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DLXXXIX.*

CYLINDER PROPORTIONS FOR COMPOUND ENGINES DETERMINED BY THEIR FREE EXPANSION LOSSES.

BY FRANK H. BALL, NEW YORK CITY.

(Member of the Society.)

AT the Chicago meeting of this Society, forming part of the International Engineering Congress, a paper was presented entitled "Compression as a Factor in Steam-Engine Economy," † in which a theory was elaborated for measuring and harmonizing the free expansion losses at both ends of the diagram. In the paper referred to it was also suggested that this system of measurement might furnish valuable information as to the relative losses from free expansion in the several cylinders of compound engines, and the Society was promised a paper on this subject at a future meeting.

In offering this paper as a fulfillment of that promise, the author is aware that he is widening the application of a law suggested in the former paper, which law was not as generally accepted as had been anticipated. This scepticism on the part of some of our leading members fortunately led to a series of experiments, since conducted at the Stevens Institute of Technology, which experiments are the subject of a paper presented at this meeting of the Society by Prof. Jacobus who conducted the experimental work. The results as reported seem to confirm the law in question, and it is therefore with greater confidence that its further application is here made.

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* Presented at the Montreal meeting (June, 1894) of the American Society of Mechanical Engineers, and forming part of Volume XV. of the *Transactions*.

† Volume XIV., *Transactions American Society Mechanical Engineers*, page 1067.

To make this application, let it be assumed that cylinders are to be selected for a triple expansion engine, where the boiler pressure is 150 lbs. above atmosphere, and the vacuum gauge shows 26 inches. Allowing for wire drawing, let it be assumed that the initial pressure in high cylinder will be 160 lbs. absolute, and the back pressure in low cylinder 3 lbs. absolute. The total range of pressure is therefore 157 lbs., and the corresponding range of temperature 221° Fahr.

The object of a compound engine being to reduce cylinder condensation by dividing the range of temperature judiciously between two or more cylinders, the first step is to decide through what range of temperature each cylinder shall work. In doing this, the desirability of a tolerably uniform division of work beween the various cylinders forming the system must not be overlooked, although it cannot be considered good engineering to impair the economy of the engine materially to accomplish this result, as each engine of the system may be built to carry any load found desirable to put upon it. If the range of temperature is divided equally between the three cylinders in the proposed engine, the greater internal surface of the low cylinder would warrant the expectation of greater cylinder condensation than in the smaller cylinder, and if so, the total condensation can be reduced by giving the low-pressure cylinder less range of temperature and the high cylinder more.

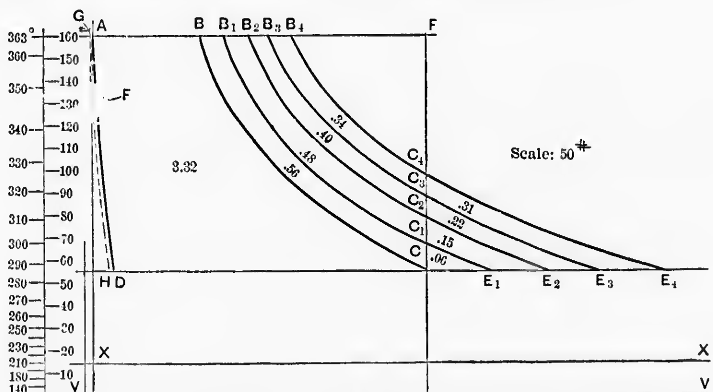

Fig. 1.

Cylinder condensation in this investigation, whether considered relatively or collectively, must be made to include the steam consumed in the jackets of each cylinder, if jackets are used. Whatever may be true in regard to the best range of temperature for each cylinder, the logic of what is to follow will apply with equal force, and therefore, for the purpose of illustration, it will be assumed that the temperature is to be equally divided. This will require that the high cylinder works between 160 lbs. absolute and 57 lbs., the intermediate between 57 and 16 lbs., and the low cylinder between 16 lbs. and 3 lbs. absolute pressure.

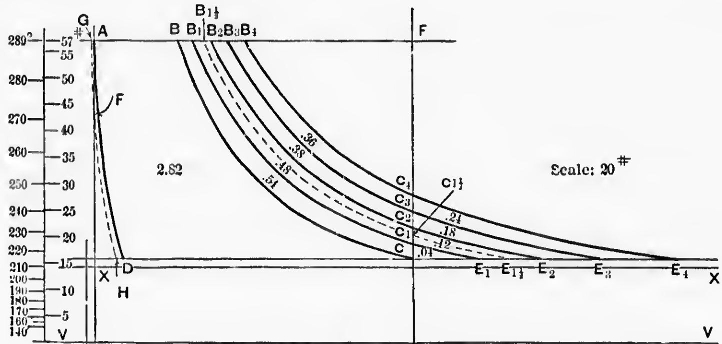

Fig. 2.

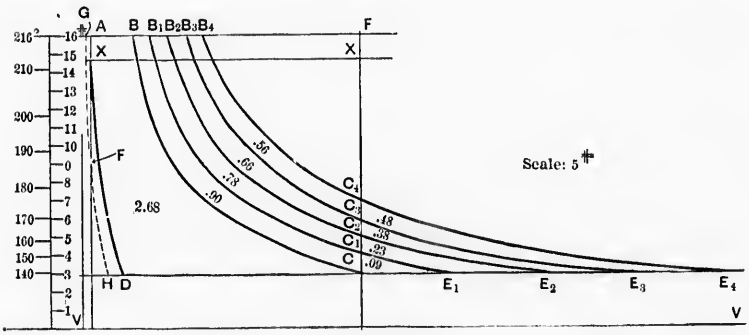

Fig. 3.

Figs. 1, 2, and 3 represent theoretic diagrams between each of the three divisions of pressure mentioned. In each case "*V V*" represents the vacuum line, and "*X X*" the atmospheric line, and in each case "*A F*" represents the piston travel. The clearance is assumed to be 4% of the piston displacement, as indicated. For convenience in constructing the curves and measuring their enclosed areas, the following scales have been chosen:

Fig. 1	Scale 50 lbs. to the inch,
Fig. 2	" 20 " " " "
Fig. 3	" 5 " " " "

In each case, "*A. B. C. D.*" represents a theoretically perfect diagram, so far as free expansion is concerned, because expansion is carried to the line of return pressure, and compression fills the clearance space to initial pressure. It is hardly necessary to say that the curves here shown are Mariotte curves, and not Adiabatic, as the latter are seldom used and are considered an unnecessary refinement in this investigation. The successive curves in each diagram, which follow the curves "*B. C.*" represent later points of cut-off, and they are continued beyond the limits of piston travel until they intersect the line of return pressure. The areas of enclosed spaces are indicated by figures. Thus in Fig. 3, the area of the theoretically perfect diagram "*A. B. C. D.*" is 2.68 inches, and "$B.\ B_1.\ C_1.\ C.\ B.$" is .90 inches, etc.*

The next step is to determine the best point of cut-off for each cylinder. In this investigation each cylinder must be considered separately, and treated as though it was a single cylinder engine working between the limits of pressure indicated, and it may be asserted without fear of successful contradiction that if any cylinder of a compound engine is not realizing the highest economy obtainable from a single cylinder engine working between its limiting pressures, then the engine as a whole is falling short of its possibilities. It is also true that if because of cylinder condensation it is not economy to expand to the line of back pressure in a single cylinder engine, the same is true of every cylinder of a compound engine, it being only a question of the degree of free expansion permissible in each case.

To those who believe that there ought to be no "drop" in any of the cylinders of a compound engine except the low, the foregoing will seem rank heresy. They argue that if there is "drop" in the high cylinder there is free expansion waste, and by earlier cut-off in the low cylinder the receiver pressure may be raised until the drop in high cylinder disappears, thus elimi-

* For convenience of publication, the diagrams of Figs. 1, 2, and 3 have been reduced in size, and therefore, while the areas remain relatively the same, the figures given are the actual areas of the original diagrams.

nating free expansion and improving the economy of the system. This is a plausible fallacy which represents only one side of the question, the other side being that by raising the receiver pressure the range of temperature is increased in the large cylinder, thereby increasing the cylinder condensation in this cylinder without effecting a corresponding reduction of condensation in the smaller cylinder. Looking at this question from another point of view, let it be admitted for the moment that the economy of the engine will be improved by raising the receiver pressure until the "drop" in high cylinder disappears. Then considering the high cylinder alone, we have a diagram in which expansion is carried to the line of back pressure, which cannot be considered the most economical diagram from any engine whose internal condensation is not in proportion to the steam used, which is the recognized condition of all steam engine cylinders. Therefore the economy would be improved by using a cylinder of smaller diameter, with less exposed surface for condensation and necessarily some "drop" at exhaust opening. Then if it is true that better economy will be realized by raising the receiver pressure again to eliminate the drop as before, it only requires a few successive stages of this development to dispense with the high cylinder altogether, completing the whole expansion in the low cylinder, and at the same time improving the economy at every step in that direction, reaching the highest economy when the low cylinder, covers the entire range of expansion and the engine becomes a single cylinder engine instead of a compound. To those who still adhere to the belief that what is true of one cylinder of a compound engine is not true in any degree of the others, and that one cylinder of an engine may be wasteful in its preformance, without affecting the aggregate performance of the system, the reasoning of the following pages will not be convincing. To those who believe that each cylinder must realize the most economical performance for a single cylinder working between its limits of pressure, and believe also that cylinder condensation makes it impossible to obtain this by expanding to the line of back pressure in any cylinder, the method of investigation which is to follow will be of interest.

Referring again to Figs. 1, 2, and 3, let us first investigate the low-pressure cylinder represented in Fig. 3 as being in some respects the most important one of the system. If 3 lbs. absolute be assumed to be the back-pressure in this cylinder, the diagram "*A.B.C.D.*" represents full and complete expansion, and will correspond with the highest economy of this cylinder if there was no condensation, or if cylinder condensation was a uniform per cent. of the steam used. This diagram, carrying expansion to 3 lbs. absolute, represents a total of more than 53 expansions in the system, which is recognized as being far beyond the economical limit. Following the successive expansion curves from "B_1. B_2. B_3. B_4," it will be seen that "B_1." adds an area to the useful diagram of .9 inches, or more than $\frac{1}{3}$ of the area of "*A.B.C.D.*," and the free expansion loss occasioned by this curve is only 10% of the useful area that has been realized. This loss is represented by the area of "C_1. E_1. C." Substituting curve "B_2. C_2." for "B_1. C_1.," the further addition of useful area is only .78 inches, which is accompanied by an additional free expansion loss of 29% of this amount, and in the same manner "B_3. C_3." only adds .66 inches of area with a loss of 57%, and finally "B_4. C_4." with a useful area of only .56 inches entails a loss of 85% of this amount in consequent additional free expansion. As between "B_3." and "B_4." then it is not likely that an amount of cylinder condensation is ever found in practice that would make it economy to add this last area to the diagram with its enormous free expansion loss and the terminal pressure of "C_4." representing 22 expansions in the system is therefore probably too high, and we must look for the best results between 22 expansions corresponding to "C_4." and 53 expansions due to terminal "*C.*"

If the exact amount of cylinder condensation due to each of the five points of cut-off was known, the indicated areas of the diagrams would furnish the data necessary to determine at once the exact point of cut-off where the highest economy would be realized, and just to the extent that we are able to correctly estimate this cylinder condensation, will we be able to determine correctly the best number of expansions in each cylinder and in the system. It must be here understood that it is not intended in this paper to determine absolutely the best cylinder ratios or the best number of expansions for the conditions that have been assumed because of the lack of exact data regarding cylinder condensation, but it is the purpose of the author to show that by this method of investigation even an approximation of the cylinder condensation enables the engineer to decide the question of cylinders with a comparatively small limit of possible error, and this error may be reduced toward zero just in the proportion that the truth regarding cylinder condensation is known. To illustrate the manner of applying this knowledge with the use of the diagrams of Figs. 1, 2, and 3, various amounts of cylinder condensation will be assumed and the problem worked out for each case. Before doing this it may be interesting to note the relatively greater wastefulness of free expansion in the low-pressure cylinder than in the others. Referring to Fig. 3, the removal of the point of cut-off from "B" to "B_4," adds to the useful diagram the area of "$B. B_4. C_4.C. B.$" equal to 2.90 inches. The free expansion of 4 lbs. at "C_4." results in a loss of useful work represented by the area of "$C_4. E_4. C.$" equal to 1.18 inches, or about 41% of the former. Referring to Fig. 1, representing the high-pressure cylinder, and repeating the same calculation, the area of useful work of "$B. B_4. C_4. C. B.$" equals 1.78 inches, and the drop at "C." of 40 lbs. causes a loss represented by "$C_4. E_4. C.$" equal to .78 inches area, or about 41% of the useful work in this case also, so that by comparing the two we see that in both cases the useful areas of "$B. B_4. C_4. C. B.$" are accompanied by a free expansion loss of about 41%, but in the low-pressure cylinder the terminal drop is only 4 lbs. as against 40 lbs in the high cylinder.

The foregoing ought to furnish food for thought to the engineer who is chiefly conc[illegible] about preventing drop in the high and intermediate cyli[illegible] ferring again to Fig. 3, and resuming the conside[illegible] linder condensation, let us assume certain quantiti[illegible] ut this cylinder condensation, and thus illustrate [illegible] er of applying more exact knowledge on this subject. It is evident that the conditions which make late cut-off desirable are large condensation and a constant quantity at every point of cut-off, and the reverse conditions, viz: small condensation, varying for each point of cut-off, would call for early cut-off. In illustrating this subject two rather extreme conditions have been chosen, one where the cylinder condensation is assumed to be 25% of the steam accounted for by the indicator at latest point of cut-off, and this amount to remain undiminished at the earlier points of cut-off, and the other condition where cylinder condensation is assumed to be only 15% instead of 25% as above, and to decrease at each of the earlier points of cut-off in the following manner:

14% when cutting off at B_3.
13% " " " " B_2.
12% " " " " B_1.
11% " " " " B.

Fig. 4 gives a graphic illustration of the effect on the economy of the low cylinder produced by the two assumed conditions as to cylinder condensation. Referring to Fig. 3, the steam accounted for by the indicator at latest point of cut-off may be represented by the area of $A. B_4. E_4. D. A.$ which equals 6.78 square inches. If the steam condensed on entering the cylinder is 25% of that accounted for by the indicator at latest point of cut-off it may be represented by 25% of the area 6.78″ = 1.69″.

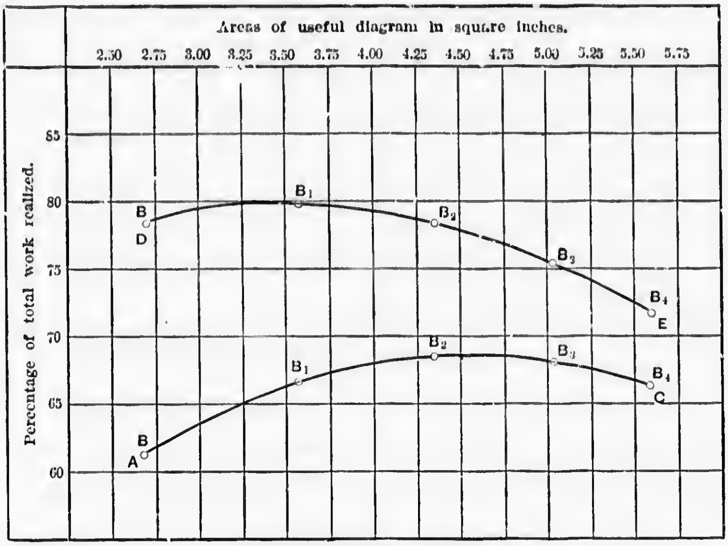

Fig. 4.

This last area then, under the assumed conditions, will be a constant loss at every point of cut-off. An additional loss by free expansion occurs at every point of cut-off later than B.

These free expansion losses are represented by the indicated areas beyond the limits of piston travel, which combined with the area representing condensation, and compared with the areas of useful diagram, produce the curve "$A.$ $C.$" (Fig. 4) in the following manner. Measurements on abscissa correspond to the useful areas of diagrams at the five points of cut-off indicated. Measurements on ordinates are obtained as follows:*

For cut-off "*B*" the area of useful work is 2.68 inches, and the assumed constant loss by condensation of 1.69 inches makes the total area due to the steam consumed equal to 2.68 inches + 1.69 inches = 4.37 inches. Of this amount the area actually realized, 2.68 inches, is 61.3%, which is measured on ordinates and establishes the point "*B*." For cut-off "B_1," in the same manner as before, we have useful area of,

"A. B_1. C_1. C. D. A."	3.58 inches.
Free expansion of "C_1. E_1. C."	.09 "
Assumed condensation	1.69 "
Total area due to steam used at cut-off B_1	5.36 inches.

Of this area only 3.56 inches has been realized, or 66.7%, which establishes point "B_1" in curve "*A. C.*" (Fig. 4.) The succeeding points on this curve are found by the same process, using the indicated areas at each progressive step.

Curve "*D. E.*" is produced by the same method, the only difference being that the smaller and varying condensation is assumed, thus instead of the constant area of 1.69 as assumed in curve "*A. C.*", the condensation is supposed to be represented by the following areas:

.74	inches	for	cut-off	B.
.81	"	"	"	B_1.
.88	"	"	"	B_2.
.95	"	"	"	B_3.
1.02	"	"	"	B_4.

These quantities are substituted for the constant quantity, 1.69 inches, used in curve "*A. C.*" and the result is curve "*D. E.*"

From an examination of these curves it appears that with the conditions assumed for curve "*A. C.*" the highest economy is obtained at or near cut-off "B_2.", while with the conditions which produce curve "*D. E.*", the highest economy is found at or near cut-off B_1.

If the condensation assumed for either of these curves was known to be correct, then the best point of cut-off would at

* This method is fully illustrated on page No. 1067, Vol. XIV., *Transactions American Society Mechanical Engineers.*

once appear, but even without exact knowledge as to condensation, the range covered between the two assumed conditions is so great that the actual condensation would probably produce a curve between the two, and if so, then the terminal pressure at release in low pressure cylinder of the proposed engine, should not be less than 4 lbs. absolute, nor more than 5 lbs., and the corresponding number of expansions of the system will not be more than 40 nor less than 32. For the purpose of keeping the low pressure cylinder as small as possible, the fewest number of expansions should be employed that promises approximately the best economy, and therefore we will select 32 expansions, and the expansion curve in low pressure cylinder will be B_2. C_2.

Referring to Fig. 4, the lower curve assumes the greatest cylinder condensation and on this assumption B_2 appears to be

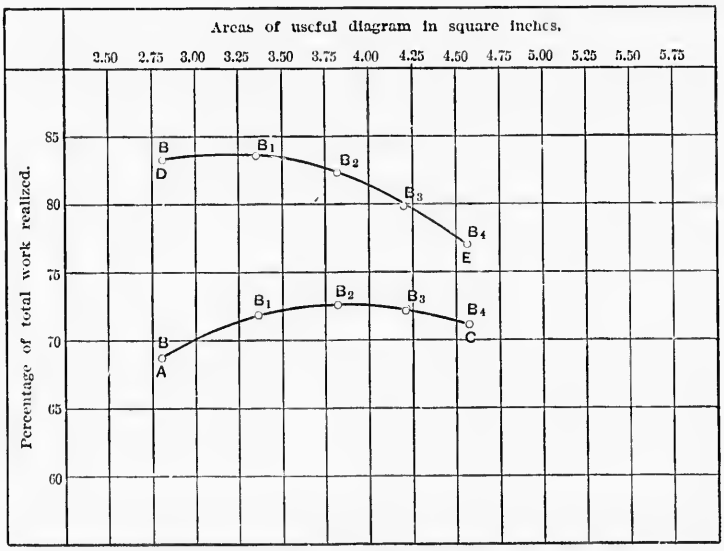

Fig. 5.

the best point of cut-off. The condensation here assumed, if referred to the area of "A. B_2. C_2.C. D." will be found to equal 47% of the steam accounted for by the indicator when cutting off at "B_2", which in view of the cut-off being later than 1/4 stroke and the total range of pressure in the cylinder only 13 lbs., is an altogether improbable amount. It is also equally improbable that the actual loss by condensation would not decrease slightly with earlier points of cut-off, so that in selecting 32 expansions for the proposed engine, it is done with the idea of using the least permissible number that will even approximate the best economy. Having determined that 32 expansions will be obtained in the proposed engine, and that "$A.\ B_2.\ C_2.\ C.\ D.$" of Fig. 3, will be the diagram of low pressure cylinder, we will next proceed to investigate the intermediate and High Pressure cylinders.

Beginning with the intermediate, Fig. 2 represents a series of possible diagrams between the pressures that have been allotted to this cylinder, and Fig. 5 represents the economy of each of these points of cut-off under the two extreme conditions of condensation that were assumed in Fig. 4. The method of locating the points on the curves of Fig. 5 is exactly the same as that of Fig. 4, merely substituting the areas of Fig. 2 for those of Fig. 3, and need not be again explained. Following the curves of Fig. 5, it appears that for the smallest condensation the best economy is at or near cut-off "B_1", while with the largest condensation the best result is with cut-off somewhat later than "B_2." Between these two points then we must probably look for the desired point of cut-off, and as before stated, if the exact condensation for each point was known it could be very quickly determined. As between this cylinder and the low we may assume that the condensation will be somewhat less in the smaller cylinder because of its smaller area of surface. This would be favorable to earlier cut-off, and the practical limitations as to size of cylinder do not interfere, as is the case of the low cylinder. On the other hand, free expansion is not a total loss in either the high or intermediate cylinder, as its superheating effect re-evaporates a certain quantity of the moisture in the steam, thus delivering to the receiver an appreciably greater volume of steam than that accounted for by the indicator at exhaust opening if much "drop" occurs. For this reason, "drop" is less objectionable in these cylinders than in the low, where no such redeeming feature is found. After due consideration of these modifying influences, it is not improbable that about midway between B_1. and B_2. will approximate the best point of cut off for this cylinder, and to continue the illustration of the proposed method, the dotted curve $B_{1\frac{1}{2}}\ C_{1\frac{1}{2}}$ will be selected as the desired curve.

Proceeding in the same manner with Fig. 1, representing the high pressure cylinder, and what has just been said about the intermediate cylinder applies to this equally as well. From a study of the curves of Fig. 6, as representing the performance of the high pressure cylinder at the various points of cut-off under the same conditions as to condensation that were assumed in Figs. 4 and 5, and keeping in mind that unlike the low cylinder no practical difficulty exists as to its size, we may with confidence select B_1, as a point of cut-off that promises approximately the best results that may be obtained from this cylinder.

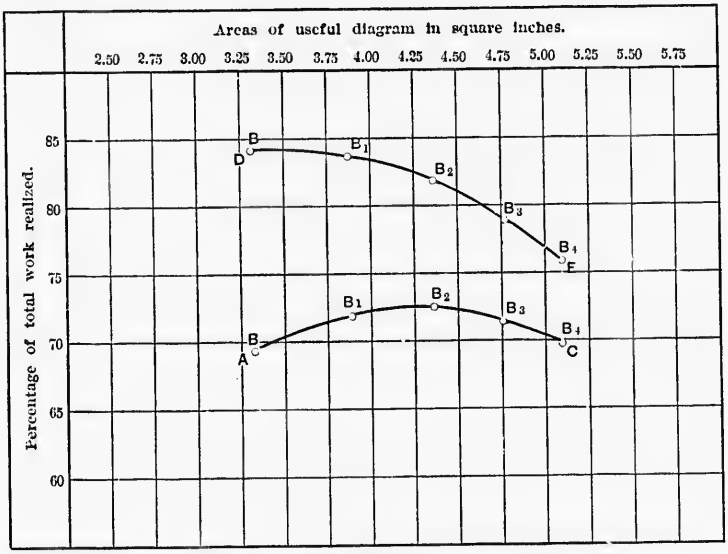

Fig. 6.

We have now established the expansion curves that we desire to produce in each cylinder, and to prevent confusion Figs. 7, 8 and 9 represent diagrams from the three cylinders, in which only the desired expansion curves appear.

So far, in this investigation, no attention has been paid to the compression curves further than to state at the beginning that the compression curves shown are full compression curves, which entirely fill the clearance spaces by compression, and rise without interruption to the initial pressure of the diagrams. Under no condition can these curves be the most economical, unless it has been shown that the best economy is obtained by expanding fully to the line of back pressure, as *B. C.* (Figs. 1, 2 and 3). Following the law relating to compression curves, suggested in Vol. XIV. of the *Transactions* of the American Society of Mechanical Engineers, page 1070, the curves *H. F.* have been produced as the compression curves in each case that correspond with the expansion curves that have been adopted. The completed diagrams, then as sought to be produced, are

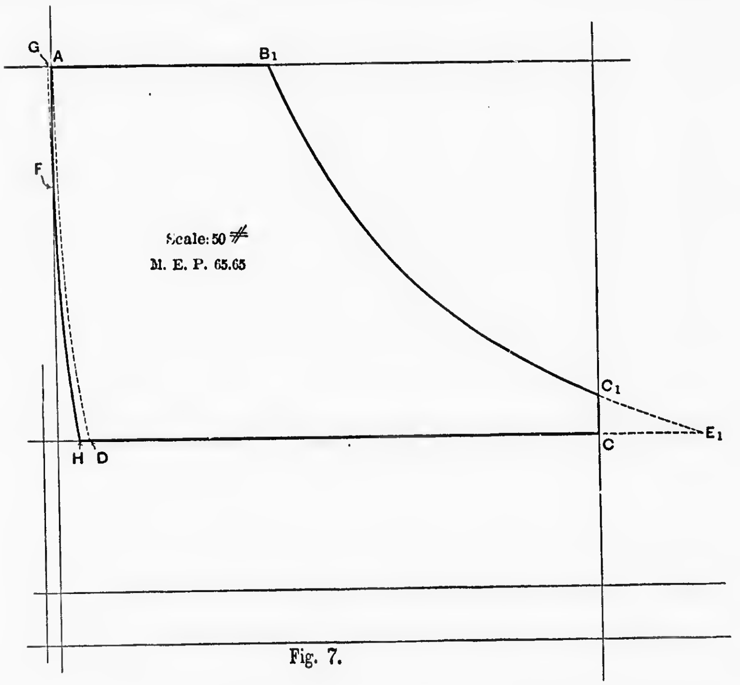

Fig. 7.

represented by full lines in Figs. 7, 8 and 9. The next step is to ascertain the ratio of cylinders which will produce these respective diagrams, and to do this the diagrams must be compared as to the relative volumes of steam which they indicate. A very convenient graphical method for doing this is the following.*

* The author is indebted to his son, B. C. Ball, member of the class of '95 at Stevens Institute of Technology, for this method, which is believed to have been original with him.—F. H. B.

First, continue the compression curves *H. F.* of Figs. 8 and 9 to the line of highest pressure of each diagram, as shown.

Next continue the expansion curves of Figs. 7 and 8 to the intersection of the line of lowest pressure of each diagram as shown.

Assuming that the lengths of these diagrams representing the piston travel are the same, and that the line $G.\ B_2$ in Fig. 9 represents the same pressure as the line $H.\ E_{1\frac{1}{2}}$ (Fig. 8), it is only necessary to compare the length of the line $G.\ B_2$ with $H.\ E_{1\frac{1}{2}}$, and

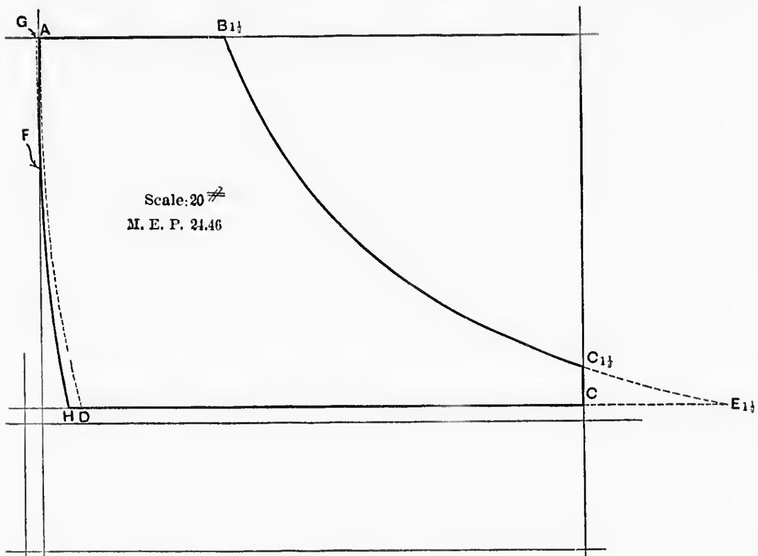

Fig. 8.

the inverse ratio will be the ratio sought. Thus, in this case, the line $G.\ B_2$ measured, with a scale of 100 to the inch, measures 92, and in the same manner $H.\ E_{1\frac{1}{2}}$ measures 368, therefore the ratio of the intermediate to low cylinder will be $\frac{368}{92} = 4$.

By the same method $G.\ B_1$ (Fig. 8) measures 104, and $H.\ E_1$ (Fig. 7) = 342, and therefore the ratio of high to intermediate cylinders will be $\frac{343}{104} = 3\ 3$.

Reviewing these figures we have the ration of high to intermediate 3.3, and of intermediate to low 4, and consequently of high to low 13.2.

It sometimes may be more convenient in measuring cylinder ratios by the method just described to extend both the compression and expansion curves of the lower diagram upward to

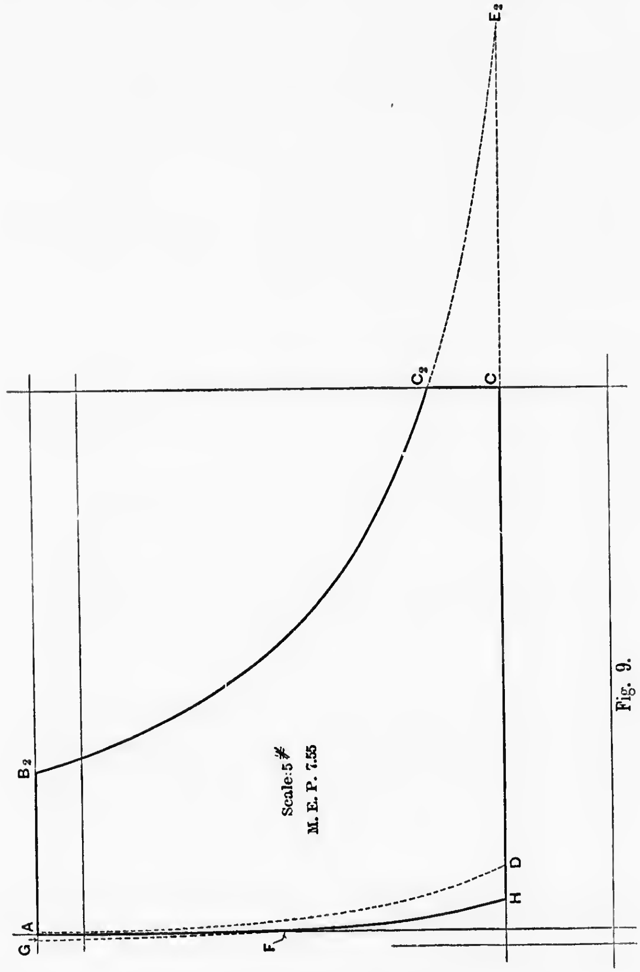

Fig. 9.

the line of terminal pressure of the next higher diagram, and use this line for measuring the ratios. The result will be the same in either case.

If these ratios are used, and the valves of each cylinder are set to give the steam distribution indicated, the actual diagrams from the engine will approximate very closely to those of Figs. 7, 8 and 9, except as they may be slightly modified by cylinder condensation. Where steam-jackets are used the loss by cylinder condensation after cut-off in high-pressure cylinder is largely restored by heat from the jackets, so that frequently no allowance need be made in the ratios of cylinders for this loss. With unjacketed cylinders a progressive deficiency will appear in each successive diagram of the system as compared with

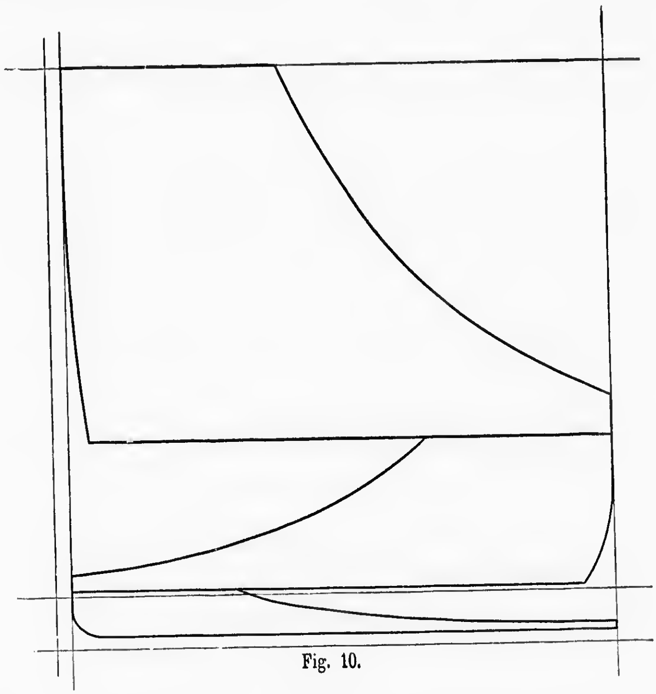

Fig. 10.

the theoretical diagrams, unless an allowance is made in the cylinder ratios to compensate for the progressive loss occasioned by condensation in the cylinders.

Continuing the study of the diagrams of Figs. 7, 8 and 9, the same diagrams appear in Fig. 10, reduced to the scale of the high-pressure diagram, and in Fig. 11 they are reduced in length to correspond with the respective cylinder ratios, thus representing the total expansion referred to the low-pressure cylinder.

The mean effective pressures of these diagrams are as follows:

High cylinder	65.65 lbs.
Intermediate cylinder	24.46 lbs.
Low cylinder	7.55 lbs.

Or, referred to the low cylinder, as follows:

High cylinder	4.96 lbs.
Intermediate cylinder	6.10 lbs.
Low cylinder	7.55 lbs.
Total	18.61 lbs.

These figures show a progressive increase of indicated work in each cylinder from the high to the low.

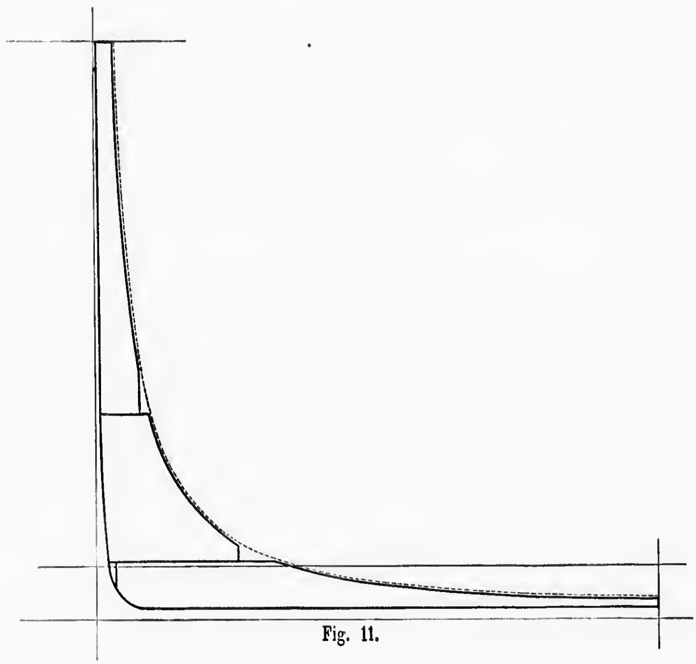

Fig. 11.

A more even division of work would be obtained by decreasing the range of pressure in the low cylinder, and increasing the range in the high. It has already been suggested that because of the relatively larger area of surface of the low cylinder a modification of this kind would probably reduce the total condensation, therefore it seems desirable that such a modification should be made, but the work will not here be reviewed for that purpose.

GENERAL CONCLUSIONS.

First, that in current engineering too few expansions are obtained in compound engines for best economy.

Second, that with 150 lbs. pressure and a good vacuum at least 32 expansions should be realized in a triple-expansion engine.

Third, that the cylinder ratios ordinarily used are too small, because they give too little "terminal drop" for best economy.

Fourth, that too little attention is given to the compression curve, which should be determined by the expansion curve, and should never reach initial pressure.

The foregoing is submitted with the full knowledge that the conclusions may not be generally accepted because of a very commendable disposition on the part of the fellows of our Society to take more kindly to demonstrated facts than to theory, even of the most plausible kind.

While waiting for the verdict of future experiments the author will still further risk his engineering reputation (if he has any) by venturing the prediction that, when under the conditions assumed on the foregoing pages as to boiler pressure and vacuum, a triple-expansion engine shall be provided with cylinders proportioned to produce approximately the final diagrams of the series in respect to the number of expansions, the terminal drop, and the compression curves, or such slight modification of them as may be suggested by the line of reasoning that has been followed, then a horse-power will be developed from 11 lbs. of steam per hour.