over 87-octane fuel and engines when used in present planes. The authors allow additional payload only during those periods of peak demand when present ships go out fully loaded, and conclude that a value of 0.2 to 0.5 cents per octane number per gallon is probably justifiable. This does not recognize the validity of postulating an increasing utilization of higher octane fuels on the basis of their probable ultimate increased earning capacity. It seems that the true evolutionary character of such a shift in fuel specifications is not appreciated, for, whereas only a few operators may find it immediately advantageous to incorporate 100-octane fuel and engines in their present planes on the basis of incremental values cited, eventually the collaboration of fuel manufacturers, airplane and engine designers and builders, and airline operators will make possible full realization of the ultimate increased earning capacities of the higher octane fuels. Whether it be by normal expansion in traffic or by obsolescence or both, airline operations using 100-octane fuel will be made fully as suitable for then existing conditions as is 87-octane fuel for the present.

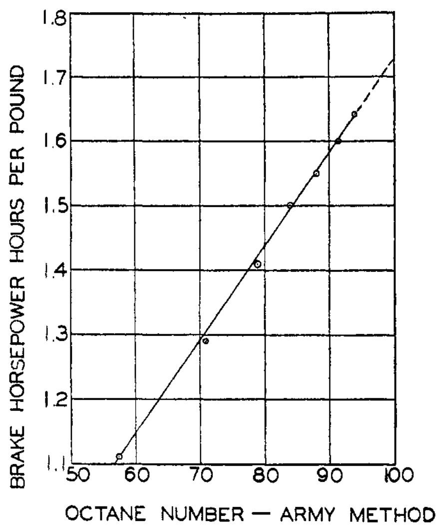

FIG. 1. Plot of engine efficiency versus fuel octane number. Data obtained on the Army C.F.R. engine. The curve holds for fuels of the same calorific value as isooctane.

It would seem more reasonable for the present paper to compare 87- and 100-octane fuels on the basis of identical load factors for the given operation, if the resulting values are to serve as a criterion for indicating the probable future of high octane number aviation fuels. While the values cited by Barnard represent the most optimistic outlook, those given in the present paper should be regarded as representing an unjustifiably pessimistic viewpoint. It would appear that a more conservative outlook could be based on an average load factor of 60 per cent, for which differential values between 1 and 1.5 cents per octane number per gallon are more nearly indicative of the probable ultimate increased earning capacities of higher octane fuels.

F. L. GARTON (Shell Petroleum Corporation, Wood River, Illinois):[1] With the advent of transoceanic flights, the importance of high-octane fuels is increasing rapidly, and the authors' remarks on the economics of these fuels are very timely. In this connection I should like to explode a fallacy which has been current during the last few years. It is often stated that octane numbers are larger, the higher in the octane range one goes. It is true that an increase from 85 to 90 octane number will allow a greater increase of compression ratio than an increase from 45 to 50 octane number. However, the curve of thermal efficiency versus compression ratio falls off at the higher ratios and tends towards a maximum. The net result is that the efficiency is roughly a linear function of fuel octane number over the practical range. This is shown in the attached figure, in which the efficiency, expressed as brake horsepower hours per pound of fuel, is plotted against fuel octane number. This curve is derived from data obtained on the Army C.F.R. engine and holds for fuels of the same calorific value as isoöctane.

It will be noted that the curve is sensibly linear and does not show signs of approaching a maximum. The possible increase in efficiency on changing from an 87- to a 100-octane fuel is indicated to be about 11.5 per cent. However, it has been shown by Barnard (S.A.E. Journal (Trans.) **32,** 418 (1937)) and others that in this high octane range greater improvements in efficiency can be obtained by supercharging than by increasing the compression ratio.

[1] Received September 18, 1937.