TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 162

THE ARITHMETIC OF DISTRIBUTION IN MULTI-CYLINDER ENGINES.

By Stanwood W. Sparrow,
Bureau of Standards.

October, 1923.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL NOTE NO. 162.

THE ARITHMETIC OF DISTRIBUTION IN MULTI-CYLINDER ENGINES.

By Stanwood W. Sparrow.

Causes of, and cures for, poor distribution have long been favorite topics for discussion among engineers. This note consists of a brief study of the "disease" itself, namely, a consideration of the effect on engine performance of a known inequality of distribution.

In what follows, distribution is considered perfect when all cylinders receive the same quantity and quality of charge. It is realized that there are engines, some cylinders of which require a different fuel-air ratio than others. Such a state of affairs is evidence of poor engine condition or design and need not be considered here.

The effect of imperfect distribution as regards quantity of charge is fairly obvious. When one cylinder of a multi-cylinder engine receives a smaller weight of charge than the remainder, its power and the power of the engine are decreased accordingly. This does not change the specific fuel consumption in pounds of fuel per indicated horsepower-hour, but the pounds of fuel per brake horsepower-hour change because the ratio of friction horsepower to indicated horsepower increases as the indicated horsepower decreases. Ordinarily the amount of this change is extremely small. The problem thus resolves itself into a study of the consequence of failing to supply all cylinders of a multi-cylinder engine with mixtures of the same quality.

As a basis for comparison, actual measurements of engine performance under conditions of perfect distribution are necessary. "All" of the cylinders of a multi-cylinder engine receive the same quality of mixture and hence such an engine satisfies the defined requirements for perfect distribution. In single-cylinder as well as in multi-cylinder engines the quality of mixture entering each cylinder probably varies from cycle to cycle. This narrows the range of mixtures over which the engine can operate and prevents the attainment of as low specific fuel consumptions as would be possible otherwise. It does not affect to any extent the value of single-cylinder tests as a basis for comparing engine performance under conditions of perfect and imperfect distribution.

In Fig. 1 are plotted curves of indicated mean effective pressure and specific fuel consumption as determined by actual measurements of the performance of a single-cylinder engine. The extent of these curves and of all others in this report represents the range of mixtures over which the engine can operate. All other curves in this report are derived from these two by the use of simple arithmetical processes. For this reason, "The Arithmetic of Distribution" was selected as a title for this note.

Fig. 2 will serve to illustrate the general method of obtaining the curves. The lower curve labeled "All cylinders receive the same quality mixture," is the same as that shown in Fig. 1. It represents what can be obtained with a six-cylinder engine, each cylinder

of which is the same as the cylinder of the single-cylinder engine and receives the same quantity and quality of charge. The remaining curves show the result when 5, 4, 3, 2, or 1 of the 6 cylinders receive a mixture whose fuel content is 20% less than that of the remainder. It is assumed that each cylinder when supplied with a certain fuel-air ratio, develops the I.M.E.P. shown in Fig. 1 to have been developed by the single-cylinder engine. In testing multi-cylinder engines, measurements are made of the total weights of fuel and air received by the engine in unit time and of the total power developed by it. Results that would be obtained from such measurements are shown in the figures. Consider the case when three of the cylinders are 20% lean. These receive a mixture of fuel and air in the ratio .8 (.08) when the other three cylinders receive an .08 mixture. The apparent mixture ratio is $\frac{3(.8)\ (.08) + 3(.08)}{6}$ which equals .072. For a fuel-air ratio of .8(.08) = .064 the lower curve of Fig. 1 gives an I.M.E.P. value of 68.8 and for a ratio of .08 the value is 73.4. Hence, when 3 cylinders are 20% lean the I.M.E.P. is $\frac{3(73.4) + 3(68.8)}{6} = 71.1$.
What is termed "apparent" fuel-air ratio is the ratio ordinarily plotted and is the ratio given in the figures. The reason for the term "apparent" is obvious from the sample calculation given above. These show that when three cylinders receive a mixture having a fuel-air ratio of .08 and the remaining three a ratio of .064, the "apparent" fuel-air ratio as obtained by measuring the total quantities of fuel and air received by the engine in unit time is .072

although no cylinder actually receives a mixture of such proportions.

All of the curves shown in figures are derived as described in the previous paragraph. They show values of mean effective pressure and specific fuel consumption for the following conditions:

(a) when 5, 4, 3, 2, or 1 of the 6 cylinders are 20% leaner than the remainder.

(b) when 5, 4, 3, 2, or 1 of the 6 cylinders are 40% leaner than the remainder.

(c) when 5, 4, 3, 2, or 1 of the 6 cylinders are 50% leaner than the remainder.

(d) when 5, 4, 3, 2, or 1 of the 6 cylcinders are 20% richer than the remainder.

(e) when 5, 4, 3, 2, or 1 of the 6 cylinders are 40% richer than the remainder.

(f) when 5, 4, 3, 2, or 1 of the 6 cylinders are 50% richer than the remainder.

(g) when 1 cylinder is 20% leaner and 1 cylinder is 20% richer than the remaining 4.

Table I.

Condition	Maximum I.M.E.P.	Minimum lb fuel per I.HP hr.	% decrease in max. I.M.E.P. caused by imperfect distribution.	% increase in min. lb fuel per I.HP hr. caused by imperfect distribution.
Perfect distribution	73.9	.432	0	0
5 cylinders 50% rich	72.4	.506	2	17
4 cylinders 50% rich	71.8	.504	3	17
3 cylinders 50% rich	71.6	.496	3	15
2 cylinders 50% rich	72.0	.479	3	11
1 cylinder 50% rich	72.9	.458	1	6
5 cylinders 40% rich	72.9	.482	1	12
4 cylinders 40% rich	72.4	.482	2	12
3 cylinders 40% rich	72.2	.478	2	11
2 cylinders 40% rich	72.8	.468	1	8
1 cylinder 40% rich	73.2	.452	1	5
5 cylinders 20% rich	73.4	.449	1	4
4 cylinders 20% rich	73.7	.453	0	5
3 cylinders 20% rich	73.4	.452	1	5
2 cylinders 20% rich	73.3	.449	1	4
1 cylinder 20% rich	73.8	.442	0	2
5 cylinders 50% lean	66.5	.497	10	15
4 cylinders 50% lean	66.5	.543	10	26
3 cylinders 50% lean	67.4	.590	9	36
2 cylinders 50% lean	68.0	.625	8	45
1 cylinder 50% lean	69.2	.655	6	52
5 cylinders 40% lean	71.2	.471	4	9
4 cylinders 40% lean	71.0	.501	4	16
3 cylinders 40% lean	70.8	.527	4	22
2 cylinders 40% lean	70.8	.538	4	24
1 cylinder 40% lean	71.8	.548	3	27
5 cylinders 20% lean	73.5	.442	0	2
4 cylinders 20% lean	73.2	.450	1	4
3 cylinders 20% lean	73.0	.453	1	5
2 cylinders 20% lean	73.3	.458	1	6
1 cylinder 20% lean	73.9	.453	0	5
1 cylinder 20% rich and 1 cylinder 20% lean	73.1	.462	1	7

Table 1 is a tabulation of some of the most interesting facts shown by the curves. Of chief interest is the percentage decrease in power and increase in specific fuel consumption resulting from imperfect distribution. For the most part the decrease in maximum power is not very large, which explains to some extent why poor distribution in an engine is tolerated.

In service the penalty for poor distribution is likely to be greater than would be indicated by Table 1. The spark advance for best performance depends upon the fuel-air ratio. When all cylinders do not receive the same quantity and quality of mixture the spark advance, being the same for all cylinders, must be incorrect for some in order to be correct for others. This effect is most pronounced in motor car engines having fairly low compression ratios and operating on lean mixtures. It probably is much less serious in aviation engines. In service, the large increase in fuel consumption due to faulty distribution, often can be traced to the natural reluctance of the engine operator to make frequent adjustments of the fuel-air ratio. He is willing to buy performance and freedom from the nuisance of continually making adjustments at the cost of increased fuel consumption. If, anywhere in the range of engine operation the mixture is so lean as to fire back in the intake pipe, the tendency is to enrich the mixture and let it remain rich even though elsewhere it already may be richer than necessary. Thus, like the chain whose strength is determined by the weakest link, the mixture strength of an engine may be determined by the weakest cylinder. When such a state of affairs exists it is quite possible for the fuel consumption in service to be increased 20% solely because one cylinder is 20% lean, although the increase in fuel consumption when the mixture is adjusted as necessary is but 5%.

One fact evident from the figures is that when distribution is faulty, multi-cylinder engine tests do not furnish satisfactory data for discussion combustion phenomena in an engine cylinder. For example, compare in Fig. 4 the results with 5 and with 1 cylinder 40% lean. If one did not know that the distribution was faulty he would conclude from a test under the former conditions that the operating range of mixtures was from .057 to .080 whereas the range under the latter conditions would appear to be from .080 to .112. Actually in the case under discussion the range is from .052 to .120 as shown by the curve plotted for conditions of perfect distribution.

It may be that by comparing results of engine tests with sets of curves such as shown in this report, one may be able to form an opinion as to the probable amount the distribution is at fault. It is not safe, however, to assume that the ability of an engine to operate over a wide range of fuel-air ratios is proof of good distribution. Only when the range is increased and the engine still operates on as lean a mixture as before and with as low specific fuel consumption, is it safe to conclude that the distribution has been improved. Fig. 15 illustrates a broadening of the operating range of mixtures with no change in the equality of distribution. Curves have been drawn for two conditions, in one of which the proportion of the fuel supplied the engine, that is, vaporized in time to enter effectively into combustion, is only one-half as great as under the other conditions. Under such circumstances, the apparent mixture must be twice as rich if the effective ratio is to be the same. It will be noted, however, that the minimum specific fuel consumption is higher, and the leanest point at which the engine will operate is richer, under these conditions. This, as mentioned earlier, makes it easy to detect when the broadening of the mixture ratio range has been caused by poor vaporization.

Recently much publicity has been given to the difficulty of satisfactorily vaporizing and distributing the present day (1923) motor car gasoline because of its comparatively low volatility. From this one might expect aviation engines to be free from distribution troubles because they are supplied with a much more volatile fuel. Incomplete vaporization, however, is not the only cause of poor distribution. When an engine requires several carburetors, poor distribution occurs unless all carburetors supply the same quantity and quality of charge under the same conditions. Aviation engines usually have several carburetors and so are particularly liable to trouble from this source.

It was stated at the outset that this note would confine itself to discussing the effect of various degrees of imperfect distribution and would not venture to predict the degree of faulty distribution likely to be found in service. If, however, the reader questions the possibility of one cylinder ever receiving a mixture having a fuel content 50% different from that received by other cylinders, it is suggested that he calculate for some engine with which he is familiar, the volume of liquid gasoline per cylinder per cycle necessary to produce such a difference.

It is realized that only a few of the possible conditions of unequal distribution have been plotted in this report. Nevertheless, it is believed that the conditions are sufficiently representative to furnish some idea as to the general consequences of poor distribution and to serve as examples from which the engineer can plot similar curves for the engine and conditions in which he is most interested.

Fig. 1.

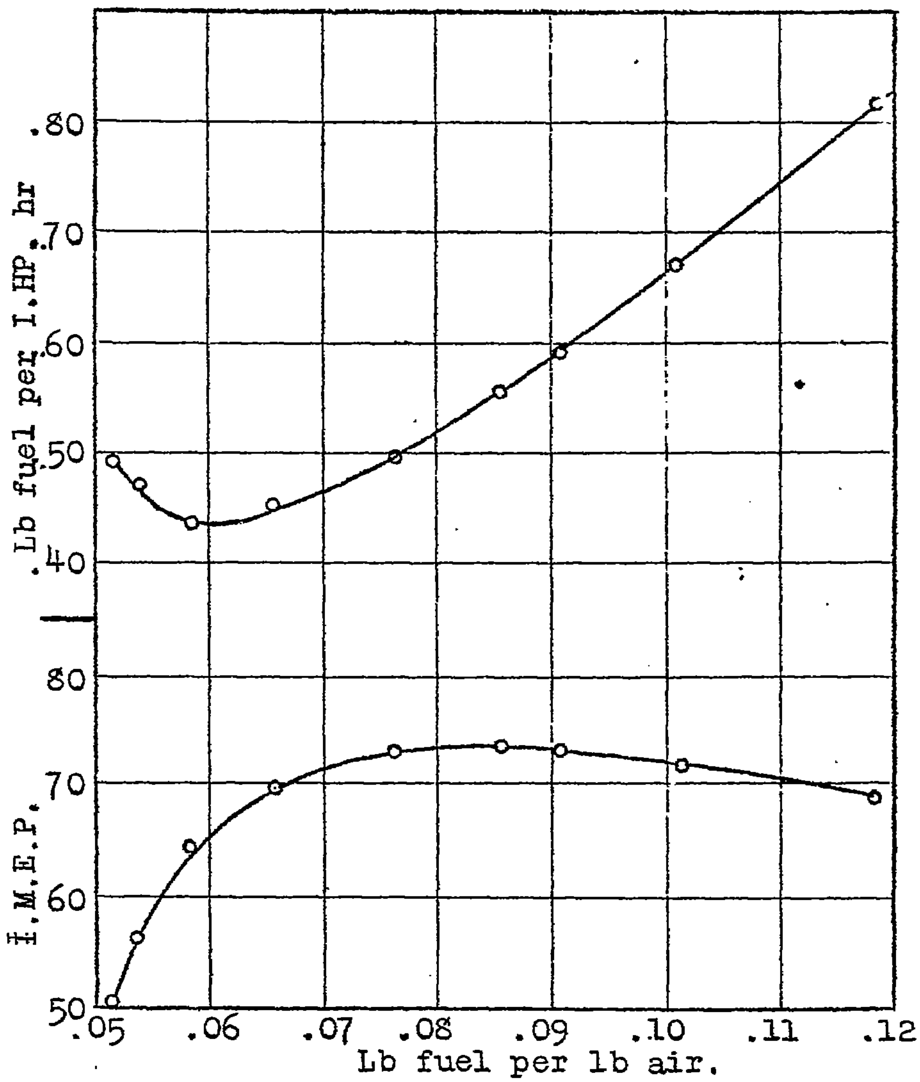

Fig. 1. Single cylinder engine test.
Engine bore = 5" Compression ratio 5:1
Engine stroke = 7" Engine speed 1400 R.P.M.
Part load.

Fig.2.

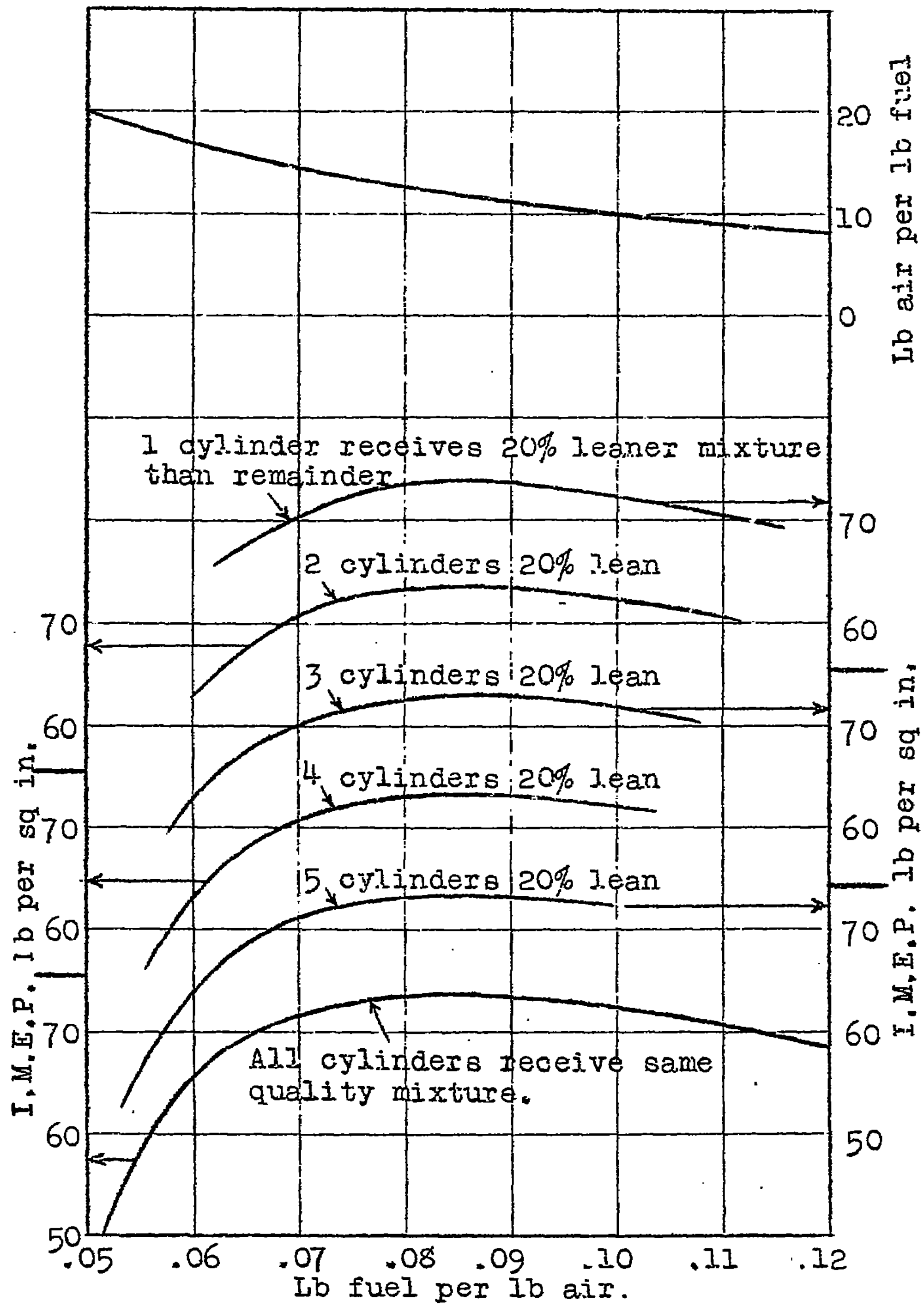

Fig.2. Effect of changes in distribution-6 cylinder engine.

Fig. 3.

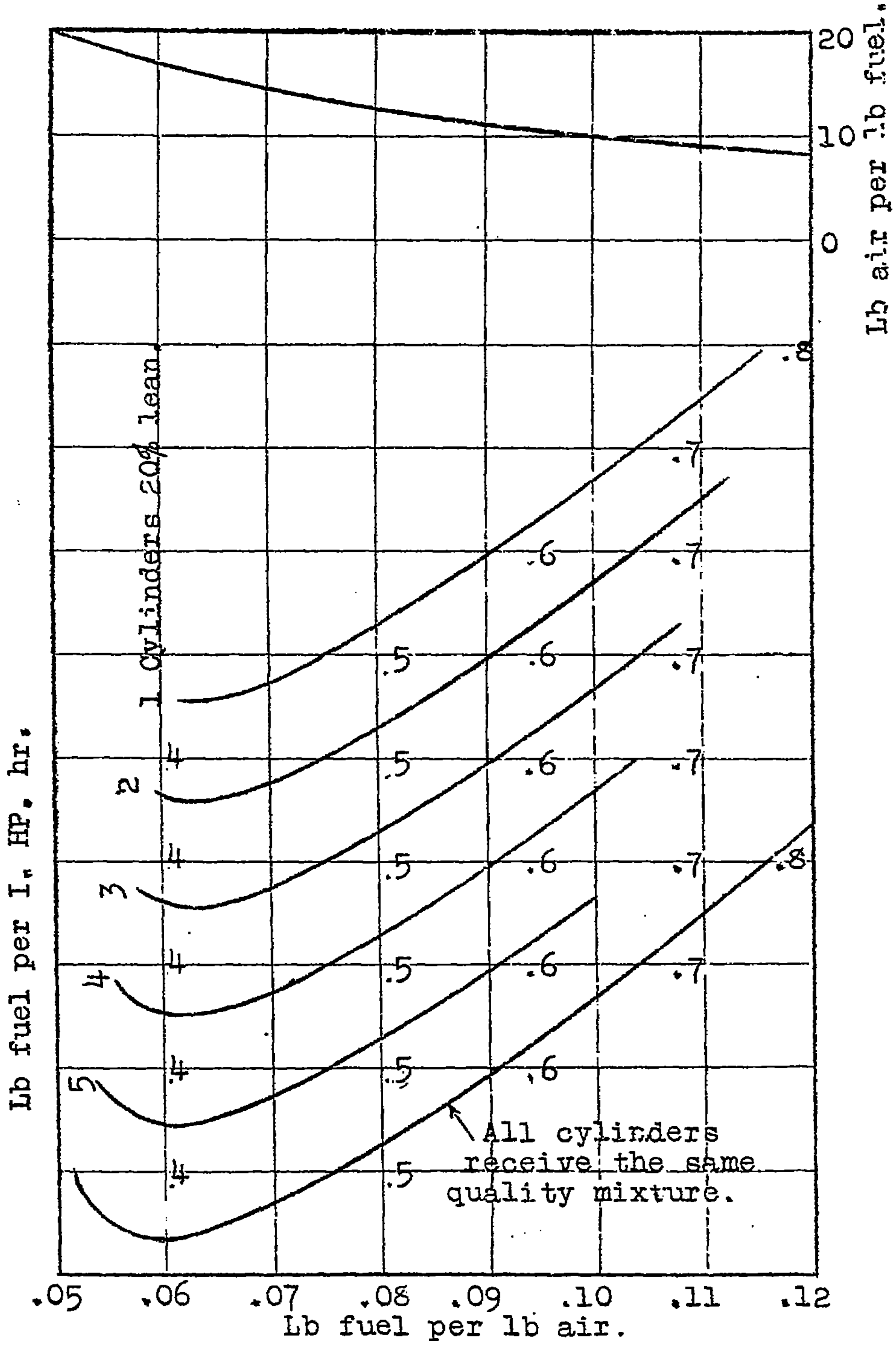

Fig. 3. Effect of changes in distribution-6 cylinder engine.

Fig.4.

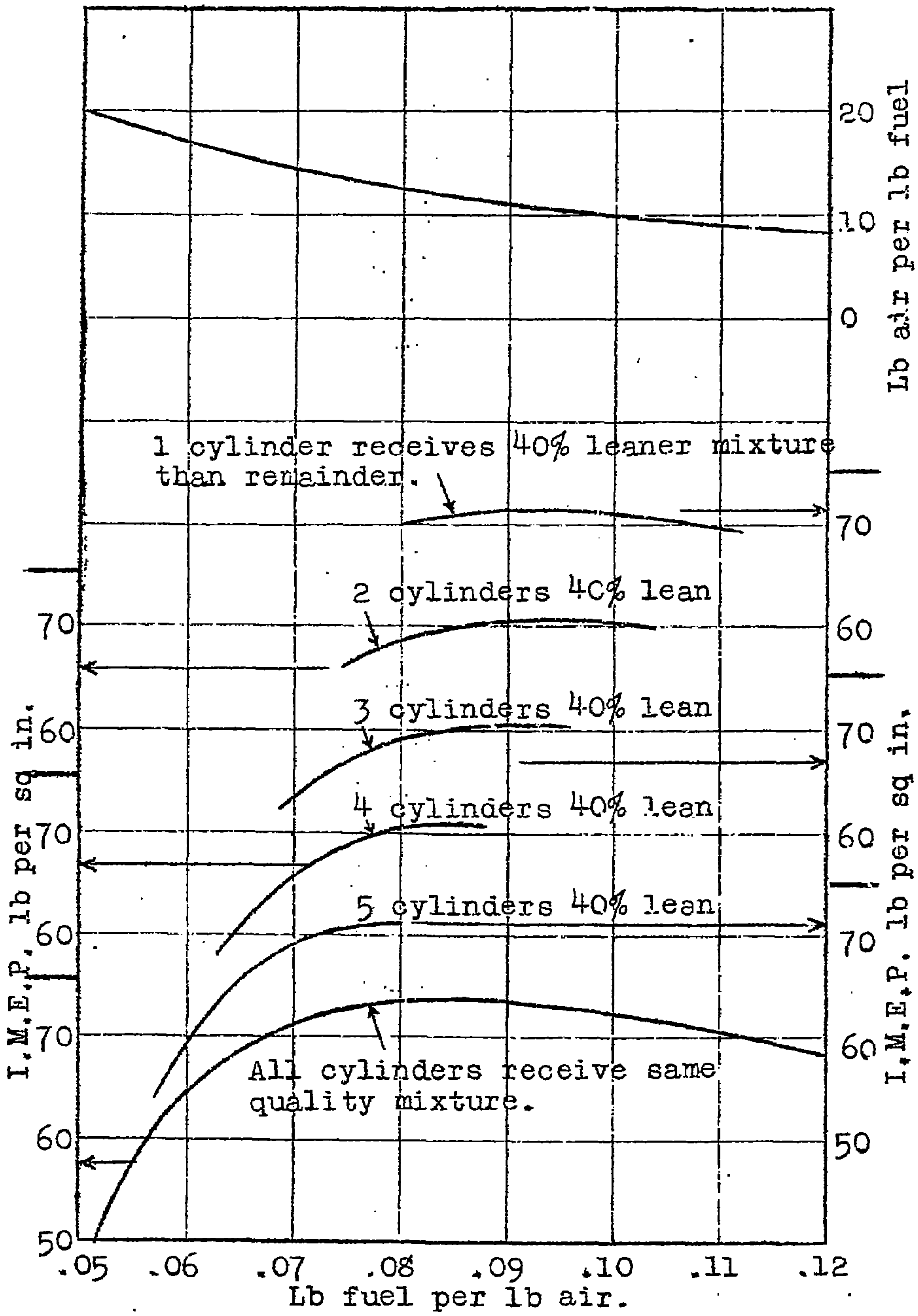

Fig.4. Effect of changes in distribution - 6 cylinder engine.

Fig.5.

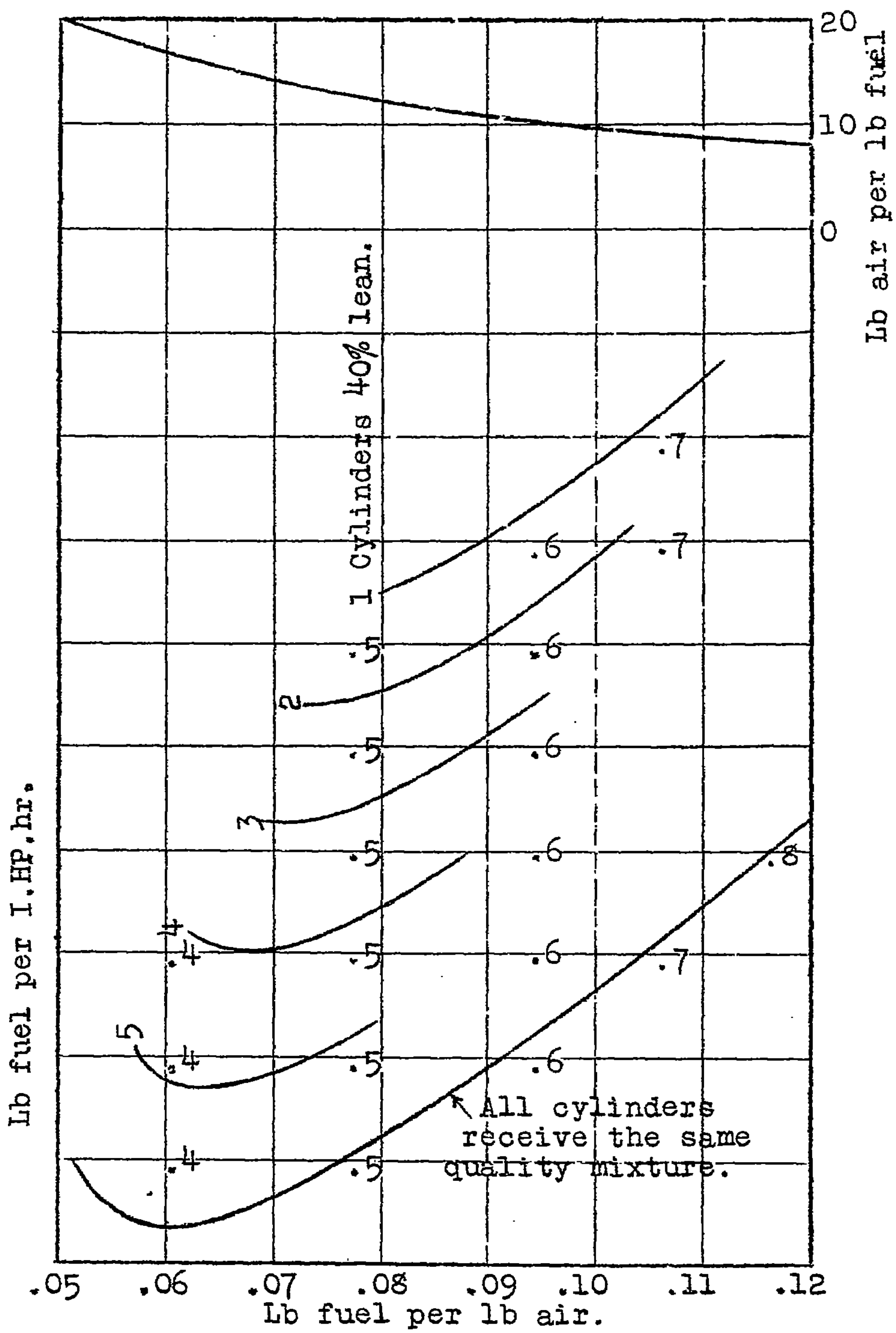

Fig.5. Effect of changes in distribution - 6 cylinder engine.

Fig. 6.

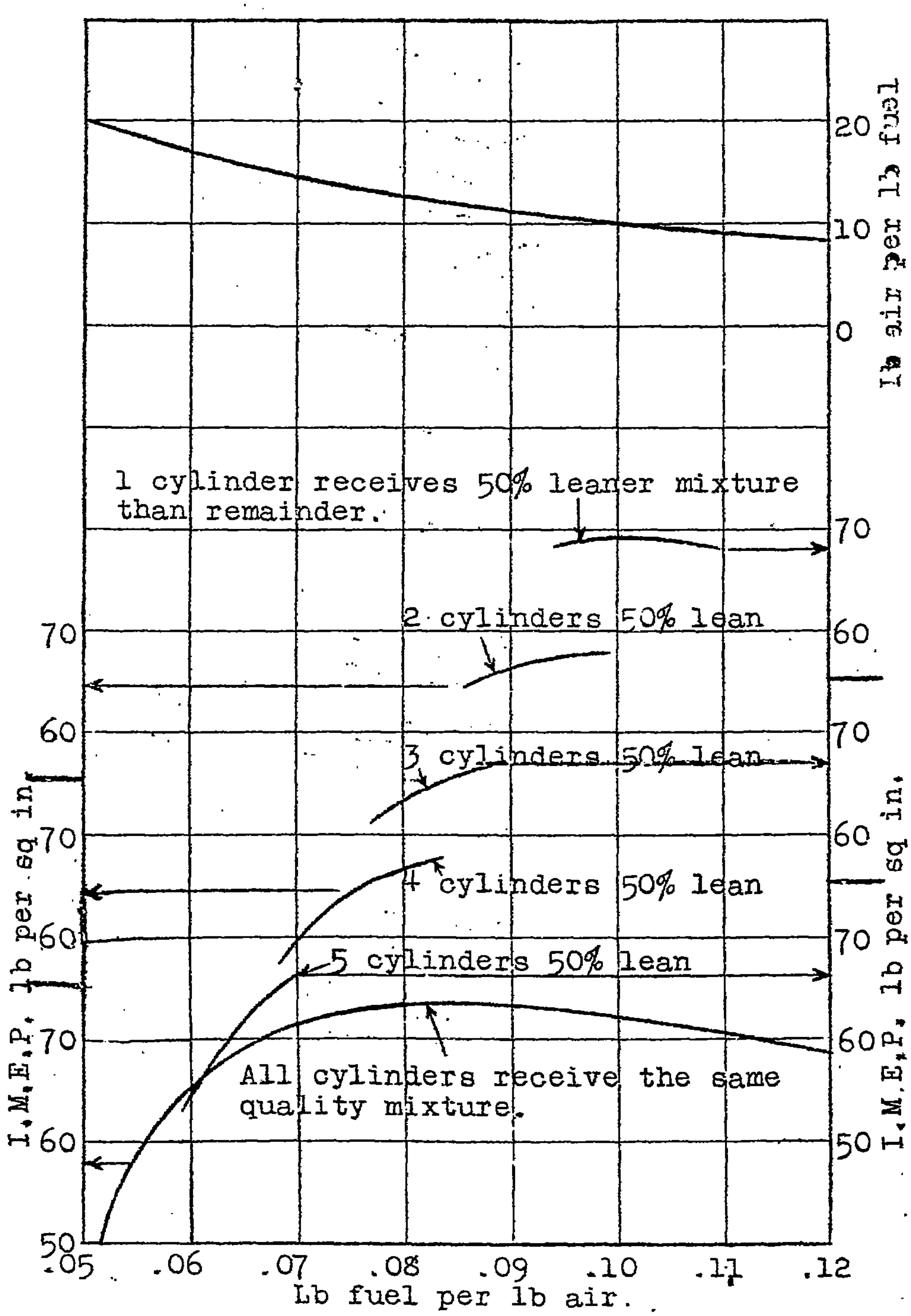

Fig. 6. Effect of changes in distribution - 6 cylinder engine.

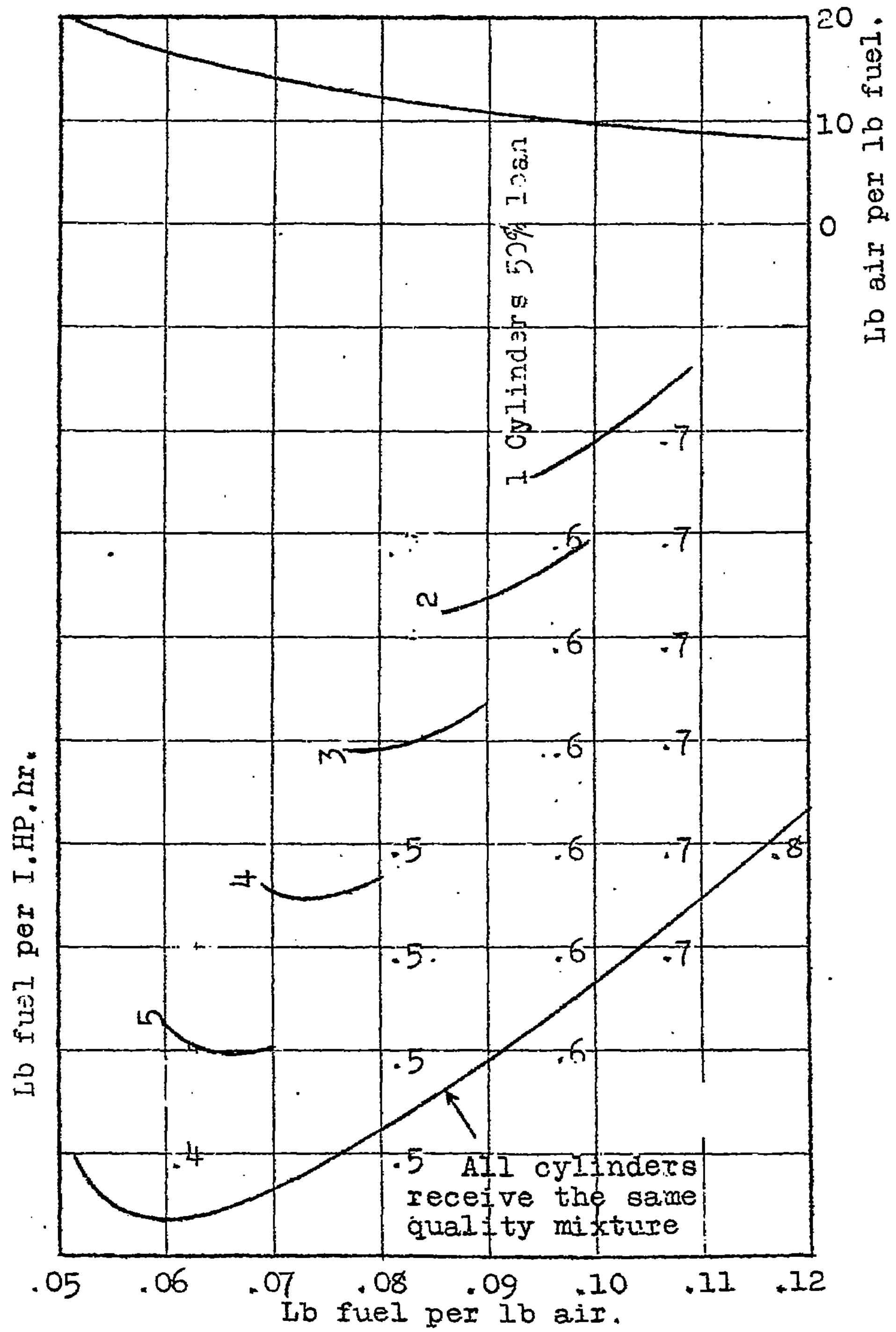

Fig.7. Effect of changes in distribution - 6 cylinder engine.

Fig.8.

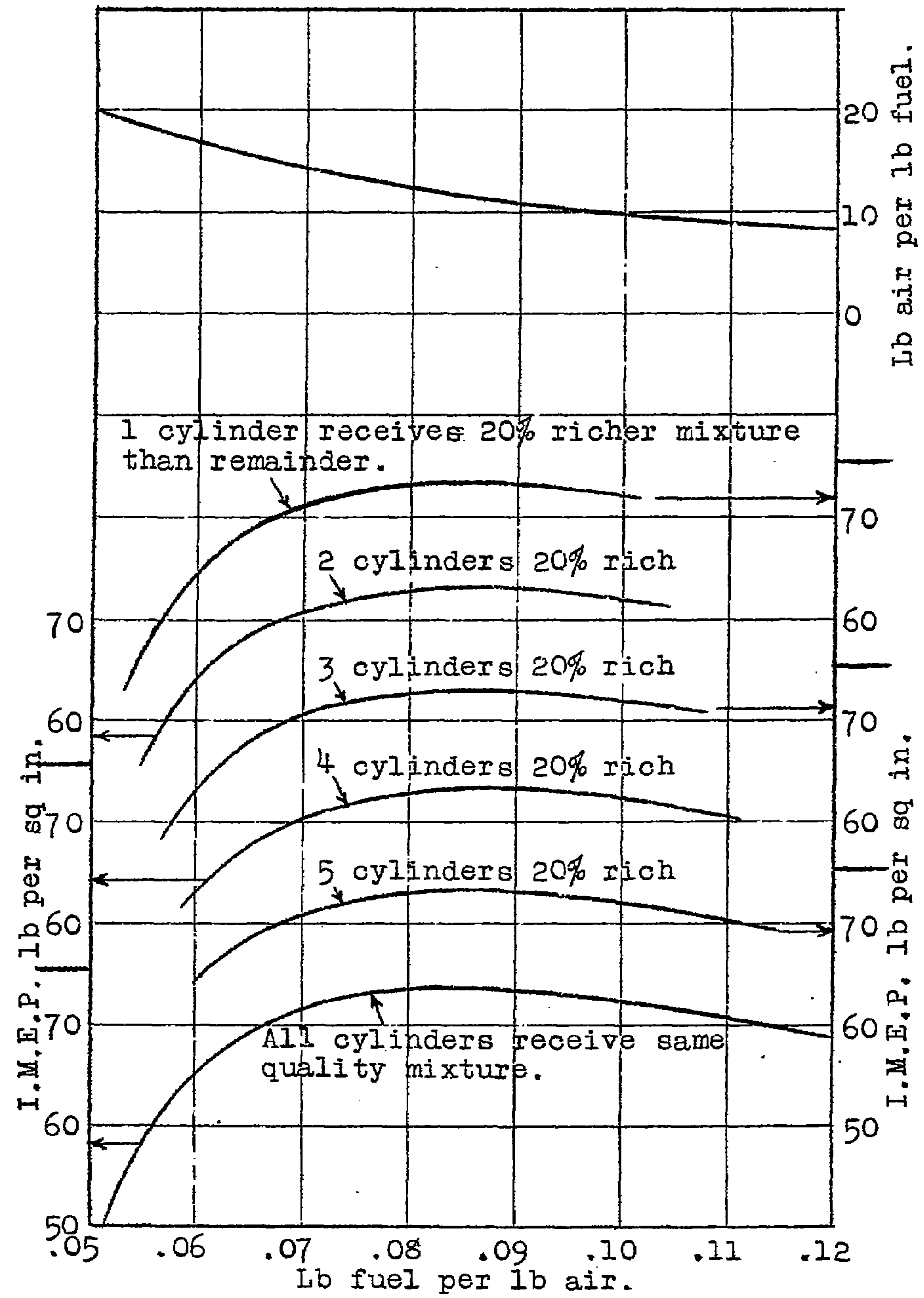

Fig.8. Effect of changes in distribution - 6 cylinder engine.

Fig.9.

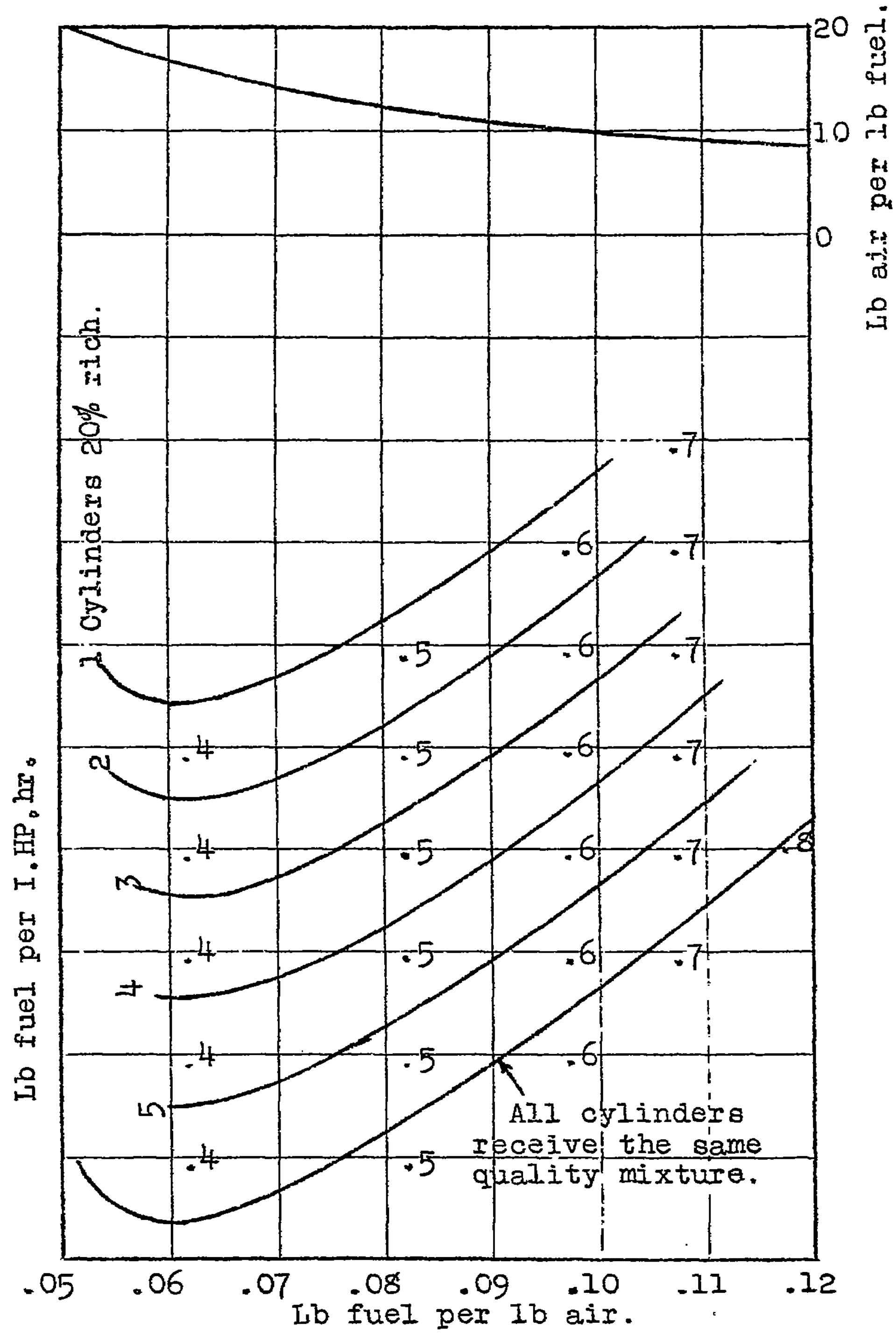

Fig.9. Effect of changes in distribution - 6 cylinder engine.

Fig.10.

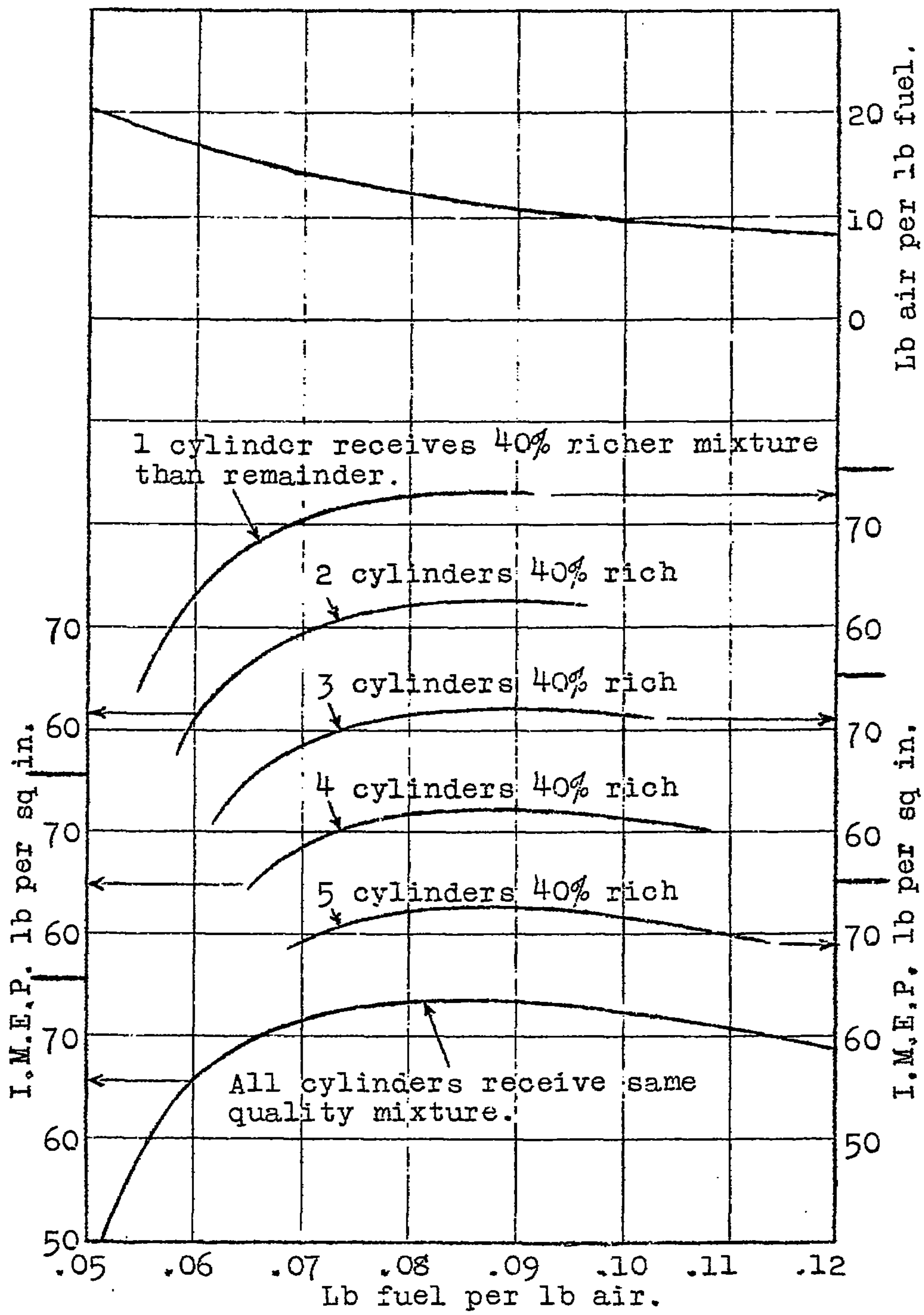

Fig.10. Effect of changes in distribution - 6 cylinder engine.

Fig.11.

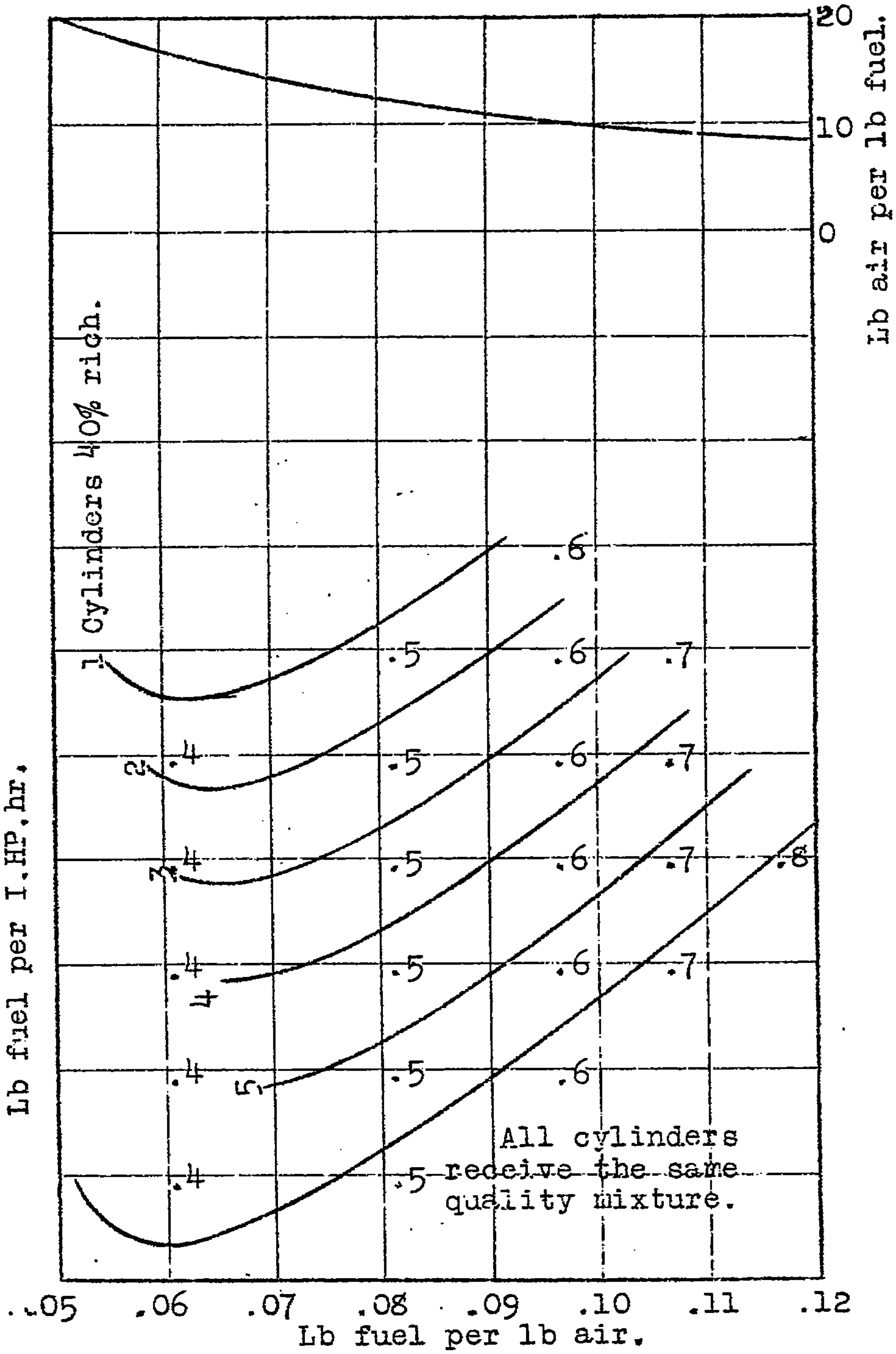

Fig.11. Effect of changes in distribution - 6 cylinder engine.

Fig.12.

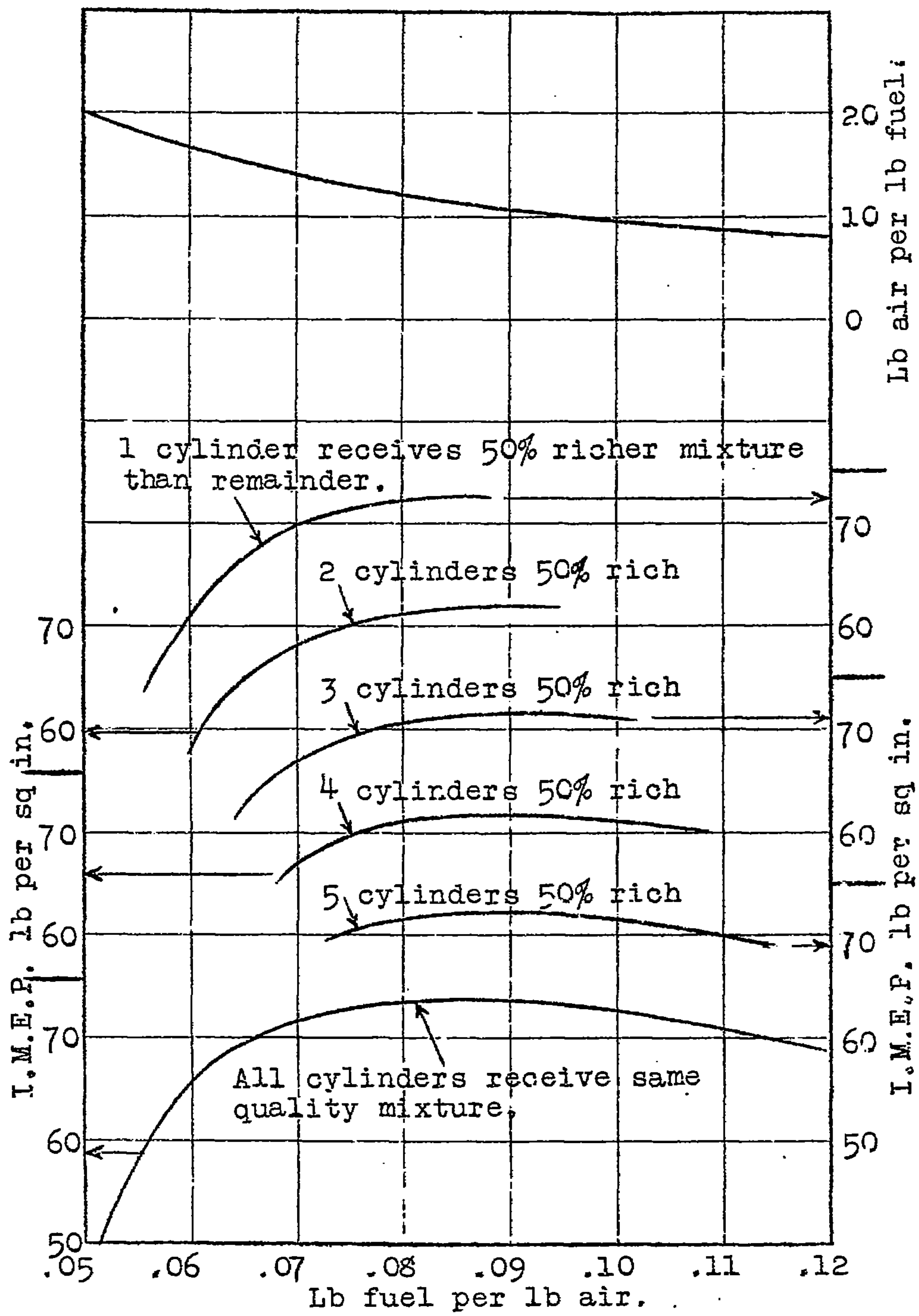

Fig.12. Effect of changes in distribution - 6 cylinder engine.

Fig.13.

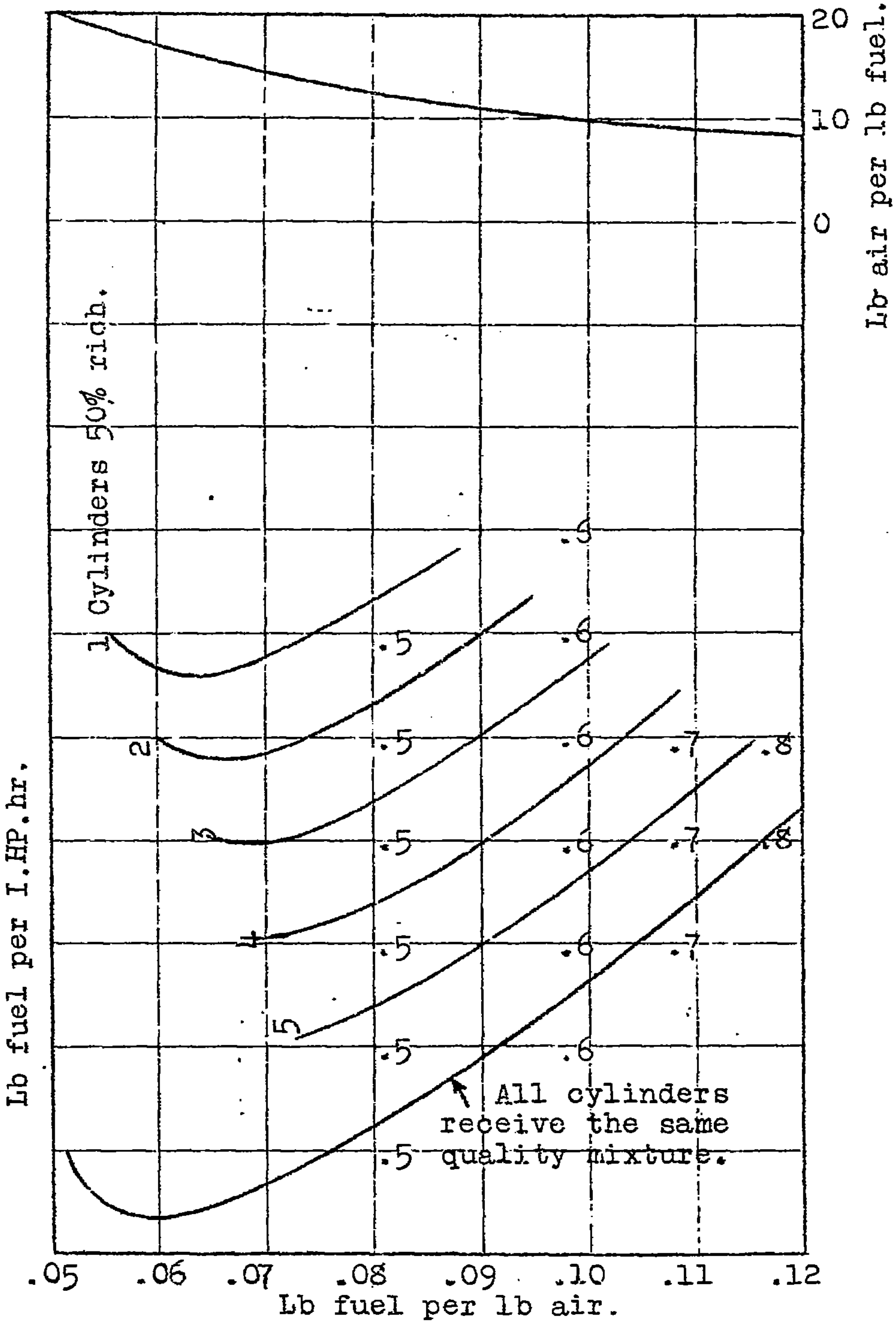

Fig.13. Effect of changes in distribution - 6 cylinder engine.

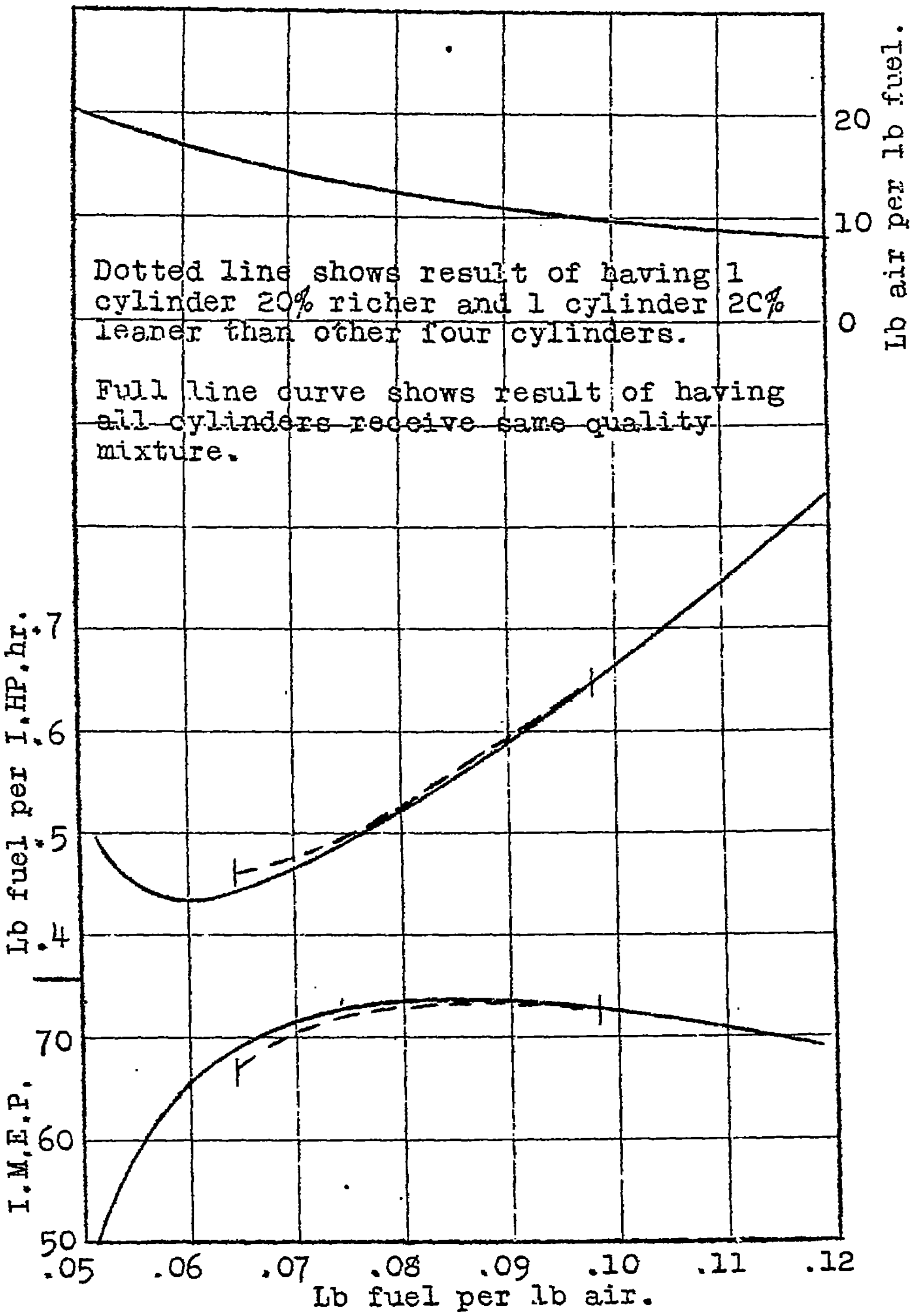

Fig.14. Effect of changes in distribution - 6 cylinder engine.

Fig.15.

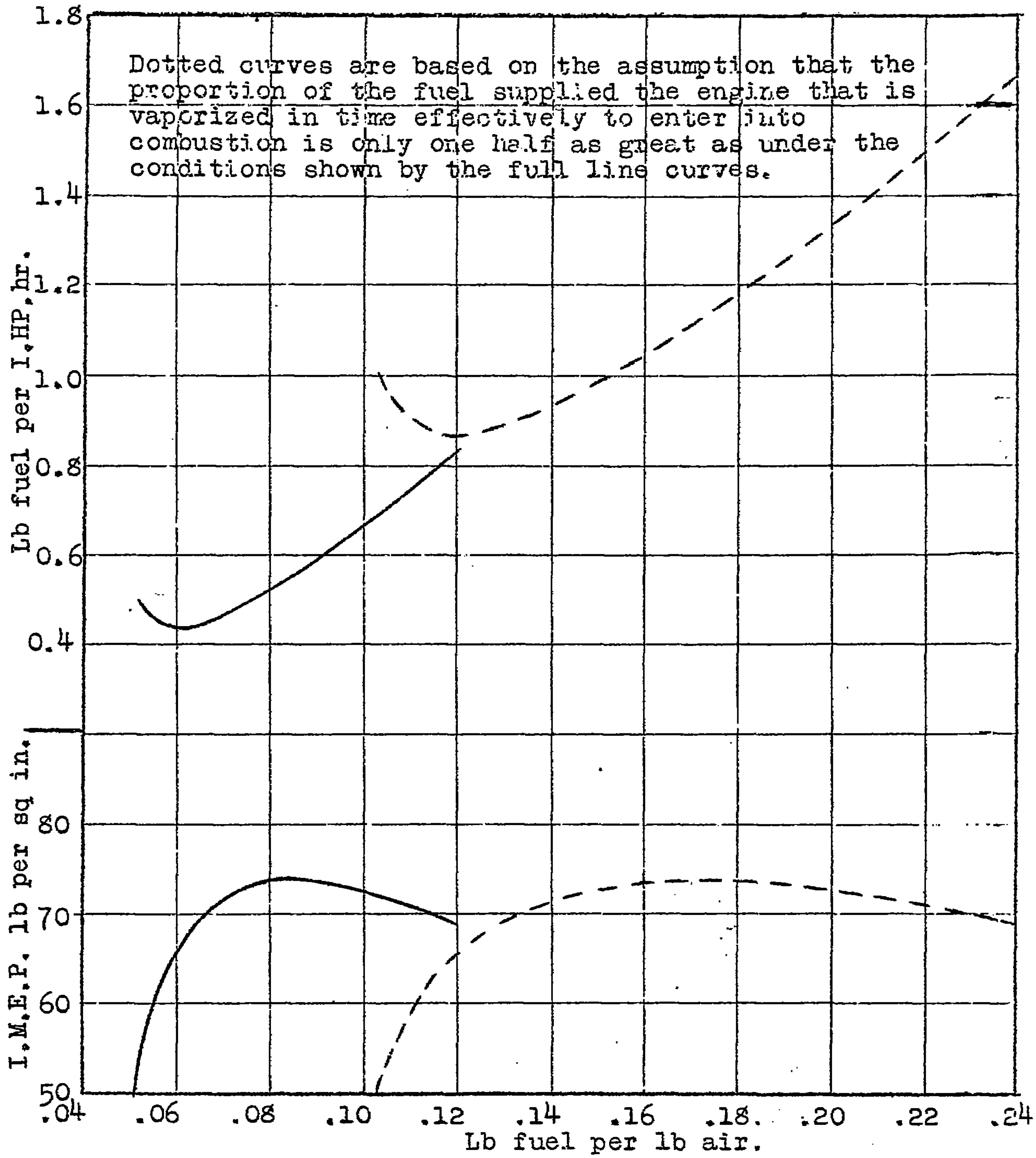
Dotted curves are based on the assumption that the proportion of the fuel supplied the engine that is vaporized in time effectively to enter into combustion is only one half as great as under the conditions shown by the full line curves.
Lb fuel per I.HP.hr.
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
I.M.E.P. lb per sq in.
80
70
60
50
.04
.06
.08
.10
.12
.14
.16
.18
.20
.22
.24
Lb fuel per lb air.

Fig.15.