MEASUREMENT OF SCAVENGING EFFICIENCY OF THE TWO STROKE ENGINE: A COMPARISON AND ANALYSIS OF METHODS

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Professor Joseph S. Newell
Secretary of the Faculty
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Dear Sir:

In partial fulfilment of the requirement for the degree of Naval Engineer, from the Massachusetts Institute of Technology, we hereby submit our thesis entitled: Measurement of Scavenging Efficiency of the 2-Stroke Engine: Analysis and Comparison of Methods.

Respectfully,

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SUMMARY

The formula i.h.p. $= \rho_s N V_D \frac{r}{r-1} e_s F/A E_c \eta_i$ (symbols defined below) demonstrates the relation between the indicated horsepower of the two stroke engine and the engine operating variables.

ρ_s = scavenging density: air density at inlet temperature and exhaust pressure - lbs/ft^3

N = Power strokes per minute

V_D = displacement volume - piston area x stroke in ft^3

r = compression ratio - non dimensional

F/A = lbs fuel/lbs air - based on air retained in the cylinder - fuel-air ratio

E_c = Heating value of fuel - btu/lb fuel - 18,900 for 100 octane

η_i = Overall indicated thermal efficiency - non dimensional

i.h.p. = indicated horsepower of two stroke engine

e_s is defined as the ratio

$$\left[\frac{\text{air retained in cyl. in lbs/min}}{\rho_s N V_D \frac{r}{r-1} \text{ (Air, of density } \rho_s\text{, required to fill cylinder in lbs/min.)}}\right]$$

and is known as scavenging efficiency.

R_s is defined as the ratio

$$\left[\frac{\text{air supplied to engine, in lbs/min}}{\rho_s N V_D \frac{r}{r-1}}\right]$$

and is known as scavenging ratio.

It can be seen from the above information that, all other variables being equal, the ihp of the two stroke is proportional to e_s. It follows that an accurate means of determining e_s is

a necessity.

The object of this thesis has been to establish comparative information on the accuracy of four accredited methods for measuring this quantity.

A corollary to the main work was the design and test of a sampling check valve. The general characteristics of the valve were suggested by Profs. A. R. Rogowski and C. F. Taylor. Fig. XIX shows photographs of completed design. The methods were run simultaneously on an engine in steady state conditions, defining four curves (one per method) for each speed run. Runs were made at 1000 and 1400 RPM, and at each speed, R_s was varied from 1.0 to 1.8, in six steps. The engine used in the evaluation was a single cylinder two-stroke, loop-scavenged spark ignition, Waukesha CFR type.

The cylinder is an M.I.T. design, for two stroke operation mounted on the Waukesha CFR crankcase. Briefly, the methods employed were as follows:

<u>Tracer Gas Method</u> - Hereafter known as Method I.

Monomethylamine gas was injected into the inlet air stream, giving concentrations of from 1 to 2% by volume, of monomethylamine. The monomethylamine gas in the air retained in the cylinder dissociated in the combustion chamber, under the heat of burning while gas in bypassed air remains unaffected. By measuring the concentrations of monomethylamine in the inlet and exhaust streams, direct measures of the ratio of the amount of air entering engine, to the air <u>not</u> retained in cylinder were obtained.

Application of corrections for burning efficiency and shrinkage, and use of calculations as outlined by Schweitzer and DeLuca in NACA Technical Notes #838 led to determination of e_s. Details of procedure and calculation in Appendix A.

Gas Analysis of Compression and Expansion Samples - Method II.

A sampling valve capable of drawing samples from any point in the cycle was used in conjunction with an Orsat analysis, to analyze a compression, and an expansion sample. The Cox valve used for sampling occupied 8 and 11 degrees crank angle at speeds of 1000 and 1400 RPM, respectively, from "start of open," to "fully closed." An oxygen content balance was used, with straightforward weight calculations, to evaluate e_s. The Gerrish and Meems chart and the D'Alleva and Lovell chart of "Analysis of Exhaust Gases of 4 stroke Engine" were used to evaluate molecular weight of residuals. Isentropic expansion and compression were assumed in the region of port openings on expansion through the early part of compression, for the evaluation of temperatures accompanying samples. An arbitrary 300°F temperature drop due to "blowdown" heat exchange was assumed. Samples for all runs were drawn at crank angles of 111° (just prior to opening of exhaust ports) and 309° (about 60° after exhaust ports close, on compression stroke).

Details of procedure and calculations in Appendix A.

Gas Analysis of Expansion Sample - Method III.

The results of analysis of the residual gas sample described in Method II were used to establish a vertical line on each of

the two Exhaust Gas Analysis Charts. The ordinates of the charts were "% by volume" of the elements and compounds in in residual gases plotted against fuel-air ratio as abscissae. The fuel-air ratios defined by the vertical lines established as above, were used as the fuel-air ratio, under the particular conditions, and a single calculation produced e_s. Details in Appendix A.

Isac Method (Indicated specific air consumption) - Method IV. Sloan Laboratory made available a 4-stroke CFR type single-cylinder spark ignition engine of the same bore and stroke as the two-stroke used in the thesis. This 4-stroke engine was run at the same piston speed, jacket water outlet temperature, inlet air temperature, and compression ratio as the two stroke, for speeds of 1400 and 1000 RPM. Best power fuel-air ratio was used (.078). Indicator cards, and air and fuel data were taken. Comparison of the 2 stroke and 4 stroke data in conjunction with corrections applied on a calculated basis gave an approximation of the indicated specific air consumption of the two stroke engine. This figure combined with the i.h.p. as taken from the two-stroke card yielded "air retained," thence e_s. Details in Appendix A.

The sampling check valve was tested to determine its suitability as an alternative for the electrically operated timed sampling valve, as used in Methods II and III. It was mounted in the exhaust ports as shown in Fig. XIV, and could be used to take exhaust samples only.

General Information

The Waukesha engine used in this work was run at best power settings for the particular operating conditions. This was done for two reasons: First, it permitted the use of the Isac Method which requires comparison of 2-stroke and 4-stroke engines at, or near, best power conditions, and second, because the operation of the Waukesha was steady at best power conditions.

Results

Smooth curves of e_s vs R_s were obtained from Methods II, III, and IV over the range $R_s = 1.0$ to $R_s = 1.8$ at speeds of 1000 and 1400 RPM. The curves of e_s vs R_s for Method I were the least predictable from results obtained. Method I was the most troublesome of all used, and any estimate of its value must be qualified. These qualifications are enlarged on, in appropriate sections.

The early tracer gas method results were extremely bad, due to burning and dissociation of monomethylamine outside cylinder, and loss of monomethylamine to condensation liquids in exhaust tank. It was not until a method was devised of picking up the exhaust stream samples just outside the ports, that tracer gas method results improved. The first gas samples taken with the Cox sampler gave erratic results. After a system was set up for constantly checking the valve for the smallest leak, results steadied down. Technique improvement on the Orsat

gas analysis equipment led to reliable results soon after first runs were made. Methods II and III were both extremely sensitive to the Orsat analysis results.

The final curves of e_s vs R_s showed surprisingly small discrepancies among the methods. The differences between the results of any two methods in e_s at the same R_s on the curves were never more than .061 and averaged close to .04. The curves exhibited similar tendencies in slope, curvature, and intersection. At $R_s = 1.0$, curves of 1400 RPM intersected curves of 1000 RPM, for Methods I, II, and III. Above $R_s = 1.0$, 1400 RPM curves showed higher absolute values of e_s than 1000 RPM curves. Taking any single curve (1000 or 1400 RPM) the "Spreads" in e_s found by making successive runs at a single operating condition (vertical "spread") was (a) for Method I, about .10 (b) for Method II, about .05, (c) for Method III about 2%, (d) no "spread" was measured in Method IV since only one run was made or calculated at each condition.

Note that the results obtained in three of the four methods depend directly or indirectly on the performance and location of the timed sampling valve. This effect can be evaluated in sample calculation sections.

The results of the various methods compared more favorably with each other, than expected by the authors. Data figures produced the results toward which all estimates, and previous results pointed. In order to get what were considered good

results, numerous check runs were made. The results of the check runs were always an improvement, indicating that lack of precision in earlier runs was almost entirely due to either faulty technique, or, in the case of Methods II and III, small leakage in the sampling valve. The assumptions made at various steps in the methods were arbitrary, and in some cases were almost matters of individual opinion, but the end results were satisfactory nonetheless, for the effects of the assumptions were small, and they served the purpose of permitting the methods to be evaluated, using simple, rapid calculations.

The sampling check valve tested successfully for five hours running time. It gave the most satisfactory gas analysis results, using the Orsat equipment, and on the basis of those results, surpassed the timed sampling valve. At the end of five hours time, it stopped operating, and examination revealed that it had clogged with residue from exhaust gases. Enough values for one e_s vs R_s curve, at 1000 RPM were obtained. Time precluded further investigation.

Conclusions

The one solid conclusion that can be drawn from this work is that all the methods will give the same quantitative answer within 10 percent "precision," where "precision" is used to describe a variation, and not absolute values.

Having drawn this conclusion, facts pertinent to the advantages or disadvantages of each method may be added to permit

evaluation by interested parties.

For overall use, precision, speed, facility, simplicity, etc., Method III is chosen as most satisfactory.

The necessity for an expensive, bulky, complicated sampling valve, and the slow Orsat analysis equipment is the only detraction from this choice.

Method II gave good results but demands time, several cumbersome calculations and the use of an Orsat and sampling valve. The valve used in these runs and in Method III is expensive, and extremely sensitive to small leakage.

Method I gave acceptable results over a range from $R_s = 1.2$ to $R_s = 1.65$. At $R_s = 1.0$ and $R_s = 1.80$, unexplained poor results were obtained. This method gave the most erratic values of e_s. The adaptation of this method to spark ignition engines requires a more complete trial than this program devoted to the subject. It is felt that the method has merit, and can be made reliable.

Method IV gave the most satisfactory results on a basis of precision, and a smooth e_s vs R_s curve. The necessity for a comparable 4 stroke engine in addition to the 2 stroke being examined, and for indicating equipment limits its use to properly equipped laboratories. It is time-consuming and cumbersome because of indicator card requirements.

The sampling check valve, of the type tested, will make an acceptable substitute for the expensive, complicated, electrically operated timed sampling valve, for use with Method III. Design

changes are required to offset clogging of valve, and further testing seems well worthwhile.

Recommendations

A. For future work in this direction, it is recommended that an investigation be made of the practicability of injecting into the cylinder, after the ports have closed on the compression stroke, an inert substance which is (1) not contained in residuals or fresh charge in any quantity, (2) not decomposed by combustion temperatures, (3) may be accurately measured for its concentration in the exhaust stream by some method perhaps similar to the tracer gas concentration measurement, and (4) lends itself to injection against about 600 psia.

B. It is also recommended that technique in handling and familiarity with the type of equipment used to evaluate e_s by these various methods be highly developed prior to commencing runs for data.

C. Additional work on the tracer gas method, as applied to reliability in use with spark-ignition engines, is indicated.

D. The sampling check valve should be tested further, and its design changed, as tests indicate, to render it serviceable over long periods of operation.

INTRODUCTION AND GENERAL PROCEDURE

The importance of scavenging efficiency has increased in the past few years, with the increasing use of the 2 stroke engine. The difficulty presented is the lack of positive, accurate, simple means of determining the quantity for various R_s. Different methods have been devised in an effort to solve the problem. To the best of the knowledge of the authors, a chosen few of these methods have never been compared simultaneously, on the same engine, under the same operating conditions. This in substance, is what this thesis has attempted to do. Fig. I is a diagrammatic sketch of the entire equipment concerned with the four methods, and gives a general picture of how the work was done.

Since the "complete mixing" curve of e_s vs R_s was the only established reference curve, it will be used as a reference to permit relative evaluation of the results, and is included in all curves as such a reference.

The four methods chosen were (1) The Tracer Gas Method, (2) The Gas Analysis of compression and expansion samples, (3) The Gas Analysis of expansion samples only and (4) The I.S.A.C. Method (Indicated Specific Air Consumption) referred to hereafter as Methods I thru IV respectively.

The Engine

A single cylinder $3\frac{1}{4}$ x $4\frac{1}{2}$" modified Waukesha, CFR two stroke, loop-scavenged, spark ignition engine was used. 100 octane

gasoline was injected.

Fig. XV shows the timing diagram of the porting and injection events.

Air inlet stream was carefully controlled by a standard orifice meter, regulator valves, and Water Manometor. Inlet temperature was maintained thru Variac-controlled heater elements. Inlet temperature for all runs was 110°F.

Exhaust pressure was measured by manometer, on the exhaust tank, and ranged from .2 to .4 inches of mercury.

Spark advance was controlled by neon flash on a graduated dial.

Fuel was metered thru a rotameter to a Bosch injection pump.

With the decision to run at, or near best power conditions, it was necessary to obtain curves of best power information to permit setting the engine in a consistent manner. This was done by setting a scavenging ratio and speed on the engine, and reducing the fuel rate until the engine barely performed steadily. At the fuel setting, the spark advance was varied from 30° to 0°, and Brake load readings noted on the hydraulic scale manometer. The fuel was increased by an increment on the rotameter and the process repeated, and so on, until engine started missing due to excess fuel. For each increment on the rotameter, a plot of brake load versus spark advance gave a peak point of brake load. A plot of brake load "peaks" against fuel rate gave best power point fuel rate and spark advance. This process,

repeated 5 to 6 times for each speed, for varying R_s, gave best power curves with sufficient information to set the engine at, or near, best power for all conditions needed. These curves have been turned over to Sloan Laboratory for use with the engine.

Timed Sampling Valve

The valve used to draw samples for the gas analyses was the *pressure element* of a Cox Type VI Direct Pressure Indicator. Phasing of sample extractions was accomplished using the phasing equipment which is ordinarily part of the direct pressure indicator. The valve was solenoid-operated, by condenser discharge and opened against a spring. It started opening, and closed fully in 8 crank angle degrees at 1000 RPM, and in 11 crank angle degrees at 1400 RPM, according to tests run by Cox Co. Tests by Cox Co. also found that a pressure gauge in the sampling system read the pressure in the cylinder at the point in the cycle at which the valve completed its closing motion. A reasonable check of this value was obtained by comparison of values on the pressure gauge, in sampling system, with predicted pressures taken from indicator diagrams. The position of the valve in the engine head, and in the overall layout may be seen in Figs. I and XIV.

The Tracer Gas System

The flow of monomethylamine gas from the gas bottle into the inlet air stream was controlled by a water manometer across an orifice plate. Diameter of the orifice was .041 inches, and

calibration of the orifice was accomplished by varying manometer readings and measuring inlet concentrations. Samples were drawn thru perforated collector tubes in the inlet and exhaust streams, and bubbled thru a solution of H_2SO_4, colored with 3 or 4 drops of modified methyl red indicator, thence thru a wet gas meter, to a surge tank, using a water aspirator. Since only one gas meter was available, inlet and exhaust samples were taken separately. Neutralization of the indicated H_2SO_4, by monomethylamine was signalled by a change in color of the bubbler solution from purple to clear water color. Further addition of methylamine turned solution bright green, indicating a basic solution. Titration burettes (2) completed the necessary equipment for determining the exact point at which neutralization occurred. A step-by-step procedure is included in Appendix A.

The Gas Analysis System

Samples at a chosen point in the engine cycle were passed from sampling system piping into a standard Orsat by displacing 100 cc of saturated salt solution. CO_2, O_2, and CO, in the sample were removed in that order, by KOH, Oxorbent and Cosorbent (the latter two by Burrell & Co.) solutions respectively. Four "passes" of the sample thru each of the three solutions were used.

RESULTS AND DISCUSSION

Figures II thru IX are the master curves of e_3 vs R_s obtained from the data points shown on each sheet. The points designated by ⊙ on all curves indicate that their lack of precision is due to lack of technique, and all these points were taken prior to April 6, 1949. Points on curves of Methods II and III designated by ◬ indicate that their lack of precision is due to small leakage in the Cox sampling valve. This valve is constructed so that cylinder pressure tends to open it, against a spring force. The most minute failure of tightness between disc and seat, in the valve resulted in sufficient leakage to noticeably affect results. Unexplained deviations from the preponderance of results are designated by ⊡ on all curves.

The master curves are combined by speeds in Figs. X and XI, by method, in Fig. XII.

Table I is a numerical comparison of curve values of e_s at regular increment of R_s over the range from $R_s = 1.0$ to $R_s = 1.8$. From this table the comparison of absolute values, and percentage variation on the specified basis, can be seen at a glance, listed against speed and method. All curves exhibit a narrowing of the gap between absolute values of e_s at 1400 and 1000 RPM as R_s decreases from 1.80 to 1.00, for this particular engine. Methods II and III show an intersection or joining of the two curves at $R_s = 1.00$, while Methods I and IV show an imminent intersection

or joining at $R_s = 1.00$. The slopes of the curves of all methods, for a particular speed, are very nearly the same at all points, and bear a marked resemblance to the slopes of the complete mixing curve at the same point. There seems to be no doubt that e_s is greater, for this engine, at 1400 RPM than at 1000 RPM, over the range $R_s = 1.0$ to $R_s = 1.8$.

Table II lists the authors' evaluations of and information on, the four methods using a few chosen criteria that appear to be factors in choosing the method most suitable for use under various conditions. Table II in section on Conclusions.

Fig. XIII is the single curve of the results of the sampling check valve tests. The curve is judged to be good, as far as it goes. No opportunity to obtain estimates on precision, or to increase the number of points on the curve, was available.

Since three of the four methods depend on sampling valve performance on an expansion sample it follows that if the electrically timed sampler was replaced by the check valve sampler, the results would differ generally as the gas analysis, resulting from the performances of the two valves, differed. This difference in e_s vs R_s curves, would be direct relations between fuel-air ratios found by respective gas analyses, in Methods III and IV. The effect on Method II is more obscure. For purposes of illustration, a curve of e_s vs R_s, at 1000 RPM for Method IV has been modified by the ratio of (F/A) using timed sampler to (F/A) using sampling check valve, and placed on Fig. XIII for comparison with 1000 RPM Sampling Check Valve results.

R_s	RPM	Method I	Method II	Method III	Method IV	Mean of 4 methods	Sampling Check Valve with Method III	methods I thru IV based on low - % variation = $\frac{\text{high-low}}{\text{low}} \times 100$
1.00	1000	51.1	51.1	52.6	50.2	51.25	54.0	4.8
	1400	51.5	51.3	52.6	52.0	51.85	-	2.54
1.20	1000	56.0	56.5	56.7	54.6	55.95	60.0	3.84
	1400	57.2	57.6	58.5	58.8	58.02	-	2.30
1.40	1000	59.0	60.3	59.8	57.7	59.20	64.7	4.50
	1400	61.5	62.4	63.0	63.7	62.65	-	3.58
1.60	1000	61.0	63.5	62.5	60.3	61.83	68.8	5.30
	1400	64.7	66.2	67.0	67.5	66.35	-	4.33
1.80	1000	62.3	66.0	65.0	62.2	63.88	72.5	6.10
	1400	67.5	69.6	70.2	70.5	69.45	-	4.45

CONCLUSIONS

Table II summarizes the conclusions and evaluations of the four methods, with tabular information on various aspects of the problem for each method. This section will be devoted to enlarging on pertinent points in the table, and to the conclusions drawn regarding the sampling check valve.

Method I

The titration process involved in the use of tracer gas evaluation of e_s is one of the governing factors in accuracy, and must be done with extreme care. The location and type of sample collector used with the method is another factor of extreme importance in results obtained. The assumptions required are valid, and the figures for these correction factors as recommended in NACA Tech. Notes #838 are realistic. The erratic character of measurements of e_s are unexplained in some cases, and attributable to lack of technique in others. Control methods for the use of tracer gas are important, and must be of an accurate nature. The volume of the H_2SO_4 used in bubblers, affected the result. Generally, the larger the volume of H_2SO_4 the better the result. This factor must be balanced against the time consumed in neutralization of the H_2SO_4 by the monomethylamine gas.

In its present condition, this method is limited in its scope, and development is required before it will be satisfactory

enough to be used, without reservation, on any engine, the exhaust stream of which, has a temperature of about 800°F, or higher. Indications are, that the acceptance of this method, in its present stage of development, as achieved in this work, would involve an individual problem of adaptation to a particular engine, and a means of comparing results to a dependable source, or calculations.

Method II

Method II is an unwieldy, cumbersome method in comparison with the other three. The extraction of two samples for each run, with an Orsat analysis of each is tedious work. The method is weakened immediately by the large number of assumptions required, although the results, which are good, do not reflect this weakness. One of the big disadvantages of the method is the large amount of time consumed in operation. The sensitivity of the sampling valve to leakage has a large effect on results obtained. Therefore, the preferred type of sampling valve is one which tends to close when exposed to cylinder pressure. The Orsat analyzer for flue gases appears to be completely satisfactory for this type of work.

In the face of results obtained using Methods I, III, and IV, Method II is adjudged least desirable of all methods.

Method III

As the preferred method, this procedure has as a sole disadvantage, the necessity for dependence on the performance of

the sampling valve, the dependability of the gas analysis charts, and the extraction of a representative sample; its advantages outweigh this, however, since it gives precise, accurate, quick results. Calculations are direct and simple. A good sampling valve, properly located, would provide the answer to any weakness in the method. The sampling check valve tested in this work appears to be a step in this direction. Very satisfactory results were obtained.

Method IV

The curves of e_s vs R_s obtained using this method were the most accurate of all results. No check runs were required or made, hence no information on duplication of results is available. With necessary equipment available, i.e. a 4 stroke engine "comparable" to the 2 stroke being examined, and indicating equipment, the method is desirable of use. The procedure is unwieldy, tedious, and time-consuming. Generally speaking, the method is very satisfactory on a basis of results obtained, but practical requirements limit the availability and desirability of the procedure.

Sampling Check Valve

Since only five hours operation were recorded on this valve, no positive statement of its worth can be made. The operation of the valve was sufficiently satisfactory, during the five-hour period to permit a positive conclusion to be drawn, i.e. that further work with this valve, or a similar design is

definitely indicated. The test was terminated because the valve clogged, and ceased to operate. Modifications of design could alleviate this condition. Fig. XIII aids the contention that the valve is worthy of further work. The ultimate elimination of the ordinary complicated, bulky, timed sampler, in favor of the small simple, flexible check sampler, for use with Method III appears most favorable.

Evaluation of Methods I thru IV

Method	Time Consumed to Obtain Point on e_s vs R_s curve	Essential Equipment Needed	Difficulty of Setup	Calculations (single point on e_s vs R_s curve)
I	25 minutes to obtain and titrate an exhaust and inlet sample and carry thru calculations.	1) 1 standard gas bottle (2.24 ft3) containing 40 lbs. monomethylamine under vapor pressure. (About 30 psig at room temps.) 2) 1 Wet gas meter. 3) Titration and bubbling glassware. 4) Miscellaneous glass and copper tubing.	20 man-hours of labor plus purchase time. Considerable pipefitting and general machine work is necessary.	Extremely quick and simple. Can be done in three to five minutes once equations have been adapted to use.
II	1 hr. and 30 min. to obtain and analyze a compression and expansion sample, and carry thru calculations.	1) Sampling valve. 2) Phasing accessories. 3) Orsat equipment. 4) Accurate pressure gauge, 0-200 lbs. psi.	Phasing equipment and sampler used in this work could be set up in 1 man-hour by anyone familiar with the equipment.	Most complicated and longest calculation required, of all four methods. Requires 20 minutes of calculations. A certain amount of progressive calculation during run may be made.
III	25 minutes to obtain and analyze an expansion sample and carry thru calculations.	As above, for Method II.	As in Method II.	Calculations occupy no more than a minute, and can be performed in one operation of slide rule.
IV	1 hr., 15 min. to obtain indicator cards, fuel and air data on each of 4 stroke and 2 stroke engines, in succession.	1) 4-stroke engine of comparable bore and stroke with 2 stroke being examined. 2) Pressure indicating equipment.	About 15 minutes setup time on M.I.T. Indicator, and 30 minutes setup and warmup time for each engine.	Requires about one hour to planimeter indicator cards, and utilize data to evaluate e_s.

Method	Assumption, either Required or Desirable	Consistency of Results Variations due to "experiment error"
I	1) Assumption required as to how much of monomethylamine in air retained in cylinder dissociates during combustion. 96% was used in this work. 2) A correction for the volume change of fuel air mixture, due to combustion (shrinkage factor). 7.5% was used in this work.	This method was the most difficult to control and showed the greatest variation in e_s when an attempt was made to duplicate results. These variations of e_s were as high as .10, but successive runs for duplication tended toward averaging to a good result - Details in Appendix A.
II	1) That sampler is taking a representative sample. 2) Temperature of exhaust gasss in cycle is equal to temperatures calculated for fuel air cycle. 3) Temperature loss of exhaust during "blowdown" = 300°F. 4) Isentropic expansion and compression during late expansion and early compression strokes. 5) That actual F/A is that determined by analysis of residual gas samples.	Method II showed the second largest variations of e_s when duplication of results was attempted. Technique played a large part in this method, along with a tendency to leakage exhibited by the sampling valve after from 4-8 hours of operation, and it is felt that these two factors account for a high percentage of errors.
III	1) That sampling valve is taking a representative sample. 2) That actual F/A is that determined by analysis of expansion samples.	Method III, with Method IV shared the position of showing little or no deviation from former results when duplication was attempted.
IV	1) That a 4 stroke engine, of comparable bore and stroke to a 2 stroke, if run at the same piston speed, outlet jacket water temperature, inlet air temperature, and compression ratio as the 2 stroke, will exhibit the same combustion characteristics in the cylinder as the 2-stroke. This is assumed for injection or pre-mixed charge operation, or for any combination thereof.	The absolute values of e_s obtained by this method were close to an average of all four methods and all points obtained lay on, or very nearly on a smooth curve of e_s vs R_s.

Table II (Cont'd)

Method	General Remarks
I	Method I results were the most difficult to evaluate in terms of a smooth curve of e_s vs R_s. Values of e_s were erratic, and inaccurate at $R_s = 1.0$ and 1.80, based on results of other methods, and expected results. In the region $R_s = 1.2$ to $R_s = 1.65$ results were acceptable. It is considered to be a potentially suitable method for the purpose of measuring e_s, but must be more effectively adapted to the spark - ignition engine. Were this adaptation to be accomplished more completely than in this work, with attendant reliability, this method would be judged as desirable, but inferior to Method III.
II	Method II is classed as the most unsatisfactory. The results are good, but the cumbersome procedure, long calculations, time consumed, technique requirement, and the numerous assumptions required, are all strong detractors from a choice of this method.
III	Methods III and IV would be classed as equally effective as far as consistency of performance and accuracy are concerned. Method III is chosen as a method preferred, because it does not require a 4 stroke engine, of certain size, nor does it require indicating equipment. Despite the fact that this method requires an expensive sampling valve and an Orsat, it is classified as the preferred of the four methods, on an overall basis.
IV	Using as criteria, precision, and consistency, this method ranks with III as clearly superior to I and II. The two big drawbacks connected with this method are the necessity of having available a 4 stroke engine of a size within arbitrary limits, rigged for laboratory work, and the necessity for indicator equipment. The paperwork involved per point on e_s vs R_s curve is fairly cumbersome.

RECOMMENDATIONS

The assumption that perpetuation of this type of work is desirable indicates three paths along which efforts should be directed. The first of these is the development of a method for measuring e_s, which, in general, would consist of injection, in known amounts, into the cylinder of a 2 stroke engine, after the ports have closed, an element or compound which could be identified quantitatively in the exhaust stream. Obvious requirements for such a material, that present themselves are: (1) It must not be present in the products of combustion or in the fresh charge in any quantity (2) It must maintain its identity under combustion temperatures (3) Accurate measurement of its presence in the exhaust stream must be possible and facile, and (4) It must lend itself to accurate injection against about 600 psi.

The problem outlined above is one of a chemical and practical nature. Helium suggests itself as a choice for items (1) and (2), above. No further examination of the problem will be made.

The second subject for further work is the tracer gas method. The results obtained between the end points on the e_s vs R_s curve are quite acceptable. The poor results obtained consistently at the end points are unexplained. There is room for improvement and variation in (1) The type of sample collector

tubing used (2) Its location, and (3) Control methods used. The ideas behind the method are sound, and worth an effort in the direction of practical improvement.

The further development of the sampling check valve is the third direction in which more investigation is considered worthy. The only fault to be found with the sampling check valve used is its tendency to clog with foreign matter, and cease operating. In order to enter the valve a single piece of foreign matter had to be less than 1/16" in any dimension. Once inside the valve however, the flow thru the valve seat was split four ways thru apertures 1/2 the diameter of the entrance. Thus the particle which passed the entrance orifice, may or may not have continued along the line. If further testing of this valve points up the failure due to clogging, it is recommended that a design be used that will make the entrance orifice of the valve the smallest restriction in the system from cylinder to Orsat equipment. The size of the valve used in this work was restricted only by the size of the exhaust port of the engine.

As a general recommendation, it is felt that thorough familiarity with technique involved in these methods should be cultivated by practice runs, before record runs are made.

APPENDIX A

Detailed Procedure and Sample Calculations

This section will be devoted to a short description of the engine used, and its peculiarities, followed by a step-by-step detailed description of each method in succession. A typical data run will be chosen, the engine conditions specified, and the comments on each method will be accompanied, or followed by, a set of sample calculations.

The Engine

Operation of the engine was found to be unsatisfactory for the purposes of this work when a single spark plug located near the center of the head, was used. Accordingly, an additional ignition system to a side plug was added, and performance from then on was suitable. Injection took place from a nozzle placed near the center of the head. The sampling valve was placed symmetrically with the additional side spark plug. Details of the location of plugs, injector and sampling valves may be seen in Fig. XIV.

Excellent control of air inlet temperature was obtained by mounting a "Variac" in series with the heater element in inlet piping. Inlet air temp was measured by mercury thermometer in inlet air mixing tank. Exhaust stream pressure was recorded by mercury manometer on the exhaust cooling and surge tank. See Fig. XV for diagram of port and injection timing.

Spark plugs used were BG Aviation Spark Plugs #157, and gave steady firing, with the dual ignition system. It is to be noted that while the engine ran fairly steadily at optimum settings for a certain condition of R_s and speed, using the head plug alone, any departure from optimum settings caused prohibitive misfiring, and under no conditions could anything but spasmodic firing be obtained using the side plug alone. The simultaneous use of the head and side plugs resulted in steady firing over a reasonably large variation from optimum settings. Fuel rate was controlled by rotameter between supply and injection pump.

Engine Set-Up

For the purposes of sample calculations, a run made at $R_s = 1.4$ and 1400 RPM will be used in conjunction with Method I, II, and III.

Engine Conditions

N = 1400 RPM   P atmospheric = 29.5" Hg   r = 6.72

R_s = 1.40 T_i inlet air = 110°F T_w = Outlet jacket water temperature = 195°F for all runs.

$$R_s = \frac{\text{Air delivery rate}}{\rho s \; N \; V_D \frac{r}{r-1}} = \frac{\dot{M}_{a\,del.}}{\rho s \; N \; V_D \frac{r}{r-1}}$$

$$\rho s = .0765 \times \frac{P_{exh.}}{29.92} \times \frac{520}{T_i}, \quad V_D = 37.33 \text{ in}^3, \quad \frac{r}{r-1} = \frac{6.72}{5.72}$$

$_s N V_D \frac{r}{r-1} = .03375 \frac{N \cdot p_e}{T_1} \frac{\text{lbs air}}{\text{min}}$, N = rpm

p_e = inches Hg

For these conditions $_s N V_D \frac{r}{r-1} = 2.48 \frac{\text{lbs air}}{\text{min}}$, $T_1 = 570°R$

For $R_s = 1.4$, $Ma_{del} = 1.4 \times 2.48 = 3.47 \frac{\text{lbs air}}{\text{min}}$

Air flow was set by standard orifice meter, regulators, and water manometer. Fuel rate and spark advance were taken from best power curves as determined previously. Fuel rate = .00223 lbs fuel/sec. Spark advance = 15.5°. This completed the setup of the engine for a particular run.

Method I - Reference NACA Tech Notes #838, by Schweitzer and DeLuca. See Fig. I for general setup.

Symbols

Monomethylamine CH_3NH_2

Sulphuric Acid H_2SO_4

Sodium Hydroxide NaOH

(-N) = ________normality solution

Ex. $(.1N)H_2SO_4$ = .1 normality solution of H_2SO_4

W = weight of CH_3NH_2 in lbs.

$^mH_2SO_4$ = molecular wt. H_2SO_4 = 98

$^mCH_3NH_2$ = molecular wt. CH_3NH_2 = 31

X_{cc} = Volume of $(\_N)H_2SO_4$ used in sample in c.c.

$X_{cc_{corr}}$ = X_{cc} corrected to end point of neutralization

Y_{cc} = Vol. of NaOH used to find end point in c.c.

V_g = volume passed thru gasmeter during a sample extraction - ft^3

T_g = Temperature of sample passing thru meter - $^{\circ}R$

P_g = Pressure of sample passing thru meter - $\dfrac{P_g}{P \text{ atmosphere}} = 1$

The basis on which the method is used successfully is that CH_3NH_2, if bubbled through a solution of H_2SO_4 will tend to neutralize it. If the H_2SO_4 solution is colored by an organic indicator, the passage of the solution from acid to neutral to base will be signalled by a change from, in this case, purple to clear water color to green. An equation may be set up:

Mols = Mols

$$\text{At neutralization:}\left[\frac{\text{Weight of } H_2SO_4 \text{ in sample solution}}{\text{Mol. wt. of } H_2SO_4} = \frac{\text{Wt. of } CH_3NH_2}{\text{Mol. wt. of } CH_3NH_2}\right]$$

Equivalent weight of H_2SO_4 = 49

$$\therefore \quad \frac{49 \times 10^{-3} \, (\_N)H_2SO_4}{98} = \frac{W}{31}, \qquad (\_N) \text{ in gm/cc}$$

$(.112N)H_2SO_4$ was used.

If X_{cc} is volume of H_2SO_4 solution sample of normality (_N),

$$W = (31 \times \frac{40}{98} \times 10^{-3})(\_N)_{H_2SO_4} (X_{cc_{corr}}) \times \frac{1}{454} = \text{lbs.}$$

$$\text{Concentration in inlet air} = \frac{W}{W_{air}} = \frac{3.02 \cdot 10^{-5} X_{cc_{corr}}}{V_g \cdot .0765 \cdot \frac{P_b}{29.92 \cdot 13.6} \cdot \frac{520}{T_g}}$$

$$\text{Concentration of inlet air} = \frac{.964 \cdot X_{cc_{corr}} \cdot T_g}{V_g} \qquad (1)$$

Monomethylamine is metered into the inlet air stream by use of a manometer across an orifice (The .041" orifice drop was found to be from 6 to 45 inches H_2O for satisfactory concentrations). This gas mixes with the inlet air stream, and passes into the engine. Some passes thru the engine in bypassed air, and some dissociates in the combustion process within the cylinder. Samples are drawn thru bubblers and the gas meter, at a point in inlet and exhaust streams, The tracer gas in these samples neutralizes the acid in the bubblers. The end point of neutralization was calculated as follows: 10cc of (.112N)H_2SO_4 in distilled water was placed in the bubbler. The air + CH_3NH_2 sample was drawn from the inlet stream thru the bubbler for about 10 mins. until the purple solution neutralized and turned green, indicating base. The sample is thus taken. 4 cc of (.112N)H_2SO_4 was added by burette and neutralized with Y_{cc} of (.109N)NaOH (Solution is clear water color) also from a burette. From this,

$$X_{cc_{corr}} = X_{cc} - \frac{.109}{.112} Y_{cc}$$

For this run, $X_{cc} = 10 + 4.1$ $Y_{cc} = 4.1$

$$\therefore X_{cc_{corr}} = 14.1 - (.974)(4.1) = \underline{\underline{10.1}} \text{ cc for inlet sample}$$

$$T_g = 73^{\circ}F = 533^{\circ}R \qquad V_g = .37 \text{ ft}^3$$

$$\text{Inlet concentration} = \frac{(.964)\cdot(10.1)\cdot(.533)\cdot(10^{-6})}{.37}$$

$$= .014 = \underline{\underline{1.4\%}} \text{ by weight}$$

The procedure was repeated for the exhaust sample, using 10 cc (.112N)H_2SO_4. When solution turned green, sample was completed and end point determined in the same manner as for inlet sample. Exhaust sample takes about 15 min.

Results were $X_{cc} = 14.0$ $Y_{cc} = 3.3$ $X_{cc_{corr}} = 10.8$

$$V_g = .650 \text{ ft}^3 \qquad T_g = 74^{\circ}F = 534^{\circ}R$$

At this point, the concentration of the exhaust sample could be found, as in inlet sample, but this is not necessary. Concentration of inlet samples were calculated as a means of continuous calibration of the tracer gas orifice. Except for small effects, known as "burning efficiency," and "shrinkage factor," to be discussed further along, it can easily be shown that the ratio of the concentrations in inlet and exhaust samples is also the ratio of "air delivered" to "air not retained "in cylinder. Thus, if 3 lbs of air flows into engine carrying .1 lbs of tracer

gas, and 2 lbs of air are retained, and 1 lb passes thru, the exhaust stream passes 3 lbs of air and residuals, but 2/3 of the monomethylamine is lost in combustion, hence the concentration of the exhaust stream is $\frac{.0333}{3}$ as opposed to $\frac{.100}{3}$ in the inlet stream. $\therefore$

$$\frac{\frac{.0333}{\cancel{3}}}{\frac{.100}{\cancel{3}}} = \frac{1}{3}$$

If α = ratio of exhaust concentration to inlet concentration

From (1), $\dfrac{\text{exhaust concentration}}{\text{inlet concentration}} = \alpha = \dfrac{\left\{\dfrac{.964\ X_{cc_{corr}} \cdot T_g}{V_g}\right\}\text{exhaust}}{\left(\dfrac{.964\ X_{cc_{corr}} \cdot T_g}{V_g}\right)\text{inlet}}$

$$\alpha = \frac{(X_{cc_{corr}} T_g)_{exh}}{(X_{cc_{corr}} T_g)_{inlet}} \cdot \frac{(V_g)_{inlet}}{(V_g)_{exhaust}} \qquad (2)$$

α Also = $\dfrac{\text{Air not retained}}{\text{Air delivered}} = \dfrac{\text{Air delivered - Air retained}}{\text{Air delivered}}$

$\therefore\ \alpha = 1 - \dfrac{\text{Air retained}}{\text{Air delivered}} = 1 - \Gamma$ where Γ = retention ratio

$\Gamma = {}^{e_s}/R_s$

$$\therefore\ \Gamma = 1 - \alpha \qquad (3)$$

This would be the solution of the problem, since we know the air delivered to the engine, were it not for the fact that despite the high combustion temperatures, all the tracer gas, in the cylinder, in the air retained, does not dissociate during

combustion. The correction factor is known as burning efficiency, e_b. NACA Tech. Notes #838 recommend a value of .96 for e_b, and this figure was used. In addition, the volumes of the inlet and exhaust streams are not equal due to the combustion process, the correction for which was introduced as a shrinkage factor, s. NACA Tech Notes #838 gave curves of "s" versus F/A for Diesel fuels. These curves were extrapolated and a value of .075 was assumed for s. e_b and s remained the same for all runs. Introducing the two correction factors into (3) gives

$$\Gamma = \frac{1 - \alpha}{e_b - s\alpha} \qquad (4)$$

The detailed derivation of this expression may be found in NACA Tech Notes #838.

For the run being examined, by using (2)

$$\alpha = \frac{(X_{cc_{corr}} \cdot T_g)_{exh}}{(X_{cc_{corr}} \cdot T_g)_{inlet}} \cdot \frac{(V_g)\ \text{inlet}}{(V_g)\ \text{exhaust}} = \frac{10.8}{10.1} \times \frac{534}{533} \times \frac{.37}{.65}$$

$$\alpha = \underline{\underline{.61}}$$

From (4)

$$\Gamma = \frac{1 - .61}{.96 - (.075)(.61)} = \underline{\underline{.427}}$$

$$\Gamma = {}^{e_s}/_{R_s} \text{ by definition } = \frac{\text{Air retained}}{\text{Air delivered}}$$

Air delivered = 3.47 lbs/min. from engine setup.

$\therefore$ Air retained = 3.47 · .427 = 1.481 lbs/min

$$e_s = \frac{\text{Air retained}}{\rho_s N V_D \frac{r}{r - 1}} = \frac{1.481}{2.480} = \underline{\underline{.60}}$$

There are several comments to be made on this method of determining e_s.

Monomethylamine, as an "educated" tracer gas, dissociating in the combustion process, but not in the exhaust stream, gives a reasonably satisfactory account of itself. However, certain precautions must be taken, in use with a spark ignition two stroke engine. The gas combines very readily with water, hence if condensation occurs anywhere in the system thru which the gas passes, the condensation will pick up the monomethylamine, removing it both from the system and from the calculations. In addition, there seems to be no accurate information on the temperature at which CH_3NH_2 dissociates. Schweitzer and DeLuca, in the reference NACA publication, imply that at any temperature above 800°F, it can be expected that the gas will dissociate. Since the residual gases of the exhaust are at about 2000°F, and comprise more than half the exhaust stream, the temperature of the exhaust stream is more than likely in the vicinity of 1500°F. It follows that, unless the exhaust stream sample can be taken very close to exhaust ports, and removed from the high temperature area rapidly, the tracer gas will dissociate outside the cylinder, with accompanying loss of accuracy in measurement of e_s. In the setup, the stream passed from the ports thru a foot long duct to a water-cooled surge tank, thence to the laboratory trench. The first setup for tracer gas work took inlet samples about 2 inches before entry of stream into ports,

and exhaust samples on the downstream side of the exhaust surge tank, as outlined in NACA Tech Notes #838. Thoroughness of mixing of inlet air stream and monomethylamine was assumed, based on the following: Tracer gas was injected into inlet air stream in a mixing tank, the mixture passing from the tank, through three 90° elbows into a second mixing tank, thence to inlet ports. Results were poor, and duplication of results was impossible. The NACA reference had stressed the necessity for taking several samples at intervals along the exhaust line. In the face of results, it was decided to move the sampling post to the duct between exhaust port and surge tank, and take only one exhaust sample, just outside the ports. This would eliminate possibilities of burning in exhaust stream, and the possibility of loss of tracer gas to condensation in the cooled surge tank. Accordingly, this was done using the same $\frac{1}{2}$ inch diameter perforated steel tube collector, placed across the duct. Results were equally poor, as in first tests, and it was reasoned that the collector, by virtue of its diameter being some three times the diameter of the smallest tubing in the sampling system, was permitting the tracer gas ultimately intended for the bubbler, to slow down or stop in the collector, which itself was directly in the residual gas blast. The slow-down permitted dissociation of monomethylamine in the high temperature area. In an effort to shorten the time in which the monomethylamine was exposed to high temperature, higher

velocity of gases thru the exhaust duct to sampling bubbler was achieved by using a single tube, of inside diameter 3/64" placed in the blast of center exhaust ports, and the maximum speed of bubbling thru the H_2SO_4 solution was used. The absolute values of e_s, obtained at this point dropped about 30% into the region occupied by the e_s values by other methods. Duplication of results, however, was still unreliable. A 5/16" inside diameter tube, used in a similar manner as the 3/64" single tube yielded the same characteristics. The final collector was a straight tube, placed across the duct, of 5/16" inside diameter, fed by 4 smaller tubes, mounted in the direction of flow, their apertures mounted at the centerline of each of the 4 exhaust ports, at a distance of about 1.5 inches from the ports. Details may be seen in Fig. 1A. This type of collector gave values of e_s which compared closely with values obtained by the other methods could be duplicated within .05, and fell on a reasonably smooth curve of e_s vs R_s, except at the extreme ends of the curve, where $R_s = 1.0$ and $R_s = 1.8$. Repeated check runs at these two points gave unexplained results, of e_s about .04 high at $R_s = 1.0$ and of e_s about .05 low at $R_s = 1.8$. The terms "high" and "low" refer to the smooth curve drawn through values of e_s in between the end values.

APPENDIX A (cont'd)

Method II - Gas Analysis of Compression and Exhaust Samples

Symbols

M_r = mass of residuals in cylinder - lbs.

M_m = mass of fresh mixture in cylinder - lbs. (Fresh air only.)

M_c = Total mass of gas in cylinder - lbs.

m_r = molecular weight of residual gas - $\frac{\text{lbs.}}{\text{lb mol}}$

m_m = molecular weight of fresh mixture - lbs/lb mol.

m_c = molecular weight of cylinder gas - lbs/lb mol.

x = O_2 fraction by volume in M_m - dimensionless.

y = O_2 fraction by volume in M_r - dimensionless.

z = O_2 fraction by volume in M_c - dimensionless.

$\bar{R}$ = universal gas constant = 1544 $\frac{\text{ft. lbs}}{^\circ R}$

$$R = \frac{\bar{R}}{\text{mol. weight}} = \frac{\text{lb mols. ft}}{^\circ R}$$

Subscripts

r - residuals

m - fresh charge

c - cylinder contents

i - inlet

a - air

o - point at which compression sample taken

s - point at which expansion sample taken

e - exhaust

d - displacement

1 - indicates beginning of compression stroke on indicator diagram

Other symbols, with appropriate subscripts as previously defined.

Development of Equations

An equation may be set up: Mols of Oxygen = Mols of Oxygen

$M_r + M_m = M_c$

$$\Bigg[x \cdot \left[\frac{M_m}{m_m}\right] + y\left[\frac{M_r}{m_r}\right] = z\left[\frac{M_c}{m_c}\right] = z\left[\frac{M_m}{m_m} + \frac{M_r}{m_r}\right]$$

From this -- $\left[\frac{M_r}{M_m} = \frac{x-z}{z-y} \cdot \frac{m_r}{m_m}\right]$ (1)

$$\frac{M_c}{M_m} = 1 + \frac{M_r}{M_m} \qquad \therefore \quad \frac{M_m}{M_c} = \frac{1}{1 + \frac{M_r}{M_m}} \tag{2}$$

$$\frac{M_r}{M_c} + \frac{M_m}{M_c} = 1 \qquad \therefore \quad \frac{M_r}{M_c} = 1 - \frac{M_m}{M_c} \tag{3}$$

At point "O" where compression sample is taken,

$$p_oV_o = M_cRT_o \qquad R = \frac{\bar{R}}{m_c}$$

$$M_c = \frac{p_oV_o}{R_cT_o} = \frac{p_oV_o\,m_c}{\bar{R}\;T_o} \tag{4}$$

$$e_s = \frac{M_m}{\rho_s V_D \frac{r}{r-1}} \quad \text{(one cycle)} \qquad \rho_s \text{ at } p_e, T_i$$

$$\rho_s = \frac{1}{v_s} \qquad \therefore \quad p_e \cdot \frac{1}{\rho_s} = R_mT_i \qquad R_m = \frac{\bar{R}}{m_m}$$

$$\rho_s = \frac{p_e m_m}{\bar{R}T_i}$$

$$\therefore \quad e_s = \frac{M_m \cdot \bar{R} \cdot T_i}{p_e \cdot m_m \cdot V_d \cdot \frac{r}{r-1}} \qquad V_c = V_d \cdot \frac{r}{r-1}$$

Combine with (2), $e_s = \dfrac{M_c}{1 + \frac{M_r}{M_m}} \cdot \dfrac{\bar{R}T_i}{p_e \cdot m_m \cdot V_c}$

Combine with (4), $e_s = \dfrac{1}{1 + \frac{M_r}{M_m}} \cdot \dfrac{p_o V_o m_c}{\cancel{\bar{R}}T_o} \cdot \dfrac{\cancel{\bar{R}}T_i}{p_e m_m \cdot V_c}$

$$e_s = \frac{p_o}{p_e} \cdot \frac{V_o}{V_c} \cdot \frac{m_c}{m_m} \cdot \frac{T_i}{T_o} \cdot \frac{1}{1 + \frac{M_r}{M_m}} \qquad (5)$$

All quantities in (5) are known, or can be found directly, except m_c, T_o, and m_r. The latter is concealed in $\frac{M_r}{M_m}$ as shown in (1).

p_o - Taken from gauge in sampling system - psia

p_e - Exhaust tank manometer applied to atmospheric pressure - psia

V_o - Taken from knowledge of point at which compression sample is taken. See Fig. XVIII.

V_c - Engine dimensions, compression ratio

m_m - Taken as molecular weight of air

T_i - Taken from inlet tank thermometer

The evaluation of the three unknowns was accomplished as follows, in the order given.

1) $\underline{m_r}$ - The results of the analysis of the expansion sample

were used to enter two charts of exhaust gas analyses of 4-stroke spark-ignition engines. Specific reference to charts may be found in Appendix D - Bibliography.

They are reproduced in Fig. XVI.

The charts were plots of elements and compounds as ordinates in percentage by volume, against fuel-air ratio.

The analysis of the expansion sample gave points on the CO, and CO_2 curves in both charts, and permitted the establishment of a vertical line, representing a particular fuel-air ratio. See Comments, on this method, for information on oxygen in analysis. The line on each chart allowed a buildup of the molecular weight of residuals, by fractions of each component in exhaust gases. The desired fractions were indicated by the intersection of the curve of the particular component and the established vertical line. Thus 70% nitrogen contributed $.70 \cdot 28 = 19.60$ lbs to m_r, 8% CO_2 contributed $.08 \cdot 44 = 3.52$ lbs., and so on. The results of these two processes, one on each chart were averaged, and this was taken as m_r. From m_r, x, y, z, and m_m, $\frac{M_r}{M_m}$ could be calculated, followed by $\frac{M_m}{M_c}$, and $\frac{M_r}{M_c}$.

2) m_c ---

$$m_c M_c = m_r M_r + m_m M_m$$

$$\therefore \quad m_c = m_r \frac{M_r}{M_c} + m_m \frac{M_m}{M_c} \qquad (6)$$

All quantities necessary to determine m_c, are known.

3) $\underline{T_o}$ - The expansion sample is taken at a point "S" just prior to opening of exhaust ports. A good approximation of T_r at this point may be taken from Fig. XVII by entering with the % theoretical fuel (determined by dividing the average of the fuel-air ratios taken from charts Figure XVI, by .0665), and from the proper expansion ratio line, reading the temperature of residuals in °F absolute. The expansion ratio in this case is the volume above the piston when exhaust ports just open, divided by the clearance volume.

Assume isentropic expansion from p_s to p_e, $k = 1.35$

$$T_r' \text{ at pressure } p_e = T_{r\,(\text{chart})} \cdot \left[\frac{p_e}{p_s}\right]^{\left(\frac{k-1}{k}\right)}$$

Assume 300°F loss in temperature during "blowdown" process, and the temperature of the residual gases at the beginning of compression, $T_s = T_r \cdot \left[\frac{p_e}{p_s}\right]^{\left(\frac{k-1}{k}\right)} - 300$

p_s may be taken from the gauge in sampling system in psia.
At this point, mixture of scavenging air and residuals has taken place, and from an assumption that mixing takes place adiabatically at constant pressure:

$M_c h_1 = M_m h_i + M_r h_r$, where h is unit enthalpy. For perfect gases, and assuming c_p is the same for M_c, M_m, and M_r, h is a function of T alone, hence $T_1 = \frac{M_m}{M_c} T_i + \frac{M_r}{M_c} T_s$

Assume isentropic compression from beginning of compression to point "C" at which compression sample was taken.

$$T_o = T_1 \left[\frac{p_o}{p_e}\right]^{\left(\frac{k-1}{k}\right)}$$

e_s may now be evaluated from (5).

Comments on Method II

While the setup work on this method is small, the method itself is cumbersome, and, in light of the results of the other three methods, the least desirable of all methods used. The precision is dependent almost entirely on technique, and type and location of the sampling valve. Technique can be covered be a recommendation that several "dry" runs be made prior to taking data for record. The operation of the Orsat equipment is simple, but consistency of results demands practice.

In this work the Cox sampling valve was located in a position shown in detail in Fig. XIV, and remained in that position for all data taken. This location was chosen arbitrarily, and was influenced by the holes already in the engine head and side of the head, and the fact that the injector and one plug had to remain in the head, for proper operation of the engine. All the gas analyses of expansion samples showed from 3 to 7% oxygen by volume when it was known that the engine was running "rich," and that the correct oxygen percentage should have been about 0.6%. The CO, and CO_2 contents of samples indicated a consistent fuel-air ratio, taken from the gas analysis charts, of from

.082 to .089, and previous work had established that the engine was at, or near, best-power conditions. The discrepancy in the O_2 values obtained by analysis was attributed to poor mixing in the location of the sampling valve, and O_2 results of analysis were ignored. When the fuel-air ratio was established on the analysis charts, using the CO and CO_2 fractions found by analysis, the O_2 fraction used in calculations was that shown on the charts. For all runs, the values of O_2 fraction on the charts, at the established F/A, were .3% for D'Alleva & Lovell's charts, and 1.0% for Gerrish and Meems' chart. These were averaged to .6%, and for all data runs, the quantity "y," the O_2 fraction by volume, was taken as .6%. Disregarding the O_2 fraction by Orsat analyses was an arbitrary move, dictated by various circumstances, of a practical nature. First, the "poor mixing" theory was aided by the fact that an additional spark plug mounted in the side of the head, in a position opposite the sampling valve, but symmetrical to it, with respect to inlet and exhaust ports, was incapable of running the engine alone, indicating that that area was one of incomplete mixing. Second, time was judged to be sufficiently closely scheduled as to preclude relocation of valve and the attendant machine work. Third, since the only suitable location would have been in the head, rather than the side of the head, and the head was taken up by a necessary plug and injector, the sampling valve remained in its initial location. Fourth, and most practical, the results were good. The presence

of the relatively large amounts of free O_2 affected the CO, and CO_2 fractions, causing a horizontal "spread" on each gas analysis chart. However, splitting the "spread" with a vertical line, gave fuel-air ratios, the values of which checked almost identically between charts, and contributed to satisfactory results in evaluating e_s.

A preferable situation would have been sufficient time and space to devote to trials of positions for the sampling valve, to obviate the procedure used in this work, and for future work that may be done, it is recommended that such arrangements be made.

The CO, and CO_2 fractions found by analysis were, generally speaking, further apart along the abscissa axis, on the charts, when the O_2 content of the gas analysis was high, and closer together when the O_2 fraction was low, indicating that better mixing should lead to better definition of fuel-air ratio on the charts.

Sample calculations

Using the same engine set-up as for Method I:

p_e = 29.7"hg = 14.7 psia P_{atm} = 14.5 psia.

The exhaust sample was taken at 111° crank angle - point "s." Fig XX shows position of points "o" and "s" on a typical indicator card. The values of "o" and "s" in crank angle degrees was the same for all runs. Gauge pressure, 46 psi , p_s = 46 + 14.5 = 60.5 psia. Results of Orsat analysis: CO_2 = 7.6%; CO, 6.0%; O_2, 4.4%.

Using CO_2 and CO fractions to enter charts (see Fig. XVI-0), F/A = .0875 on both charts. A vertical line is drawn on each chart at F/A = .0875. The buildup of molecular weight of residuals from charts:

<u>Find m_r</u> - Gerrish and Meems Chart and D'Alleva and Lovell Chart

Component	Mol. Wt.	% by Volume G & M	% by Volume D & L	Weight G & M	Weight D & L
N_2	28	78.0	69.0	21.85	19.3
CO_2	44	8.4	8.0	3.69	3.52
CO	28	7.6	7.2	2.12	2.01
H_2	2	3.9	3.0	.08	.06
O_2	32	1.0	.3	.32	.10
CH_4	16	.6	.5	.09	.08
H_2O	18	--	13.0	--	2.34
		99.5	101.0	28.15	27.39

$$\therefore M_r = \frac{28.15 + 27.39}{2} = \underline{\underline{27.77}} \text{ lbs/lb mol}$$

O_2 fraction = $.\underline{\underline{6\%}}$ by volume = y

The compression sample was taken at point "o" at 317° crank angle.

Gauge pressure 54 psi; p_o = $\underline{\underline{68.5}}$ psia.

V_o from Fig. XVIII = $\underline{\underline{12.3}}$ in ^{3} V_c = $\underline{\underline{43.89}}$ in ^{3}

Analysis results CO_2 = .6, and O_2 = $\underline{\underline{19.0\%}}$ = s

m_m = 28.93 (mol. wt. of air) and O_2 in air = $\underline{\underline{21\%}}$ = x

$$\frac{M_r}{M_m} = \frac{x-z}{z-y} \cdot \frac{m_r}{m_m} = \frac{21-19.0}{19.0-.6} \cdot \frac{27.77}{28.93} = \underline{\underline{.104}}$$

$$\frac{M_m}{M_c} = \frac{1}{1 + \frac{M_r}{M_m}} = \frac{1}{1.104} = \underline{\underline{.905}}$$

$$\frac{M_r}{M_c} = 1 - \frac{M_m}{M_c} = \underline{\underline{.095}}$$

$$m_c = m_m \frac{M_m}{M_c} + m_r \frac{M_r}{M_c} = (28.93)(.905) + (27.77)(.095) = \underline{\underline{28.79}} \text{ lbs/lb mol.}$$

$$\% \text{ Theoretical Fuel} = \frac{.0875}{.0665} = \underline{\underline{1.31}}$$

T_r from Fig. XVII, at expansion ratio of 5.20 is $\underline{\underline{3170}}$°R

$$T_s = T_r \left[\frac{p_e}{p_s}\right]^{\overbrace{\left(\frac{k-1}{k}\right) - 300^\circ}^{k\,=\,1.35}}$$

$$= 3170^\circ \left[\frac{14.7}{60.5}\right]^{(.26)} - 300^\circ = 2200 - 300 = \underline{\underline{1900}}{}^\circ R$$

$$T_1 = \frac{M_m}{M_c} T_i + \frac{M_r}{M_c} T_s$$

$$= (.905)(570) + (.095)(1900) = \underline{\underline{697}}{}^\circ R$$

$$T_o = T_1 \left[\frac{p_o}{p_e}\right]^{\left(\frac{k-1}{k}\right)} = 697 \left[\frac{68.5}{14.7}\right]^{(.26)} = \underline{\underline{1040}}{}^\circ R$$

Solve for e_s

$$e_s = \frac{p_o}{p_e} \cdot \frac{V_o}{V_c} \cdot \frac{m_c}{m_m} \cdot \frac{T_i}{T_o} \cdot \frac{1}{1 + \frac{M_r}{M_m}}$$

$$= \frac{68.5}{14.7} \cdot \frac{12.3}{43.89} \cdot \frac{28.79}{28.93} \cdot \frac{570}{1040} \cdot \frac{1}{1.104} = \underline{\underline{.645}}$$

Method III - Gas Analysis of Expansion Sample Alone

The symbols and subscripts used in this method are the same as those used in Method II.

The procedure in this method is identical with that of Method II up to, and including the establishment of a vertical line on the Gerrish & Meems, and D'Alleva & Lovell charts of exhaust gas analysis. When the fuel-air ratio has been found from this line, the method procedure branches off from Method II, as follows:

$$F/A = \frac{\text{lbs fuel}}{\text{lbs air}}\text{, based on air retained in the cylinder}$$

(Injection). This expression is true for a single cycle, or a rate of flow.

$$\therefore \quad F/A = \frac{\text{lbs fuel}/\text{time}}{\text{lbs air}/\text{time}}$$

$$\text{and lbs air}/_{\text{min}} = \frac{\text{lbs fuel}/_{\text{min}}}{F/A} = \frac{\text{Fuel rate}}{F/A}$$

Fuel rate and F/A are known, hence $\dot{M}_{a_{\text{retained}}}$ can be found.

$$e_s = \frac{\dot{M}_{a_{ret}}}{\rho_s NV_c}$$

Sample Calculations

Using the same engine setup as for Method I;

$\rho_s NV_c = 2.48\ \text{lbs}/_{\text{min}}$ F/A from analysis = .0875

Fuel rate = .00223 lbs fuel/$_{\text{sec}}$

$$\text{Air retained lbs/}_{\text{min}} = \frac{.00223 \times 60}{.0875} = 1.53 \text{ lbs/}_{\text{min}}$$

$$e_s = \frac{1.53}{2.48} = \underline{\underline{.617}}$$

Comments

This method gave smooth, precise results, and, except for the necessity of an expensive sampling valve, is considered to be the best of all methods used. It is subject to the same limitations pertaining to sampling valve location, as Method II. The concluding step in this work was a cursory check on the acceptability of a sampling check valve of simple construction and operation, as a suitable replacement for the expensive sampling valve used. For results of these tests, see comments and information under "Sampling Check Valve."

APPENDIX A (cont'd)

Method IV - ISAC Method - (Indicated Specific Air Consumption)

Symbols:

ihp - indicated horsepower

$_i$ - indicated thermal efficiency

FR - fuel rate - lbs fuel/sec.

AC - area of indicator card - in^2

E_c - fuel heating value, btu/lb fuel. (18,900 used for this work)

Subscripts

2 - two stroke

4 - 4 stroke

This method is based on two main assumptions:

1) That in the region of best power operation, the quantity $(F/_A E_c\ _i)$ of the expression isac $= \frac{2545}{(F/_A E_c\ _i)}$ is constant. By measuring $(\text{isac})_4$ directly, and evaluating $(F/_A E_c\ _i)_4$, correcting it for particular 2-stroke operation to $(F/_A E_c\ _i)_2$, isac and e_s may be thus evaluated.

2) That the combustion characteristics of a 2 stroke and 4 stroke cylinder are the same, providing that the following conditions are filled:

(a) Premixed charge is used in both cases.

(b) The 4-stroke and 2-stroke engines used are of the same, or nearly the same bore and stroke.

(c) The 2 engines must be run at the same piston speed, inlet air temperature, outlet water jacket temperature,

and compression ratio.

In this work, assumption 2(a) has been extended to include injection, and any combination thereof. The discrepancy that occurs in this particular case, where the 4 stroke used a premixed charge, and the 2 stroke an injection fuel system, was accounted for, by using the $(F/A)_2$ results taken from the gas analysis charts, in the correction factor, instead of assuming that at best power the $(F/A)_2$ was the same as the $(F/A)_4$.

The development of the correction factor

$$\frac{(\text{imep} \cdot \cancel{V_D} \cdot \cancel{N})_2}{(\text{imep} \cdot \cancel{V_D} \cdot \cancel{N/2})_4} = \frac{(\dot{M}_a \cdot F/A \cdot \cancel{E}_c \cdot \eta_i)_2}{(\dot{M}_a \cdot F/A \cdot \cancel{E}_c \cdot \eta_i)_4}$$

$(V_D)_2 = (V_D)_4$ in this case; $(E_c)_2 = (E_c)_4$; $(N)_2 = (N)_4$

$\dot{M}_a \cdot F/A = FR$; imep :: AC in both cases.

$$\therefore \frac{(AC)_2 \cdot 2}{(AC)_4} = \frac{(FR \cdot \eta_i)_2}{(FR \cdot \eta_i)_4}$$

$$\therefore \frac{\eta_{i_2}}{\eta_{i_4}} = \frac{(FR)_4}{(FR)_2} \cdot \frac{(AC)_2 \cdot 2}{(AC)_4}$$

$$\frac{(F/A\,\cancel{E}_c\,\eta_i)_2}{(F/A\,\cancel{E}_c\,\eta_i)_4} = \frac{(F/A)_2}{(F/A)_4} \cdot \frac{(FR)_4 \cdot (AC)_2 \cdot 2}{(FR)_2 \cdot (AC)_4} = \frac{K_2}{K_4}$$

$(F/A)_2$ is the value found by use of sampling valve and analysis charts, as explained in Method II. This correction would not be necessary were both charges premixed. $(F/A)_4$ was .078 for all

4 stroke runs.

$$\therefore\ \underline{\underline{\text{Correction factor}}} = \frac{(F/_A E_c \eta_i)_2}{(F/_A E_c \eta_i)_4} = \underline{\underline{\frac{(F/A_{chart})_2}{.078} \cdot \frac{(FR)_4}{(FR)_2} \cdot \frac{(AC)_2}{(AC)_4} \cdot 2}}$$

$$K_2 = \text{correction factor} \times K_4$$

$$(1\ \text{sac})_{2 \text{ or } 4} = \frac{2545}{\underbrace{(F/_A E_c \eta_i)}_{\overset{\shortparallel}{K_{2 \text{ or } 4}}}} = \frac{\text{lbs air}}{\text{ihp hr}} = \frac{\text{lbs air}}{\text{hr}} \cdot \frac{1}{\text{ihp}}$$

$$\therefore\ \text{Air retained} = \frac{\text{lbs air}}{\text{hr}} \cdot \frac{1}{\text{ihp}} \cdot \text{ihp} \cdot \frac{\text{hr}}{\text{min}} = \frac{\text{isac} \cdot \text{ihp}}{60}$$

The 4 and 2-stroke engines used in this work were of the same bore and stroke.

Sample Calculations

2 stroke set at best power. $N = 1400$, $R_s = 1.35$

$FR = .00219$ lbs fuel/sec., $T_i = 110°F$, $T_{water} = 195°F$,

compression ratio $= 6.72$. $\rho_s N V_D \frac{r}{r-1} = 2.51$ lbs/min

Indicator card is taken - Area of card $= 3.50\ \text{in}^2$ and Ihp :: imep

$= 13.87$ hp.

4 stroke is run; $N = 1400$, $T_i = 110°F$, $T_{water} = 195°F$,

compression ratio $= 6.72$. $FR = .00096$ lbs/sec, $F/_A = .078$

Indicator card is taken - Area of card $= 3.87\ \text{in}^2$ and Ihp :: imep

$= 7.67$ hp. - Air rate $= .0123$ lbs/sec.

Indicator cards for 4 and 2 stroke engines in Figs. XX and XXI

$(Isac)_4$ directly $= \dfrac{.0123 \times 3600}{7.67} = \underline{\underline{5.76}}$ lbs air/$_{ihp}$

$$K_4 = \frac{2545}{5.76} = \underline{\underline{441}}$$

$$K_2 = \text{corr. factor} \cdot K_4$$

$$\text{Corr. factor} = \frac{(F/A)_2}{.078} \cdot \frac{(FR)_4}{(FR)_2} \cdot \frac{(AC)_2}{(AC)_4} \cdot 2$$

$$= \frac{.0847}{.078} \cdot \frac{.00096}{.00219} \cdot \frac{3.50}{3.87} \cdot 2 = \underline{\underline{.892}}$$

$$\therefore \; K_2 = .892 \cdot 441 = \underline{\underline{396}}$$

$$\therefore \; Isac_2 = \frac{2545}{K_2} = \underline{\underline{6.43}}$$

$$\therefore \; \dot{M}_{a\,retained} = \frac{Isac \cdot ihp}{60} = \frac{6.43 \cdot 13.37}{60} = 1.685 \text{ lbs}/_{min}$$

$$e_s = \frac{\dot{M}_{a\,retained}}{\rho_s N V_D \frac{r}{r-1}} = \frac{1.685}{2.51} = \underline{\underline{.672}}$$

Comments

The assumptions made in this method appear to be correct in a relative sense, in that this method checks with the other three, within a few percent, as shown in Table I. The method as worked, required an additional equipment, in the form of a sampling valve. This was necessary only in this case where the fuel was injected in one engine, and premixed with air in the

other. Thus, in the general case, no sampling valve would be needed. Results from this method fall on, or near a smooth curve of e_s vs R_s, and on the basis of results alone, Method IV is as good, or better than any of the other three. However, the equipment needed is usually found only in a laboratory, and the purchase of necessary equipment, solely for purposes of measuring e_s, would make this method far and away the most expensive of all four methods used.

APPENDIX A (cont'd)

Sampling Check Valve

The investigation of this design was conducted with the object of ascertaining whether or not this type of valve could be used in conjunction with Method III as an alternative to the bulky, expensive timed electrically controlled sampling valve. Tests were short, and inconclusive, but of value. See Figs. XIV and XIX for location and details of valve.

The valve was mounted rigidly in place, directly in an exhaust port. The distance between the valve opening and the inside cylinder wall was about 1/8". The valve was calibrated statically to open at 30 lbs gage. It was hoped that the dynamic force of the exhaust gases during "blowdown" would be sufficient to open the valve momentarily, and that the spring, and back pressure in the sampling system would operate to keep the valve closed at all other times. The momentdry opening of the valve would permit the desired sample to enter the valve, and the closed period would exclude undesirable scavenging air. The sample was led to an Orsat analyzer, where a gas analysis was performed, and an evaluation of e_s carried out, exactly as in Method III.

Five runs were made with the valve in place, and all were completely successful. Four of the runs were made at various R_s, at 1000 RPM, and defined a smooth curve which was almost

identical with the complete mixing curve, in slope, and curvature, over the range $R_s = 1.0$ to $R_s = 1.8$. See Fig. XIII. At the end of the fifth run, the valve ceased to operate due to clogging, and the test was terminated. Five hours running time was recorded.

The results of the gas analysis by Orsat, of the samples, were judged to be better than any taken by using the timed sampling valve, since the excess O_2 found in all the timed valve samples (discussed under Method II) was lacking, and CO_2 and CO content, from analysis, plotted closer to a vertical line on the gas analysis charts, than did the timed valve sample analyses.

A peculiar type of control of the valve performance appeared in the tests. The valve was water-jacketed, and cooled by constant flow, except when samples were taken. This proved necessary due to the fact that when the valve was cooled, the spring developed enough force to keep the valve closed constantly. When the water-cooling was eliminated, the spring apparently got hot enough to cause the spring force to diminish to a point where the valve operated satisfactorily. With the cooling system on, no pressure built up in the line between valve and Orsat. When the cooling system was shut down, within a few seconds, the pressure in the line built up to approximately 10 to 15 lbs gage, somewhat in proportion to speed and R_s. If cooling water was turned on, the pressure dropped to 0 gage, in

accordance with the amount of cooling water flowing.

The $F/_A$ found using the valve were consistently lower than comparable $F/_A$ obtained using the timed sampler of Method III. Typical comparisons were: 1) .0814 to .0850, 2) .082 to .0865, 3) .0803 to .0847.

The engine was set at best power, or very nearly at best power, as described earlier. The sampling check valve gave as a result, one $F/_A$, under .08, the only result of that nature in 28 runs using gas analysis. It had been expected that best power settings would give an $F/_A$ of about .078 to .081. The timed valve results were .082 or greater. This was attributed to poor mixing, but the magnitude of the effect was unknown. The sampling check valve helps to evaluate that effect for the region in which the timed valve was located.

Sample calculations are omitted since they are identical with those of Method III.

In order to illustrate "spread" on the Gas Analysis Charts as obtained by use of the sampling check valve, compared against "spread" obtained using the timed sampler, typical runs are illustrated on Fig. XVI. Sampling Check Valve - △ , Timed Sampling Valve - ○

SYMBOLS

In Order of Appearance in Paper

e_s - scavenging efficiency $= \dfrac{\text{Air retained in cylinder in lbs/min}}{\rho_s \, N \, V_D \, \frac{r}{r-1}}$

ρ_s - scavenging density - density of air at p_e and T_i

p - pressure

T - temperature - $^{\circ}R$

N - revolutions/min

V - volume

r - compression ratio

$\dot{M}_a$ - rate of mass flow of air

M - mass of substance - used with subscript

R_s - scavenging ratio $= \dfrac{\text{Air delivered to engine in lbs/min}}{\rho_s \, N \, V_D \, \frac{r}{r-1}}$

E_c - heating value of fuel - btu/lb

η_i - indicated thermal efficiency

ihp - indicated horse power

$F/_A$ - fuel-air ratio

CO_2 - carbon dioxide

CO - carbon monoxide

KOH - Potassium hydroxide

CH_3NH_2 - Monomethylamine

H_2SO_4 - Sulphuric acid

W - weight of CH_3NH_2 in lbs.

NaOH - Sodium hydroxide

(-N) - normality fraction of solution

$m_{H_2SO_4}$ - molecular weight of H_2SO_4 - 98

$m_{CH_3NH_2}$ - molecular weight of CH_3NH_2

X_{cc} - Volume of (-N) H_2SO_4 used in sample - in c.c.

$X_{cc_{corr}}$ - X_{cc} corrected to end point by titration

End point - Point at which neutralization occurs

Y_{cc} - Vol. of NaOH used in determining end point

V_g - Gas volume passed thru gasmeter during a sample extraction - ft^3

T_g - Temperature of sample passing thru meter - °R

p_g - Pressure of sample passing thru meter

α - ratio of exhaust concentration to inlet concentration

Γ - retention ratio $= \frac{\dot{M}_{a_{ret}}}{\dot{M}_{a_{del}}} = \frac{e_s}{R_s}$

e_b - burning efficiency - used in Method I

s - shrinkage factor - used in Method I

M_r - mass of residuals in cylinder - lbs.

M_m - mass of fresh mixture in cylinder - lbs (fresh air only)

M_c - total mass of gases in cylinder - lbs.

m_r - molecular weight of residual gas - lbs/lb mol

m_m - molecular weight of fresh mixture - lbs/lb mol

m_c - molecular weight of cylinder gases - lbs/lb mol

x - O_2 fraction by volume in M_m

y - O_2 fraction by volume in M_r

z - O_2 fraction by volume in M_c

$\bar{R}$ - universal gas constant = $1544 \ \frac{\text{ft lbs}}{{}^{\circ}\text{R}}$

R - $\frac{\bar{R}}{\text{molecular weight}} = \frac{\text{ft·lb mols}}{{}^{\circ}\text{R}}$

FR - fuel rate - lbs/sec

AC - area of indicator card - in^2

K - constant term $F/_A \cdot E_c \cdot \eta_i$ - used with Method IV

Subscripts used

s - indicates point of extraction of expansion sample, except as used with e_s, R_s, ρ_s. The latter are defined in detail under Symbols.

atm - atmospheric

i - inlet

w - water

d - displacement

e - exhaust

g - gas

exh - exhaust

ret - retained

del - delivered

r - residuals

m - fresh mixture

c - cylinder contents

a - air

0 - point at which compression sample was taken

1 - beginning of compression stroke on indicator diagram

2 - 2 stroke

4 - 4 stroke

APPENDIX B

Included in this section are smooth data sheets, showing results of data and calculations for all points shown on curves of Figs. II thru IX and Fig. XIII.

TRACER GAS (MONOMETHYLAMINE) – METHOD I

				INLET SAMPLE						EXHAUST SAMPLE									
RUN	SPEED R.P.M.	R_S	e_S	X_{cc} c.c.	$\bar{X}_{cc}$(COR) c.c.	Y_{cc} c.c.	V_g FT^3	T_g °F	CONCENTR. CH_3NH_2 $\frac{\text{LBS TRACER}}{\text{LBS AIR}}$	X_{cc} c.c.	$\bar{X}_{cc}$(COR.) c.c.	Y_{cc} c.c.	V_g FT^3	T_g °F	α	S	e_b	Γ	AIR DELIVERED LBS/MIN
1	1000	1.795	0.648	14.0	10.1	4.0	0.324	77	0.0162	14.0	10.7	3.4	0.511	77	0.673	0.075	0.96	0.360	3.19
2	1000	1.795	0.602	14.1	10.2	4.0	0.330	77	0.0160	14.0	11.1	3.0	0.515	77	0.696	0.075	0.96	0.345	3.19
3	1000	1.330	0.584	14.1	10.4	3.8	0.278	80	0.0195	14.0	10.8	3.3	0.483	80	0.599	0.075	0.96	0.439	2.36
4	1000	1.250	0.558	14.0	10.2	3.9	0.312	82	0.0171	14.0	10.8	3.3	0.558	82	0.593	0.075	0.96	0.445	2.22
5	1000	1.500	0.585	14.2	10.1	4.2	0.310	75	0.0168	14.0	11.0	3.1	0.523	76	0.645	0.075	0.96	0.390	2.67
6	1000	1.500	0.617	14.0	10.2	3.9	0.210	76	0.0252	14.0	12.45	1.6	0.411	76	0.624	0.075	0.96	0.411	2.67
7	1000	1.645	0.603	14.0	10.2	3.9	0.321	76	0.01651	14.0	11.3	2.8	0.533	76	0.668	0.075	0.96	0.365	2.94
8	1000	0.996	0.576	14.0	10.3	3.8	0.240	78	0.0223	14.0	10.8	3.3	0.540	78	0466	0.075	0.96	0.578	1.77
9	1000	0.996	0.580	14.0	10.2	3.9	0.325	78	0.0163	14.0	10.3	3.3	0.745	78	0.462	0.075	0.96	0.581	1.77
10	1000	0.996	0.550	14.0	10.3	3.8	0.343	78	0.0156	14.0	10.5	3.6	0.716	78	0.490	0.075	0.96	0.551	1.77
11	1000	1.295	0.585	14.0	10.3	3.8	0.286	73	0.0185	14.1	11.0	3.2	0.522	73	0.585	0.075	0.96	0.454	2.275
12	1000	1.295	0.595	14.1	10.3	3.9	0.293	74	0.0181	14.0	11.0	3.1	0.541	74	05780	0.075	0.96	0.461	2.275
13	1000	1.795	0.573	14.0	10.1	4.0	0.351	74	0.0148	14.1	11.1	3.1	0.544	74	0.710	0.075	0.96	0.320	3.160
14	1000	1.795	0.560	13.9	10.1	3.9	0.355	75	0.0147	14.1	11.0	3.2	0.540	74	0.716	0.075	0.96	0.313	3.160
15	1400	1.790	0.580	14.0	10.2	3.9	0.414	73	0.0127	14.0	13.8	0.2	0.792	73	0.707	0.075	0.96	0.323	4.46
16	1400	1.790	0.592	14.1	10.2	4.0	0.407	75	0.0129	14.2	10.9	3.4	0.624	75	0.699	0.075	0.96	0.332	4.46
17	1400	1.009	0.501	14.0	10.4	3.7	0.460	75	0.0117	14.0	10.8	3.3	0.886	75	0.540	0.075	0.96	0.501	2.50
18	1400	1.009	0.515	14.0	10.4	3.7	0.460	75	0.0117	14.0	10.7	3.4	0.895	75	0.530	0.075	0.96	0.511	2.50
19	1400	1.180	0.542	14.1	11.1	3.1	0.375	75	0.0152	14.0	11.5	2.6	0.625	76	0.621	0.075	0.96	0.415	2.91
20	1400	1.180	0.542	14.1	11.1	3.1	0.375	75	0.0152	14.0	11.1	3.0	0.700	76	0.536	0.075	0.96	0.505	2.91
21	1400	1.395	0.715	14.1	10.3	3.9	0.375	73	0.0141	20.0	10.75	9.5	0.743	73	0.527	0.075	0.96	0.515	3.45
22	1400	1.410	0.723	14.0	10.1	4.0	0.318	73	0.0124	14.0	10.60	3.5	0.633	73	0.529	0.075	0.96	0.514	3.54
23	1400	1.410	0.66	14.1	10.3	3.9	0.293	73	0.0181	14.2	11.00	3.3	0.550	73	0.570	0.075	0.96	0.470	3.54
24	1400	1.410	0.585	10.0	10.0	0.0	0.310	73	0.0166	14.2	11.0	3.3	0.550	73	0.620	0.075	0.96	0.416	3.54
25	1400	1.725	0.610	14.1	10.1	4.1	0.336	75	0.0155	14.0	10.5	3.6	0.515	75	0.680	0.075	0.96	0.353	4.33
26	1400	1.725	0.671	14.0	10.2	3.9	0.363	75	0.0145	14.0	10.7	3.4	0.590	75	0.645	0.075	0.96	0.389	4.33
27	1400	1.725	0.680	14.1	10.2	4.0	0.402	77	0.0131	14.0	10.8	3.3	0.665	77	0.640	0.075	0.96	0.395	4.33
28	1400	1.400	0.600	14.1	10.1	4.1	0.370	73	0.0140	14.0	10.8	3.3	0.650	74	0.609	0.075	0.96	0.428	3.47

$$\bar{X}_{cc}\ (\text{COR}) = X_{cc} - Y_{cc}\left[\frac{(-N)\ NaOH}{(-N)\ H_2SO_4}\right]$$

$$\text{INLET CONCENTRATION} = \frac{\text{Constant}\left[10^{-5}\right] X_{cc}\, T_g}{V_g}$$

$$\alpha = \frac{\bar{X}_{cc}\ (\text{COR})\ \text{EXHAUST}}{\bar{X}_{cc}\ (\text{COR})\ \text{INLET}} \cdot \frac{V_g\ \text{INLET}}{V_g\ \text{EXHAUST}}$$

$$\Gamma = \frac{e_S}{R_S} = \frac{1-\alpha}{e_b - \alpha S}$$

GAS ANALYSIS - COMPRESSION AND EXPANSION SAMPLES
GAS ANALYSIS - EXPANSION SAMPLE ONLY
} Data - METHODS II AND III

Run	Speed	R_s	Rot	Fuel Rate	Compression Sample Phasing			Expansion Sample Phasing			O₂ in Air			O₂ in Res.			O₂ in chg.									
					Extraction Angle	Error	Phase Drum Setting	Extraction Angle	Error	Phase Drum Setting	x			y			z			m_m	m_r	P_o	P_s	P_c	V_o	V_c
	RPM			lbs/sec	Degs.	Degs.	Degs.	Degs.	Degs.	Degs.	CO_2	O_2	CO	CO_2	O_2	CO	CO_2	O_2	CO	lbs/lb mol	Average G+M, D+L	psia	psia	psia	in.³	in³
1	1000	1.790	12.50	.00167	293	8	285	111	8	103	0	21	0	8.6	.6	5.6	.3	19.2	.5	28.93	28.04	33.0	75.0	15.0	19.70	43.89
2	1000	1.790	12.50	.00167	317	8	309	111	8	103	–			8.0	.6	6.8	.2	19.2	.6	↓	27.85	61.5	75.0	14.85	12.30	↓
3	1000	1.790	12.50	.00167	↓	8	309	↓	8	103	↓			8.8	.6	5.6	.2	19.4	.6	↓	28.00	61.5	75.0	15.20		↓
4	1000	1.243	11.75	.00151	↓	8	309	↓	8	103	↓			8.0	.6	6.0	.6	18.4	1.2	↓	27.88	60.8	60.8	15.00	↓	↓
5	1000	1.35	11.90	.00154	↓	8	309	↓	8	103	↓			7.6	.6	6.6	1.0	18.6	1.2	↓	27.75	61.8	61.8	15.00	↓	↓
6	1000	1.505	12.10	.00158	↓	8	309	↓	8	103	↓			7.4	.6	6.4	.8	19.2	.6	↓	27.70	62.8	63.8	15.00	↓	↓
7	1000	1.66	12.30	.00163	↓	8	309	↓	8	103	↓			7.4	.6	6.6	.6	19.4	.6	↓	27.67	62.8	67.3	15.00	↓	↓
8	1000	1.795	12.50	.00167	↓	8	309	↓	8	103	↓			6.6	.6	3.7	.3	19.7	.4	↓	27.94	65.7	69.7	14.90	↓	↓
9	1000	1.33	11.90	.00154	↓	8	309	↓	8	103	↓			6.2	.6	4.2	.4	19.6	.4	↓	27.70	64.3	64.2	14.90	↓	↓
10	1000	1.25	11.75	.00151	↓	8	309	↓	8	103	↓			6.5	.6	4.8	.9	19.1	.8	↓	27.72	64.7	61.7	14.90	↓	↓
11	1000	1.645	12.30	.00163	↓	8	309	↓	8	103	↓			8.5	.6	4.2	.8	19.4	.8	↓	28.26	64.7	67.7	14.90	↓	↓
12	1000	.996	10.80	.00132	↓	8	309	↓	8	103	↓			7.6	.6	4.8	1.4	18.0	–	↓	28.05	62.7	54.7	14.80	↓	↓
13	1000	1.295	11.90	.00153	↓	8	309	↓	8	103	↓			6.9	.6	4.9	.8	18.7	–	↓	27.88	64.5	58.5	14.70	↓	↓
14	1000	1.795	12.5	.00167	↓	8	309	↓	8	103	↓			8.3	.6	5.9	.8	19.6	–	↓	28.00	67.5	63.5	14.75	↓	↓
15	1400	1.652	15.7	.00237	↓	11	306	↓	11	100	↓			7.8	.6	4.2	.2	19.7	.8	↓	28.08	64.7	74.7	15.20	↓	↓
16	1400	1.505	15.35	.00229	↓	11	306	↓	11	100	↓			7.4	.6	4.2	.6	19.4	.6	↓	28.04	63.7	72.7	15.20	↓	↓
17	1400	1.345	14.95	.00220	↓	11	306	↓	11	100	↓			7.3	.6	4.2	1.0	19.1	.7	↓	28.04	62.7	68.7	15.20	↓	↓
18	1400	1.790	16.10	.00246	↓	11	306	↓	11	100	↓			7.2	.6	4.2	1.0	19.7	.4	↓	28.05	66.7	77.7	15.10	↓	↓
19	1400	1.009	13.50	.00188		11	306	↓	11	100	↓			6.6	.6	3.4	1.2	18.2	1.2	↓	27.95	60.5	59.5	14.70	↓	↓
20	1400	1.18	14.10	.00202		11	306		11	100				7.0	.6	4.0	.6	19.0	.6		28.00	61.5	64.7	14.70	↓	↓
21	1400	1.40	15.10	.00223		11	306		11	100				7.6	.6	6.0	.6	19.0	–		27.77	68.5	60.5	14.90		

METHODS II, III DATA - PAGE 2

T_i °F	Chart Fuel Air Ratio G+M	Chart Fuel Air Ratio D+L	M_r/M_m —	M_m/M_c —	M_r/M_c —	m_c lbs/lb mol	Curve Expansion Ratio —	T_r °R	T_r' °R	T_z °R	T_1 °R	T_o °R	$1/(1+M_r/M_m)$ —	P_o/P_e —	V_o/V_c —	T_i/T_o —	m_c/m_m —	e_s Gas Anal. 2 samples	e_s G+M Chart	e_s D+L Chart	e_s Average Chart e_s
110	.083	.084	.096	.915	.085	28.83	5.20	3270	2145	1845	678	810	.915	2.20	.45	.705	.998	.636	.666	.658	.662
	.087	.0875	.0927	.915	.085	28.82		3180	2075	1775	672	978	.915	4.13	.28	.583	.998	.617	.640	.640	.640
	.0835	.084	.0850	.921	.079	28.86		3260	2155	1855	672	966	.921	4.05		.590	.999	.619	.662	.658	.660
	.086	.0865	.141	.875	.125	28.82		3210	2230	1930	741	1068	.875	4.055		.533	1.00	.530	.585	.584	.584
	.088	.088	.128	.886	.114	28.76		3165	2180	1880	719	1041	.886	4.11		.546	.998	.554	.585	.585	.585
	.0885	.0885	.093	.914	.086	28.77		3155	2165	1865	681	985	.914	4.19		.579	.999	.615	.608	.608	.608
	.0889	.0886	.0814	.924	.076	28.80		3145	2130	1830	665	965	.924	4.19		.591	.996	.636	.614	.614	.614
	.0865	.0857	.066	.939	.061	28.86		3210	2155	1855	648	955	.939	4.41		.598	.999	.690	.654	.660	.657
	.0882	.0877	.0705	.933	.067	28.85		3170	2165	1865	656	960	.933	4.31		.594	.999	.665	.591	.594	.593
	.0885	.0880	.0983	.910	.090	28.79		3160	2185	1885	688	1005	.910	4.34		.567	.995	.621	.577	.575	.576
	.0825	.083	.0830	.924	.076	28.85		3290	2220	1920	672	985	.924	4.35		.579	.999	.641	.665	.663	.664
	.085	.085	.167	.858	.142	28.79		3240	2310	2010	775	1120	.858	4.21		.508	.996	.515	.525	.525	.525
	.086	.087	.122	.890	.110	28.88		3200	2235	1935	720	1060	.890	4.39		.537	1.00	.588	.606	.600	.603
	.085	.0857	.0714	.931	.069	28.88		3225	2210	1910	663	986	.931	4.58		.578	1.00	.690	.670	.662	.666
	.0835	.084	.066	.937	.063	28.88		3260	2145	1845	650	946	.937	4.26		.602	.999	.670	.679	.675	.677
	.085	.0845	.0825	.924	.076	28.88		3240	2150	1850	667	967	.924	4.19		.590	.999	.637	.644	.647	.646
	.085	.0845	.0997	.910	.090	28.93		3240	2160	1860	687	991	.910	4.13		.575	1.00	.606	.617	.623	.620
	.085	.085	.066	.938	.062	28.89		3230	2145	1845	649	951	.938	4.41		.598	1.00	.693	.694	.694	.694
	.0865	.0855	.154	.866	.134	28.74		3220	2230	1930	752	1090	.866	4.11		.522	.995	.518	.526	.532	.529
	.086	.085	.105	.905	.095	28.86		3225	2190	1890	695	1010	.905	4.18		.565	1.00	.597	.570	.578	.574
	.0875	.0875	.104	.905	.095	28.79		3170	2200	1900	697	1040	.905	4.59		.548	.996	.645	.617	.617	.617

Formulae

$$\frac{M_r}{M_m} = \frac{x-z}{z-y} \cdot \frac{m_r}{m_m}$$

$$\frac{M_m}{M_c} = \frac{1}{1+\frac{M_r}{M_m}}$$

$$\frac{M_r}{M_c} = 1 - \frac{M_m}{M_c}$$

$$m_c = m_m \left[\frac{M_m}{M_c}\right] + m_r \left[\frac{M_r}{M_c}\right]$$

p_s = pressure of expansion sample

$$T_r' = T_r \left[\frac{P_e}{P_s}\right]^{.26}$$

$$T_1 = \left[\frac{M_m}{M_c}\right] T_i + \left[\frac{M_r}{M_c}\right] T_z$$

$T_z = T_r' - 300$°F (Blowdown heat exchange)

$$T_o = T_1 \left[\frac{P_o}{P_e}\right]^{.26}$$

$$e_s = \frac{P_o}{P_e} \cdot \frac{V_o}{V_c} \cdot \frac{T_i}{T_o} \cdot \frac{m_c}{m_m} \cdot \frac{1}{1+\frac{M_r}{M_m}}$$

Using F/A from charts:

$$e_s = \frac{\dfrac{\text{Fuel Rate}}{F/A}}{\rho_s N V_D \frac{r}{r-1}}$$

I.S.A.C. Method. – METHOD IV

Run	RPM	R_s	$(FR)_4$ lbs/sec	$(FR)_2$ lbs/sec	Card $(IHP)_4$ h.p.	$(Isac)_4$ $\frac{\text{lbs air}}{\text{ihp hr.}}$	K_4 $\left[F/A\, E_c\, \eta_i\right]_4$ btu/lb air	$(\text{Card Area})_4$ in.²	$(\text{Card Area})_2$ in.²	Average G+M–D+L $\left[F/A\right]_2$ lb fuel/lb air	Corr. factor	K_2 $\left[F/A\, E_c\, \eta_i\right]_2$ btu/lb air	$(Isac)_2$ $\frac{\text{lbs air}}{\text{ihp hr.}}$	Card $(IHP)_2$ h.p.	Air Retained lbs/min	$\rho_s N V_d \frac{r}{r-1}$ lbs/min	e_s
1	1000	1.79	.000769	.00164	5.98	5.80	438	4.23	3.71	.086	.909	398	6.40	10.48	1.119	1.79	.624
2	1000	1.24	↓	.00150	↓	↓	↓	↓	3.28	.0882	.901	395	6.44	9.20	.988	1.80	.550
3	1000	1.33	↓	.00154	↓	↓	↓	↓	3.39	.0879	.901	395	6.44	9.60	1.03	1.80	.574
4	1000	1.63	↓	.00161	↓	↓	↓	↓	3.53	.0875	.896	393	6.48	10.00	1.08	1.80	.600
5	1000	1.02	↓	.00132	↓	↓	↓	↓	2.69	.0850	.806	354	7.20	7.60	.91	1.782	.510
6	1000	1.505	↓	.00158	↓	↓	↓	↓	3.47	.0885	.905	396	6.43	9.85	1.055	1.785	.592
7	1400	1.18	.00096	.00210	7.67	5.76	441	3.87	3.24	.0855	.839	370	6.88	12.82	1.471	2.50	.589
8	1400	1.35	↓	.00219	↓	↓	↓	↓	3.50	.0847	.862	380	6.70	13.87	1.55	2.50	.621
9	1400	1.65	↓	.00237	↓	↓	↓	↓	3.96	.0838	.892	396	6.43	15.70	1.685	2.51	.672
10	1400	1.80	↓	.00246	↓	↓	↓	↓	4.19	.0820	.892	396	6.43	16.58	1.778	2.52	.706
11	1400	1.00	↓	.00188	↓	↓	↓	↓	3.05	.0860	.886	391	6.51	12.10	1.302	2.50	.521
12	1400	1.495	↓	.00228	↓	↓	↓	↓	3.72	.0840	.874	385	6.61	14.72	1.625	2.51	.647

Formulae:

$$\text{Correction factor} = \frac{\left[F/A\right]_{2\,\text{charts}}}{.078} \cdot \frac{(\text{Area Card})_2}{(\text{Area Card})_4} \cdot \frac{(FR)_4}{(FR)_2} \cdot 2$$

$$(Isac)_4 = \frac{2545}{\underbrace{\left[F/A\ E_c\ \eta_i\right]_4}_{K_4}} = \left(\text{air rate in } \frac{\text{lbs}}{\text{hr}}\right)\cdot\left(\frac{1}{\text{ihp.}}\right)$$

$$\underbrace{\left[F/A \cdot E_c \cdot \eta_i\right]_2}_{K_2} = \underbrace{\left[F/A \cdot E_c \cdot \eta_i\right]_4}_{K_4} \cdot \text{Corr. factor}$$

$$(Isac)_2 = \frac{2545}{K_2}$$

$$\text{Air retained} = \frac{(Isac)_2 \cdot (IHP)_2}{60} = \text{lbs/min} \qquad e_s = \frac{\text{Air retained}}{\rho_s N V_d \frac{r}{r-1}}$$

SAMPLING CHECK VALVE DATA

Run	RPM	R_s	Rot.	Fuel Rate	$\beta N V_d \frac{2}{\rho_T}$	CO_2	O_2	CO	F/A	F/A	G+M. $\dot{M}_{a_{net}}$	D+L. $\dot{M}_{a_{net.}}$	e_s	e_s
—	—	—	—	lbs/sec	lbs/min	% by vol.	% by vol.	% by vol.	G+M.	D+L.	lbs/min	lbs/min	G+M.	D+L.
1	1000	1.02	10.8	.00132	1.782	10.0	.4	6.0	.0811	.0817	.976	.973	.548	.546
2	1000	1.505	12.1	.00158	1.785	10.2	.3	6.4	.0815	.0820	1.162	1.158	.652	.648
3	1000	1.765	12.4	.00166	1.810	11.0	.0	4.8	.077	.077	1.295	1.295	.716	.716
4	1000	1.258	11.80	.001515	1.81	10.2	.2	6.2	.0812	.0820	1.12	1.11	.620	.613
5	1400	1.495	15.30	.00228	2.51	10.6	.3	6.1	.0800	.0805	1.71	1.70	.680	.679

$$\dot{M}_{a_{net}} = \frac{\text{Fuel Rate}}{F/A} \cdot 60 = \text{lbs}/\text{min}$$

4-Stroke Comparison Runs Data (I.S.A.C. Method)

Run	Speed RPM	$P_{atm.}$ in. Hg	P_i in. Hg	P_e in. Hg	T_i °F	Density Corr. Factor	T_o °F	ΔP_o in. H_2O	Air Cons. lbs/sec.	Fuel Cons. lbs/sec.	Spark Advance Degrees	Water out °F	Roto	F/A $\frac{\text{lbs. Fuel}}{\text{lbs. Air}}$	$T_{atm.}$ °F
1	1400	29.9	-1.0	+0.2	110	0.975	70	8.4	.0123	.00096	24	195	8.3	.078	70
2	1000	29.9	-1.0	+0.2	110	0.975	70	5.3	.00985	.000769	20	195	7.3	.078	70

APPENDIX C

Original data sheets for this work are included in the M.I.T. copy of the thesis, and are on file in Sloan Laboratory.

See Appendix B for smooth data sheets, including all points that were considered to be free from any of the causes contributing to inaccuracy or poor precision.

APPENDIX D

Bibliography:

Texts or Pamphlets

A. The Internal Combustion Engine - Taylor and Taylor

B. Report on 2-Stroke Engines - C. F. Taylor

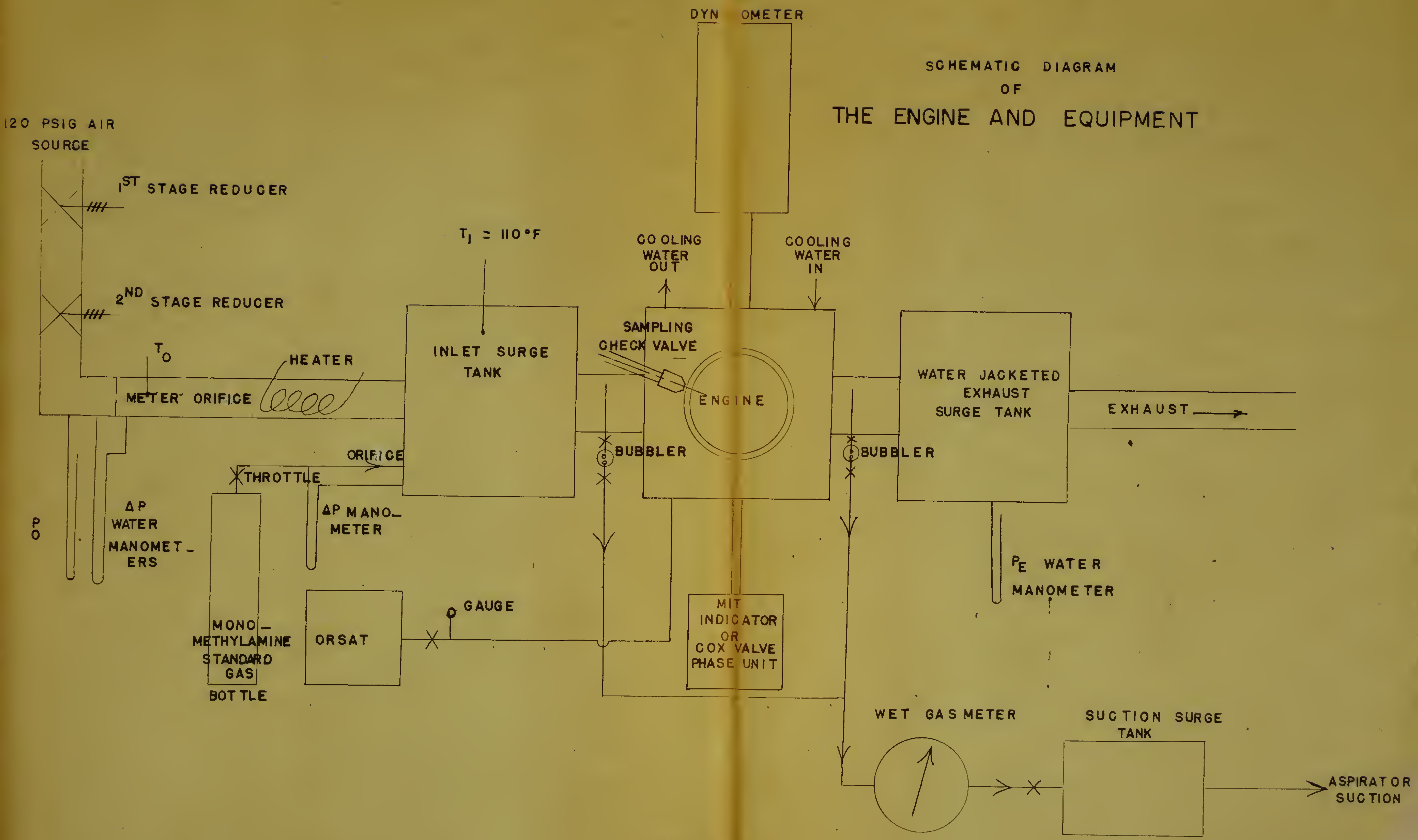
C. NACA Technical Notes #838 - The Tracer Gas Method of Determining the Charging Efficiency of Two-Stroke-Cycle Diesel Engines - Schweitzer and DeLuca

Figures or Curves

1) Analysis of Exhaust Gases from a Spark Ignition Engine - D'Alleva and Lovell - "Relation of Exhaust Gas Composition to Air-Fuel Ratio" - SAE Journal, Vol. 38, No. 3, March, 1936

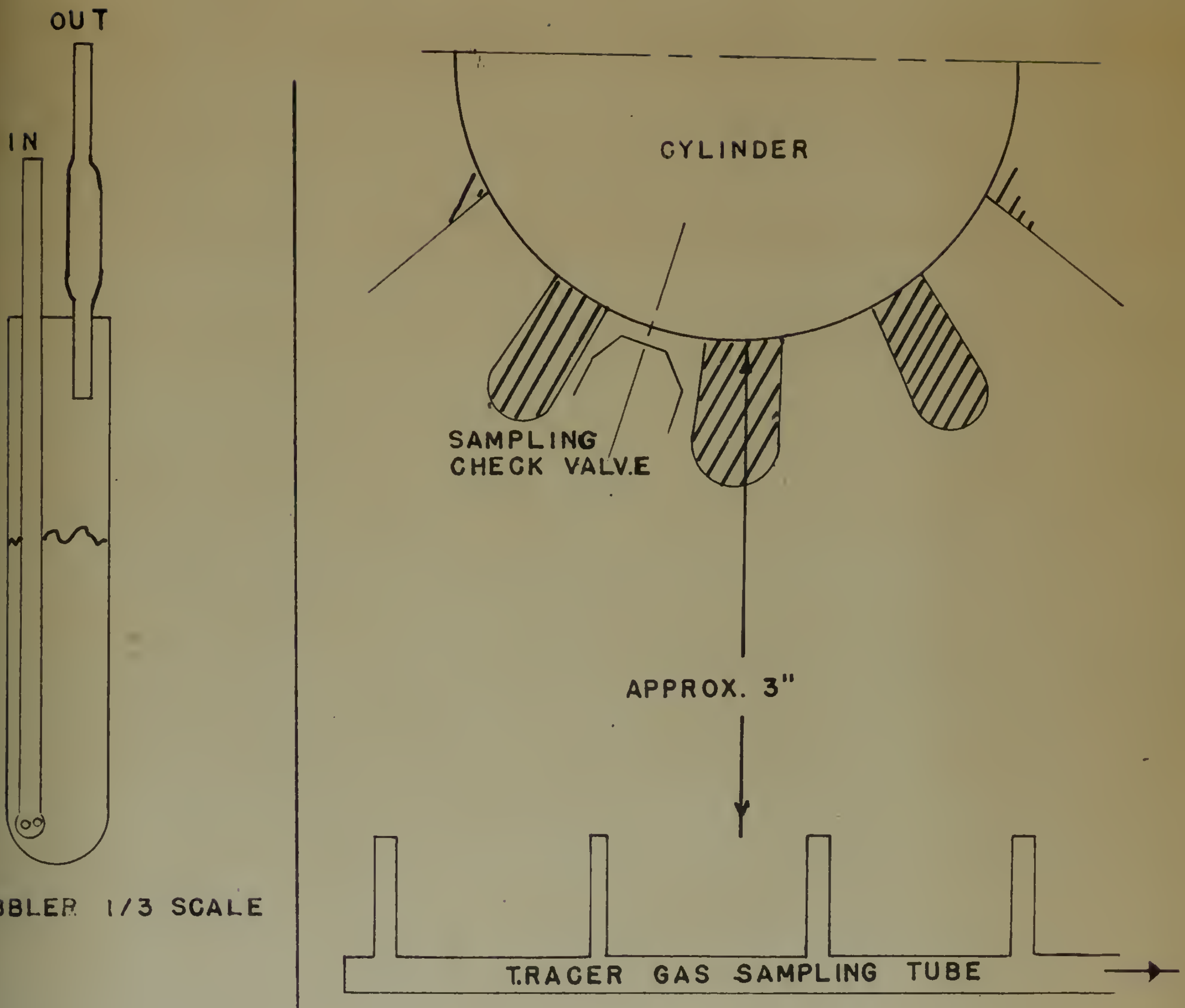
2) Relation of Constituents in Normal Exhaust Gas to Fuel Air Ratio - Gerrish and Meems - Figure 3 of NACA Wartime Report October, 1943. See NACA Report #757

3) Conditions at End of Expansion, Constant Volume Fuel-Air Cycle - Goodenough and Baker - "A Thermodynamic Analysis of Internal Combustion Engine Cycles" - Univ. of Illinois Eng. Exp. Sta. Bulletin 160, 1927



SCHEMATIC DIAGRAM OF THE ENGINE AND EQUIPMENT

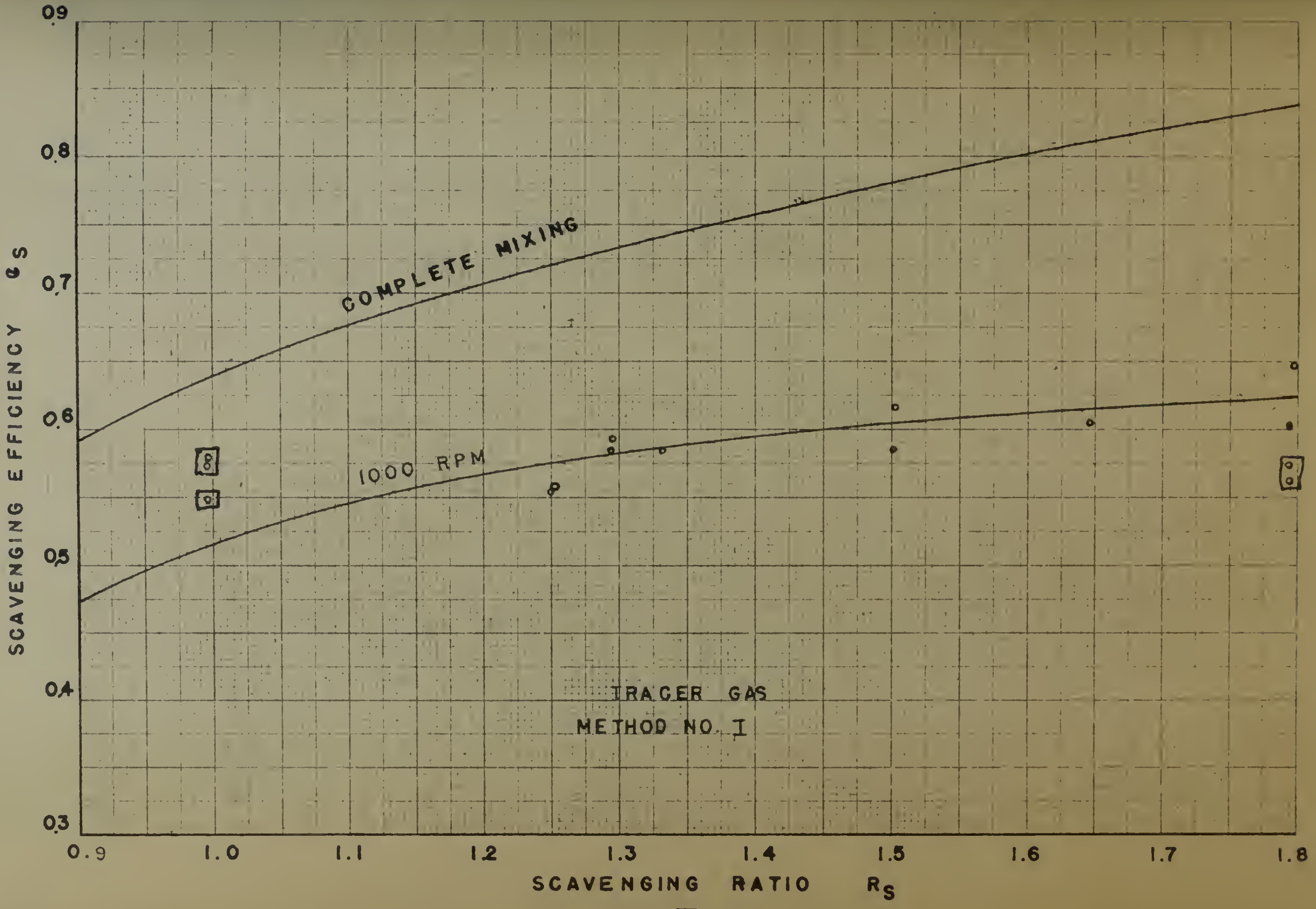
FIG I



BUBBLER 1/3 SCALE

EXHAUST SAMPLING DEVICES
FULL SCALE

FIG. 1A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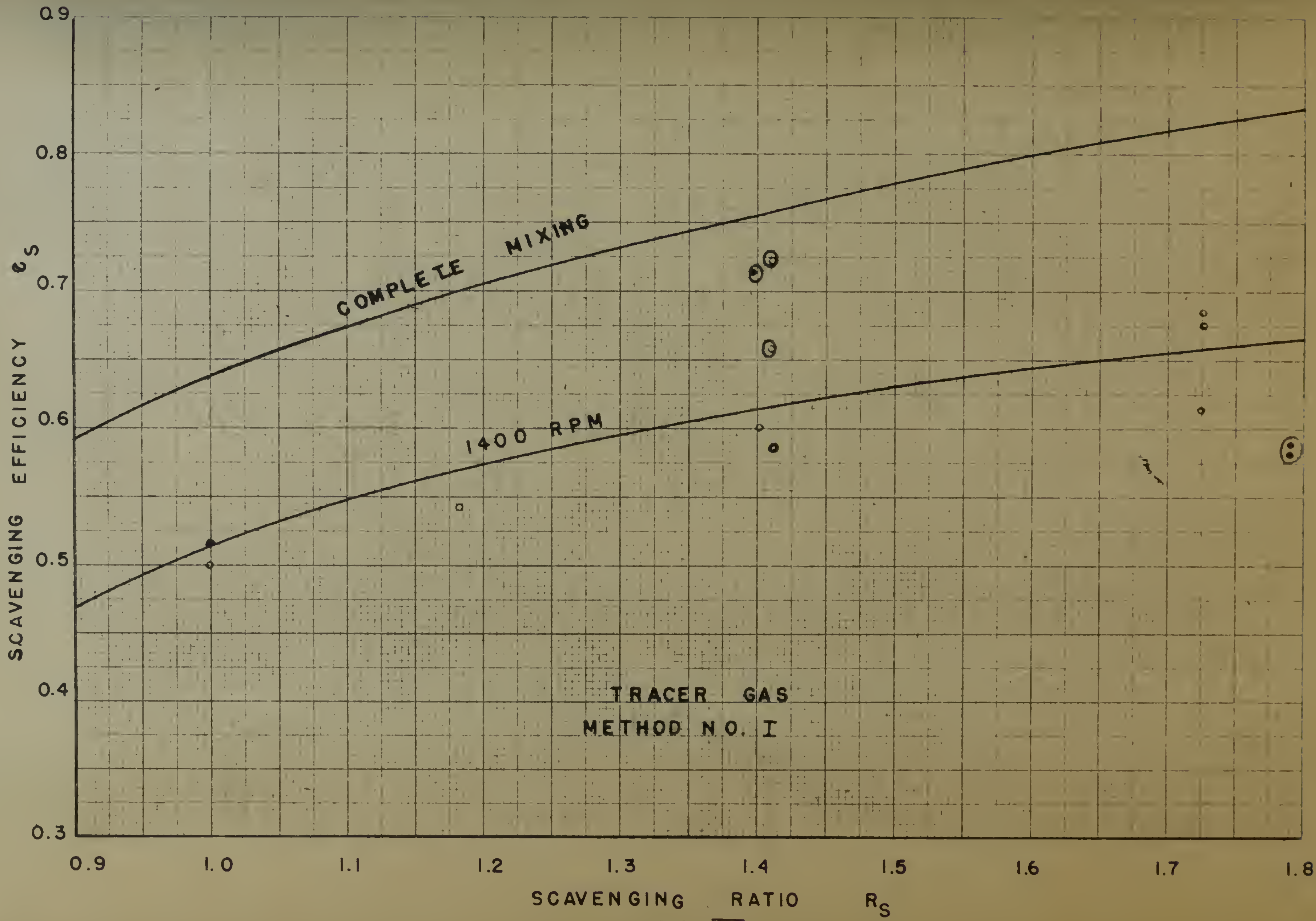
0.6
0.5
0.4
0.3
SCAVENGING EFFICIENCY e_S
COMPLETE MIXING
1000 RPM
TRACER GAS
METHOD NO. I
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S

FIG. II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SCAVENGING EFFICIENCY e_S
COMPLETE MIXING
1400 RPM
TRACER GAS
METHOD NO. I
0.9
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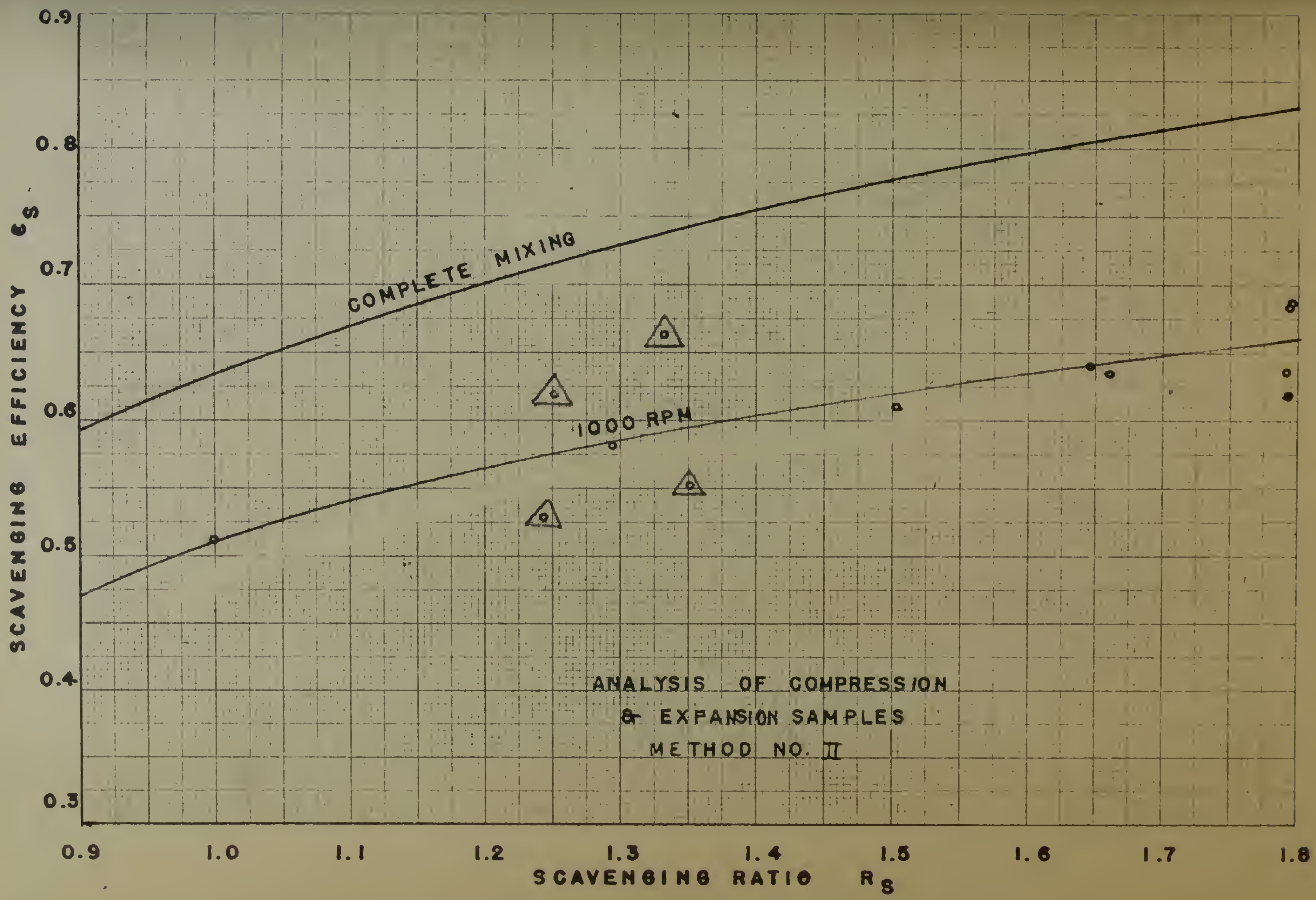
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S

FIG III


COMPLETE MIXING
1000 RPM
ANALYSIS OF COMPRESSION
& EXPANSION SAMPLES
METHOD NO. II
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0.8
0.7
0.6
0.5
0.4
0.3
SCAVENGING RATIO R_S
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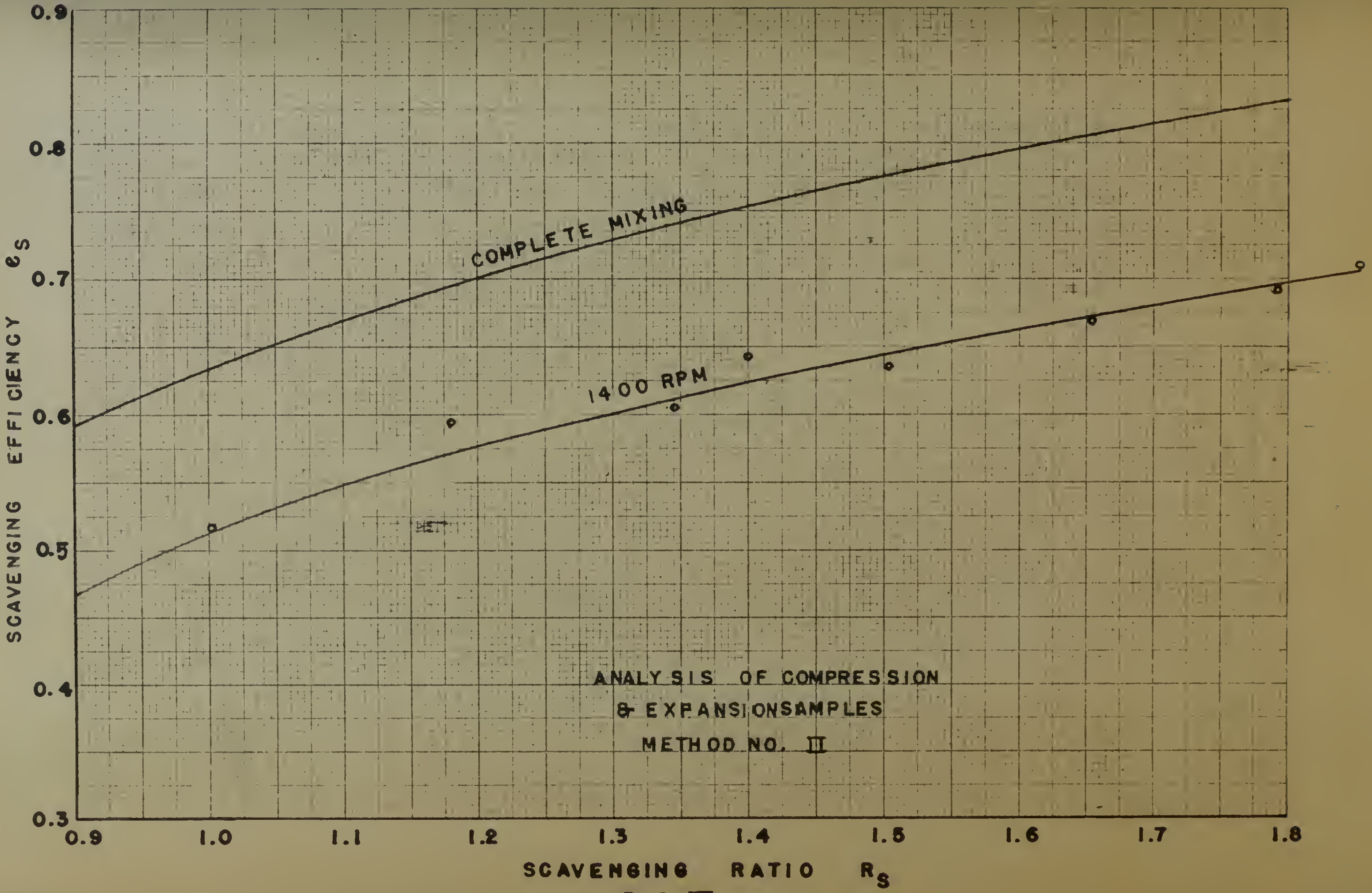
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8

FIG. IV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SCAVENGING EFFICIENCY e_S
COMPLETE MIXING
1400 RPM
ANALYSIS OF COMPRESSION
& EXPANSION SAMPLES
METHOD NO. II
0.9
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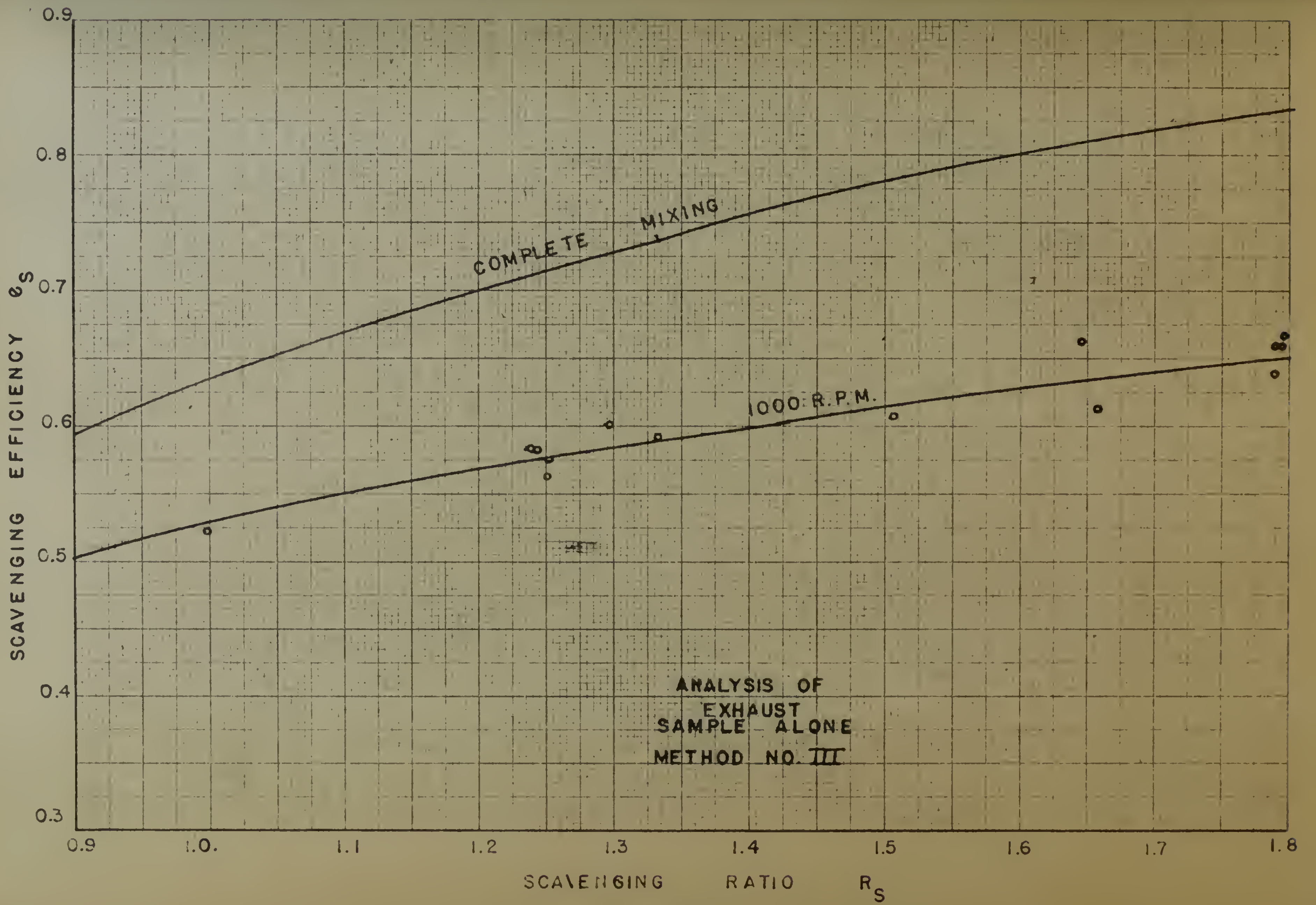
1.7
1.8
SCAVENGING RATIO R_S

FIG. V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0.3
SCAVENGING EFFICIENCY e_S
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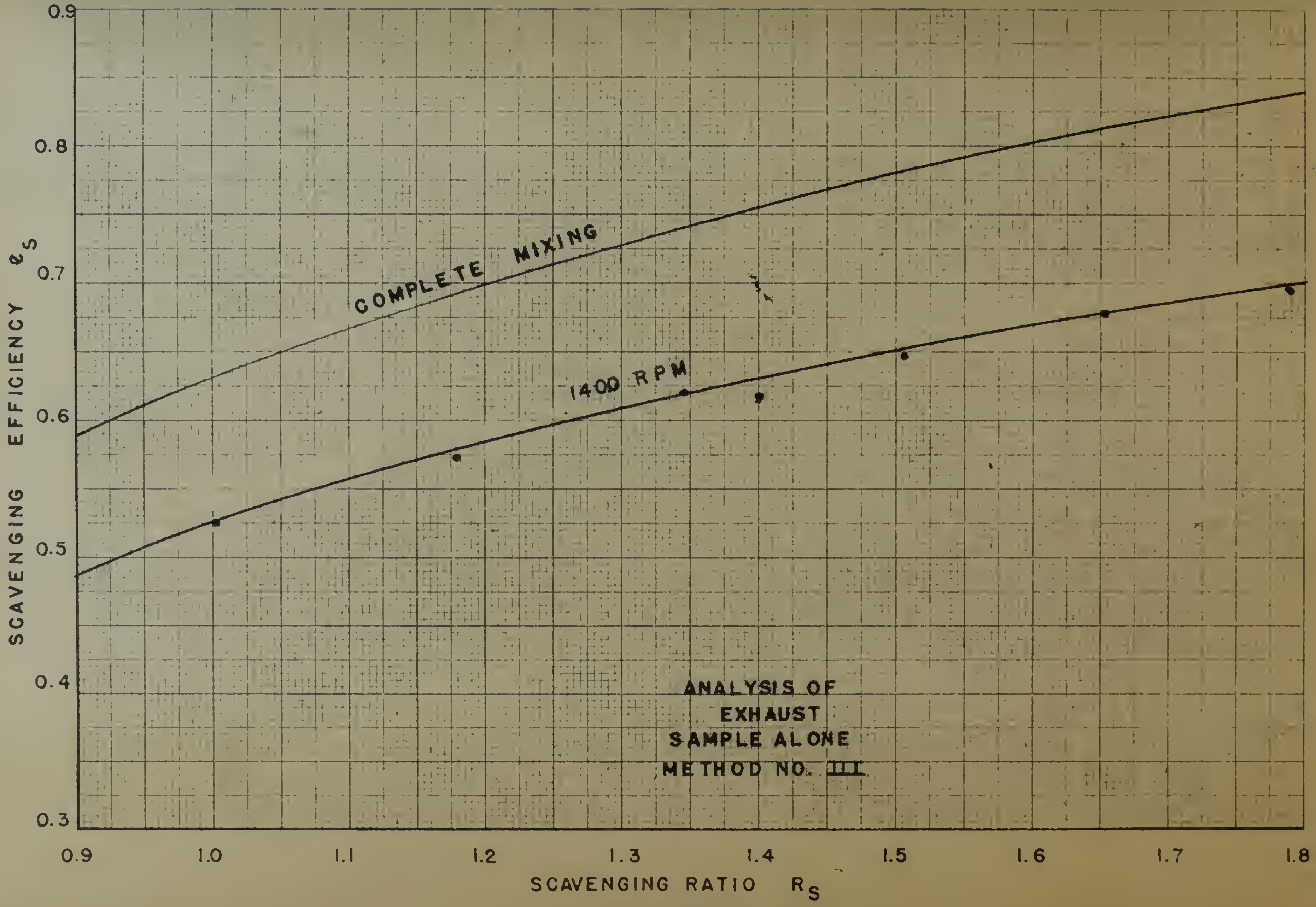
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S
COMPLETE MIXING
1000 R.P.M.
ANALYSIS OF EXHAUST SAMPLE ALONE
METHOD NO. III

FIG. VI


COMPLETE MIXING
1400 RPM
ANALYSIS OF
EXHAUST
SAMPLE ALONE
METHOD NO. III
SCAVENGING EFFICIENCY e_s
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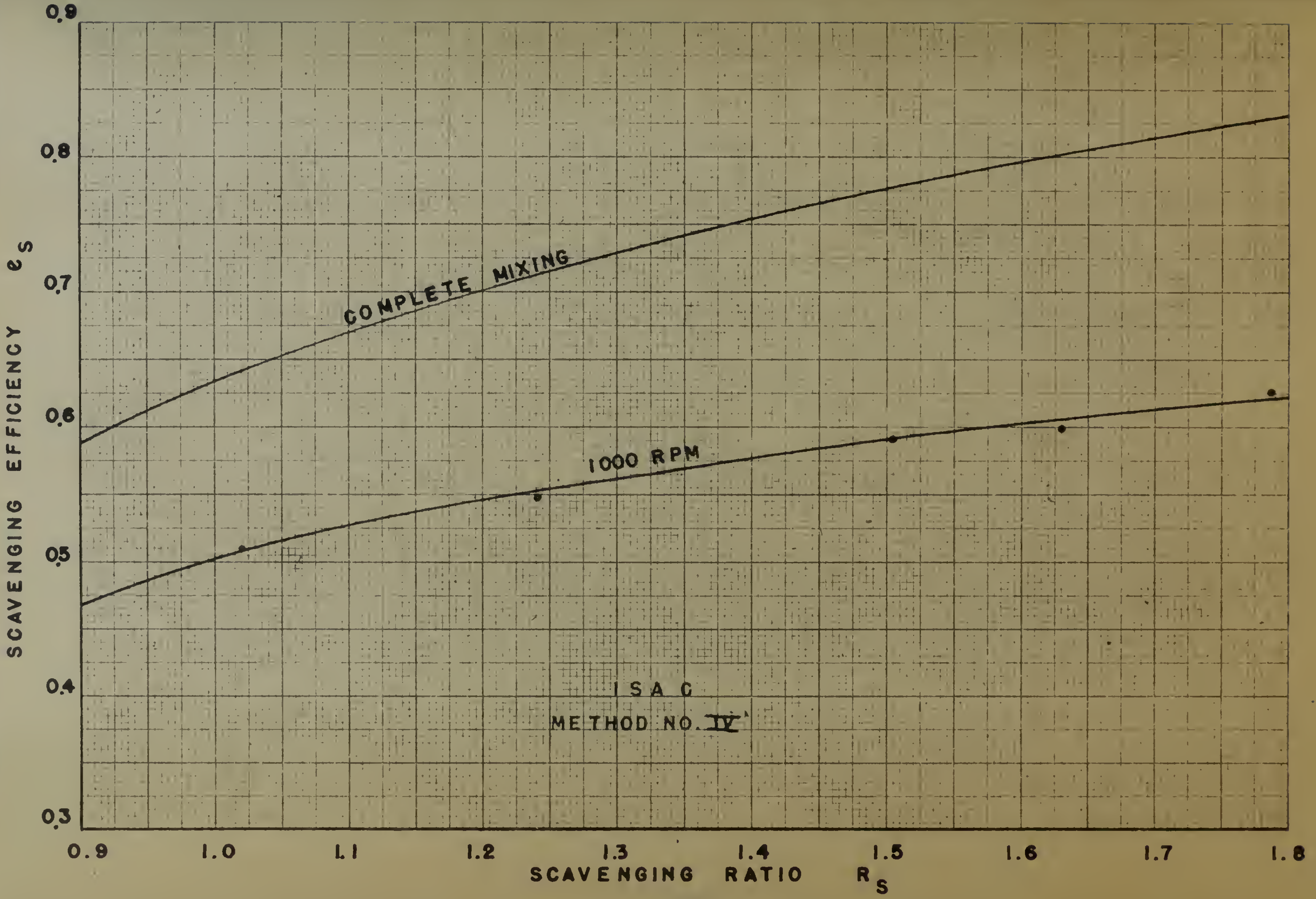
0.7
0.6
0.5
0.4
0.3
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S

FIG. VII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0.5
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SCAVENGING EFFICIENCY e_S
COMPLETE MIXING
1000 RPM
I S A C
METHOD NO. IV
0.9
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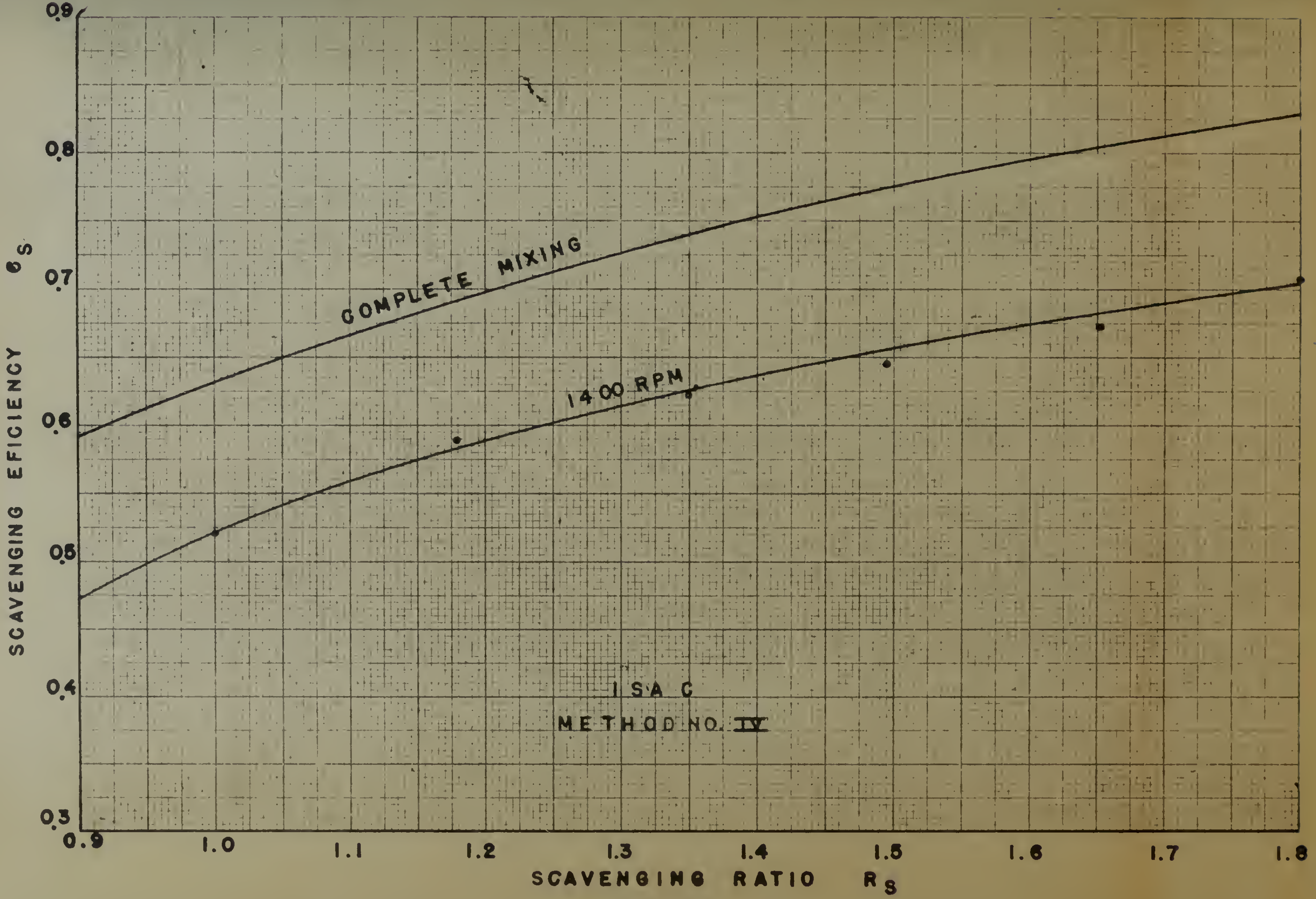
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S

FIG. VIII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0.3
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING EFICIENCY e_S
SCAVENGING RATIO R_S
COMPLETE MIXING
1400 RPM
I S A C
METHOD NO. IV

FIG IX

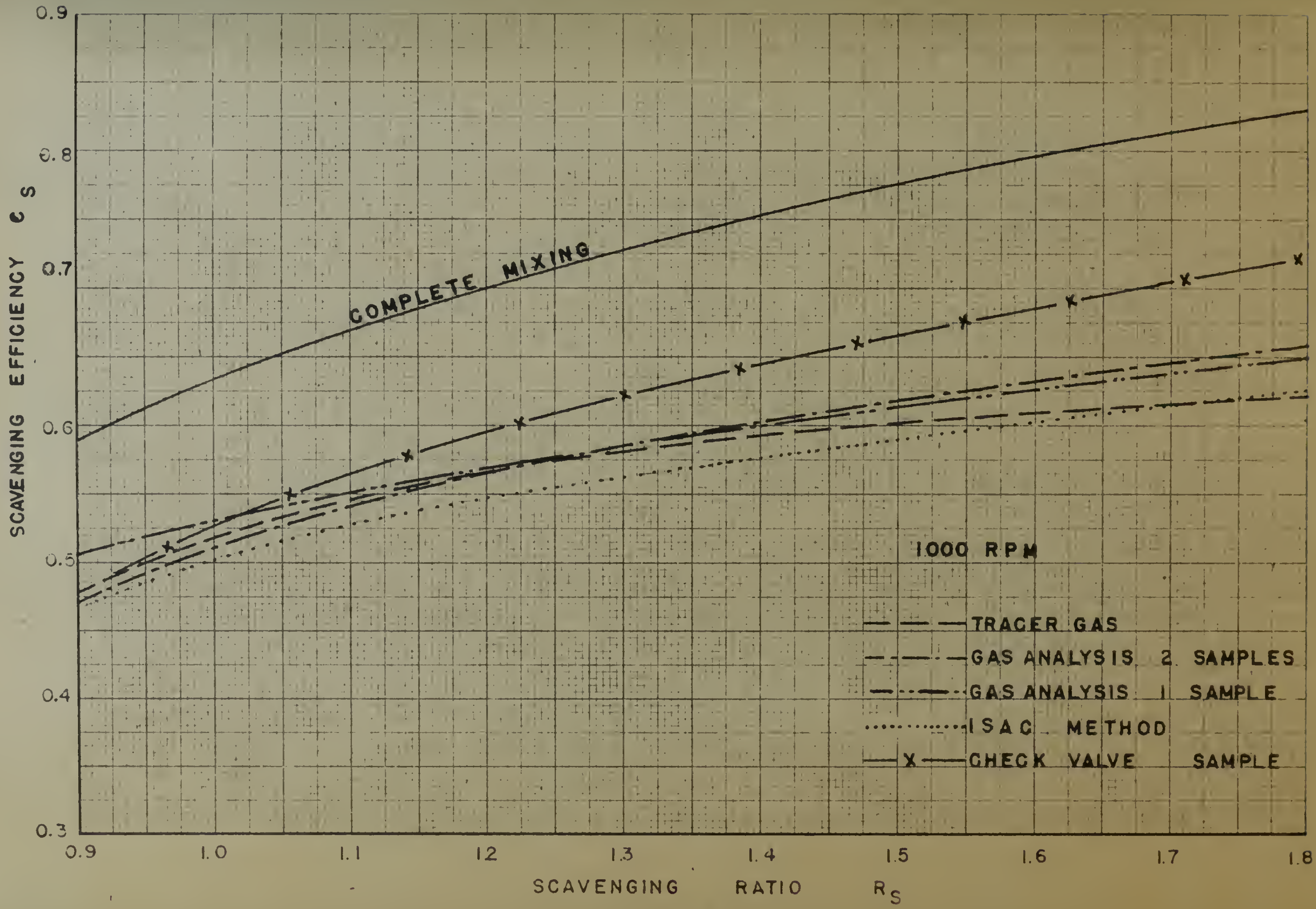

0.9
0.8
0.7
0.6
0.5
0.4
0.3
SCAVENGING EFFICIENCY ϵ_S
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S
COMPLETE MIXING
1000 RPM
TRACER GAS
GAS ANALYSIS 2 SAMPLES
GAS ANALYSIS 1 SAMPLE
ISAC METHOD
CHECK VALVE SAMPLE

FIG. X

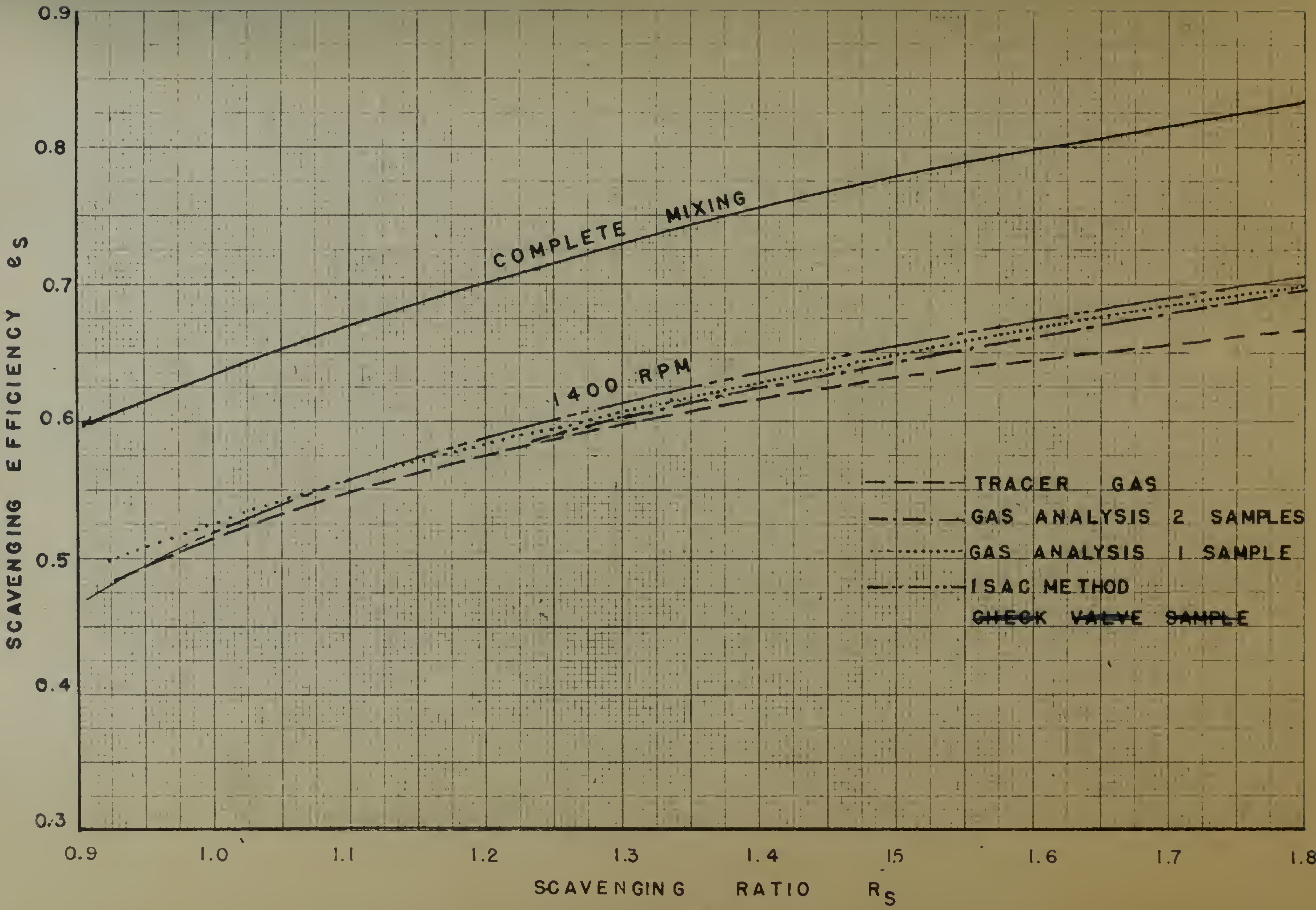

0.9
0.8
0.7
0.6
0.5
0.4
0.3
SCAVENGING EFFICIENCY e_S
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S
COMPLETE MIXING
1400 RPM
TRACER GAS
GAS ANALYSIS 2 SAMPLES
GAS ANALYSIS 1 SAMPLE
ISAC METHOD
~~CHECK VALVE SAMPLE~~

FIG. XI

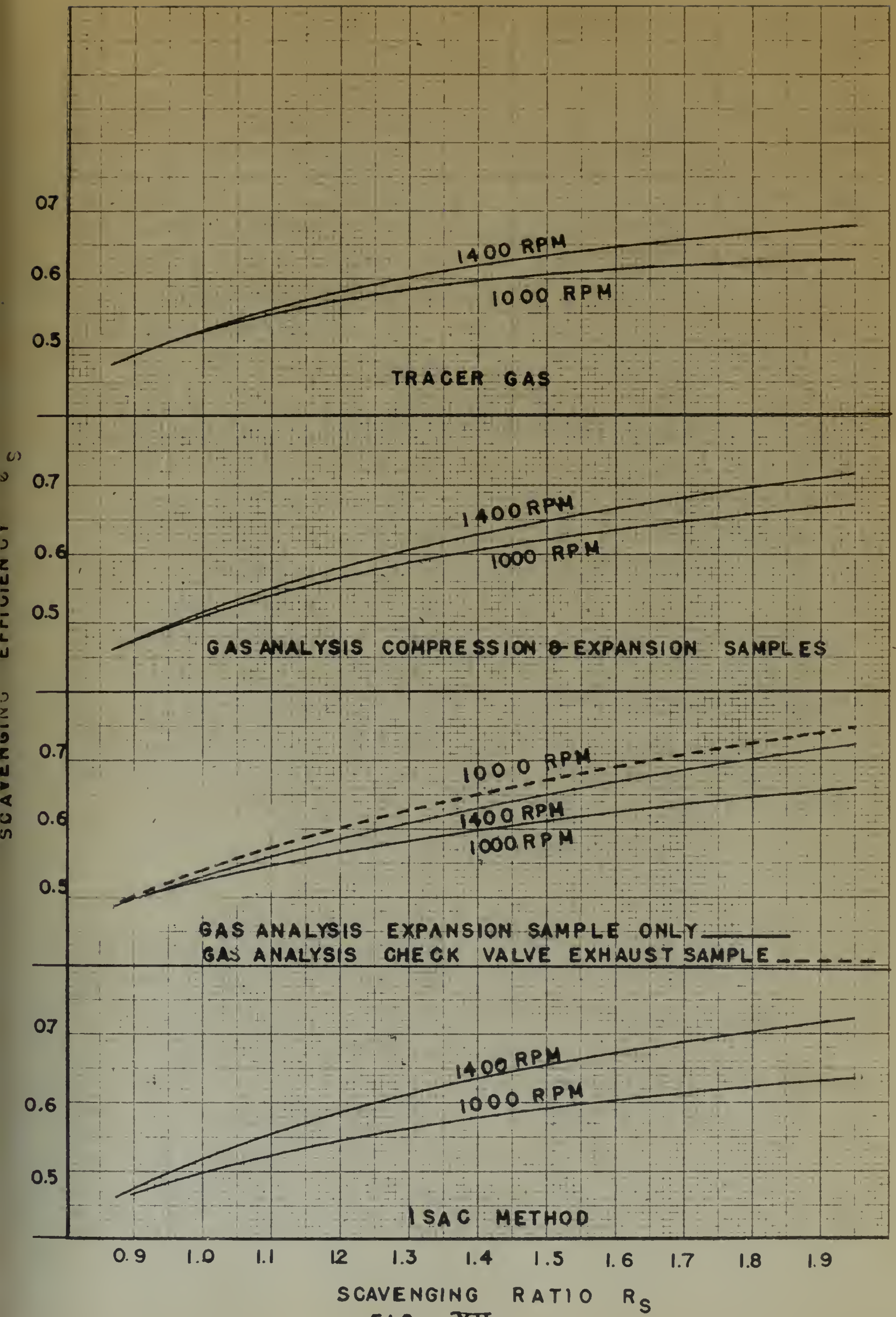

0.7
0.6
0.5
1400 RPM
1000 RPM
TRACER GAS
0.7
0.6
0.5
1400 RPM
1000 RPM
GAS ANALYSIS COMPRESSION & EXPANSION SAMPLES
0.7
0.6
0.5
1000 RPM
1400 RPM
1000 RPM
GAS ANALYSIS EXPANSION SAMPLE ONLY ———
GAS ANALYSIS CHECK VALVE EXHAUST SAMPLE - - - - -
0.7
0.6
0.5
1400 RPM
1000 RPM
ISAC METHOD
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
SCAVENGING RATIO R_S
SCAVENGING EFFICIENCY e_S

FIG. XII

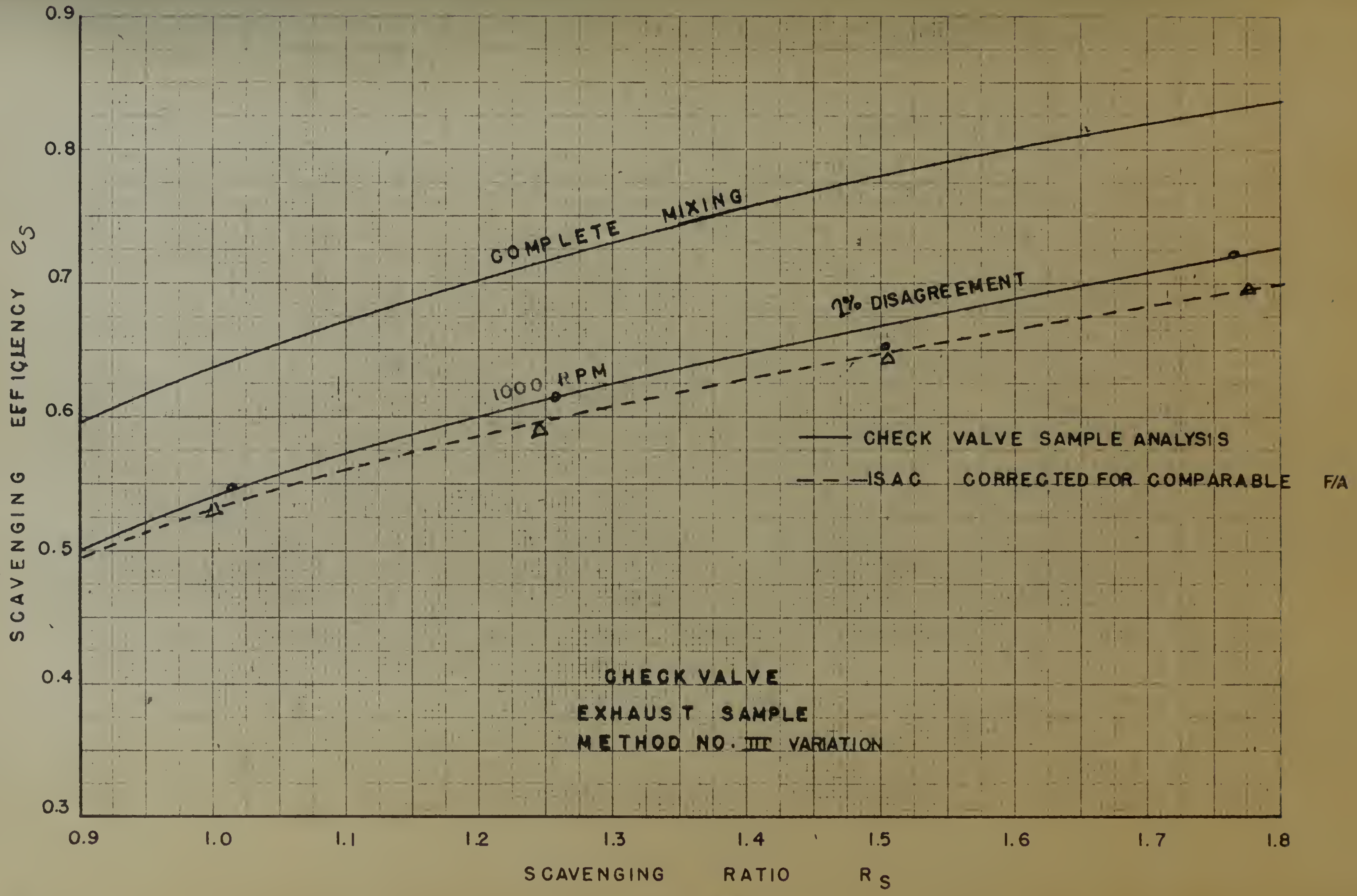
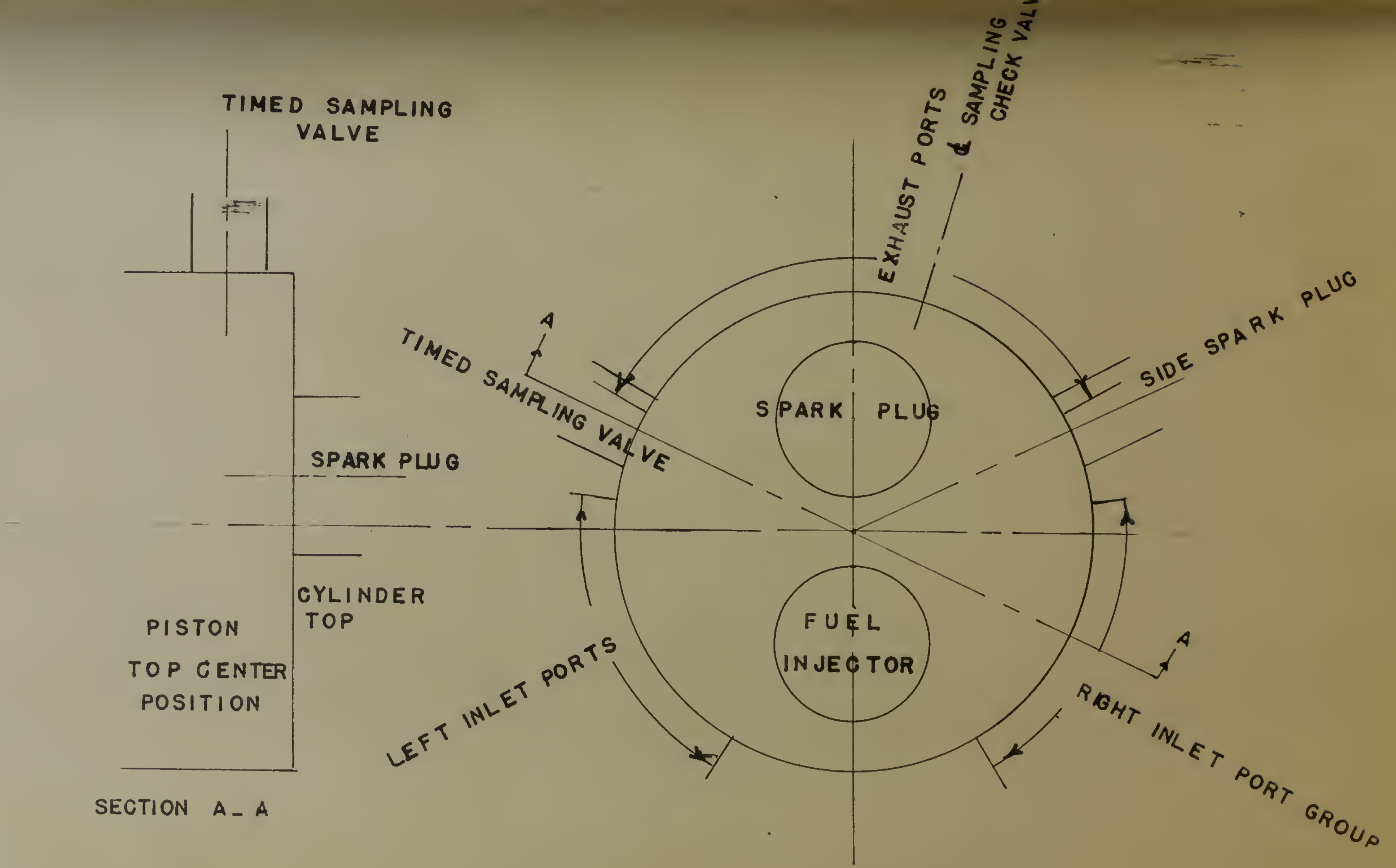

0.9
0.8
0.7
0.6
0.5
0.4
0.3
SCAVENGING EFFICIENCY e_S
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
SCAVENGING RATIO R_S
COMPLETE MIXING
2% DISAGREEMENT
1000 RPM
CHECK VALVE SAMPLE ANALYSIS
ISAC CORRECTED FOR COMPARABLE F/A
CHECK VALVE
EXHAUST SAMPLE
METHOD NO. III VARIATION

FIG. XIII



CYLINDER HEAD DETAILS

FIG XIV

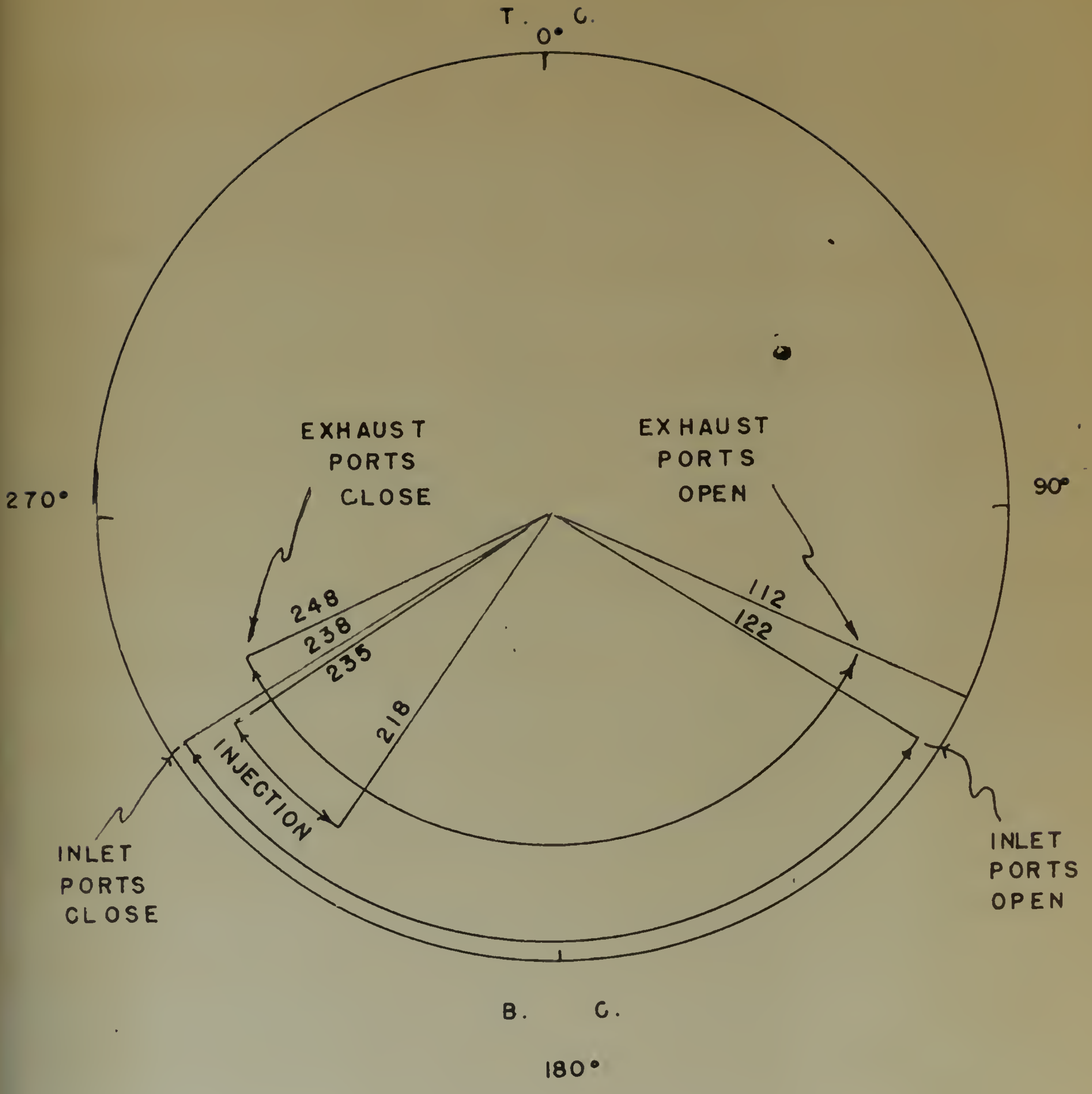


FIGURE XV
TIMING DIAGRAM

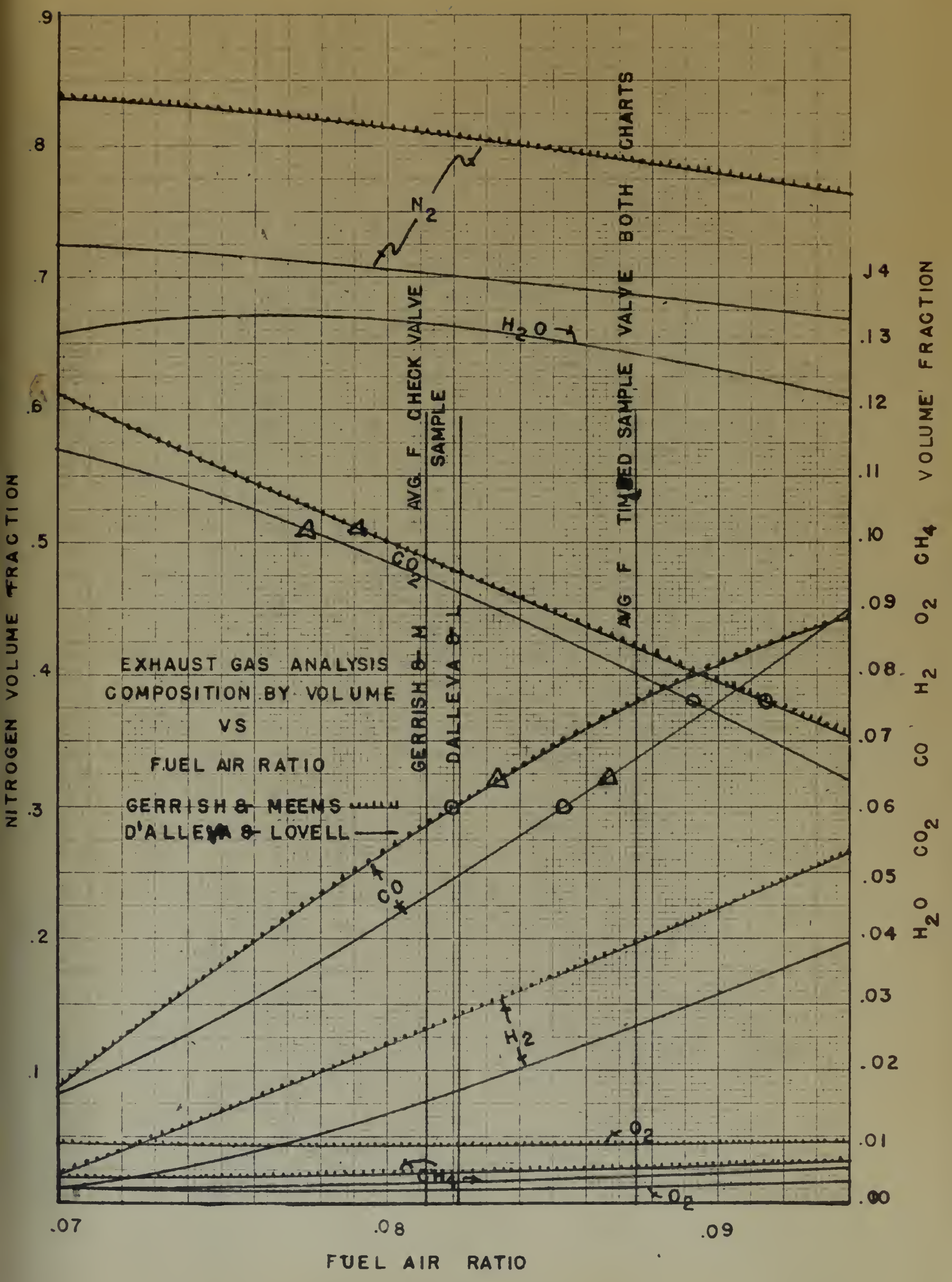

.9
.8
.7
.6
.5
.4
.3
.2
.1
NITROGEN VOLUME FRACTION
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
.00
H_2O CO_2 CO H_2 O_2 CH_4 VOLUME FRACTION
.07
.08
.09
FUEL AIR RATIO
N_2
H_2O
CO
CO_2
CO
H_2
O_2
CH_4
O_2
AVG F CHECK VALVE SAMPLE
AVG F TIMED SAMPLE VALVE BOTH CHARTS
GERRISH & M
DALLEYA & L
EXHAUST GAS ANALYSIS
COMPOSITION BY VOLUME
VS
FUEL AIR RATIO
GERRISH & MEENS
D'ALLEYA & LOVELL

FIG. XVI

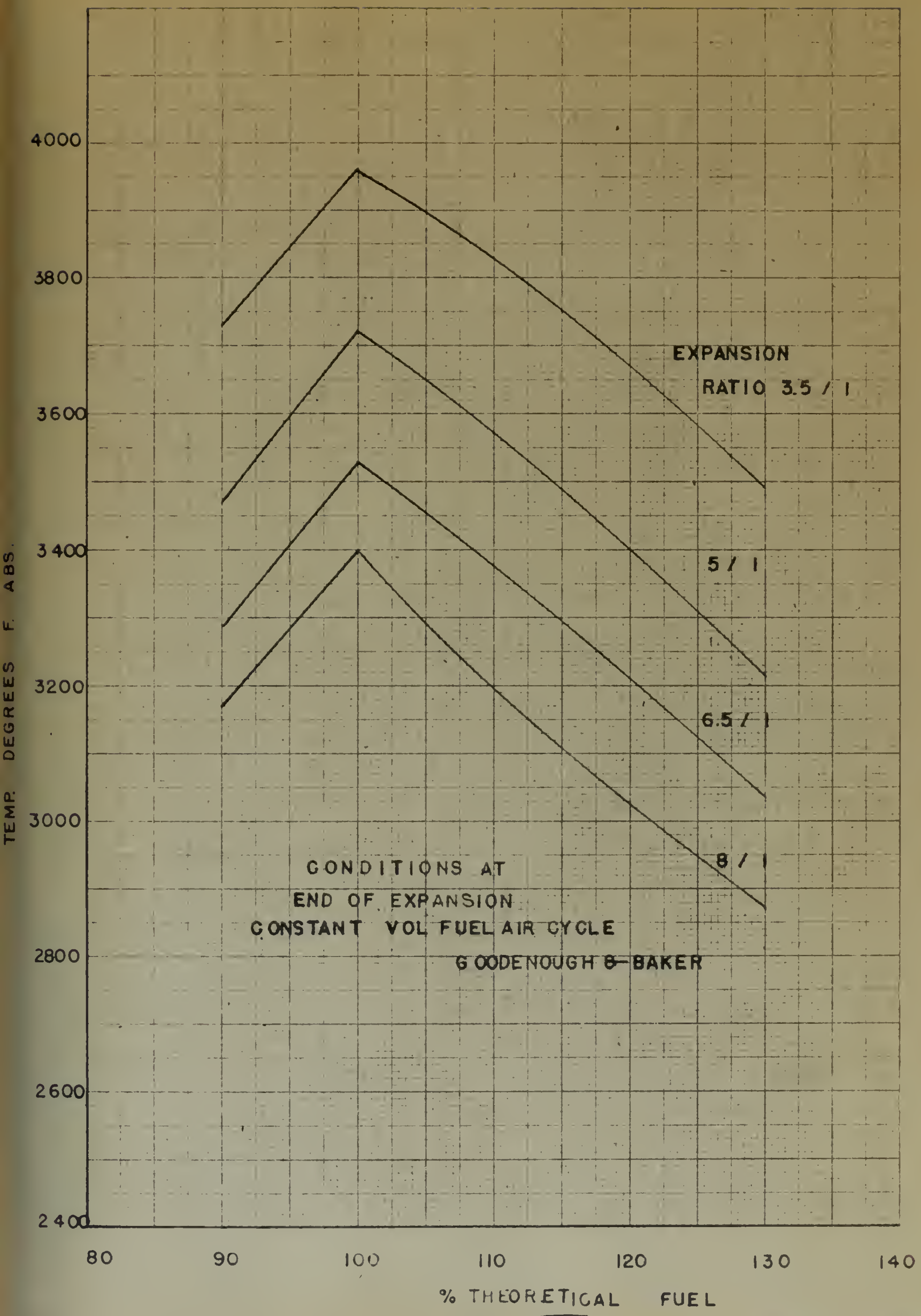

4000
3800
3600
3400
3200
3000
2800
2600
2400
TEMP. DEGREES F. ABS.
80
90
100
110
120
130
140
% THEORETICAL FUEL
EXPANSION
RATIO 3.5 / 1
5 / 1
6.5 / 1
8 / 1
CONDITIONS AT
END OF EXPANSION
CONSTANT VOL FUEL AIR CYCLE
GOODENOUGH & BAKER

FIG. XVII

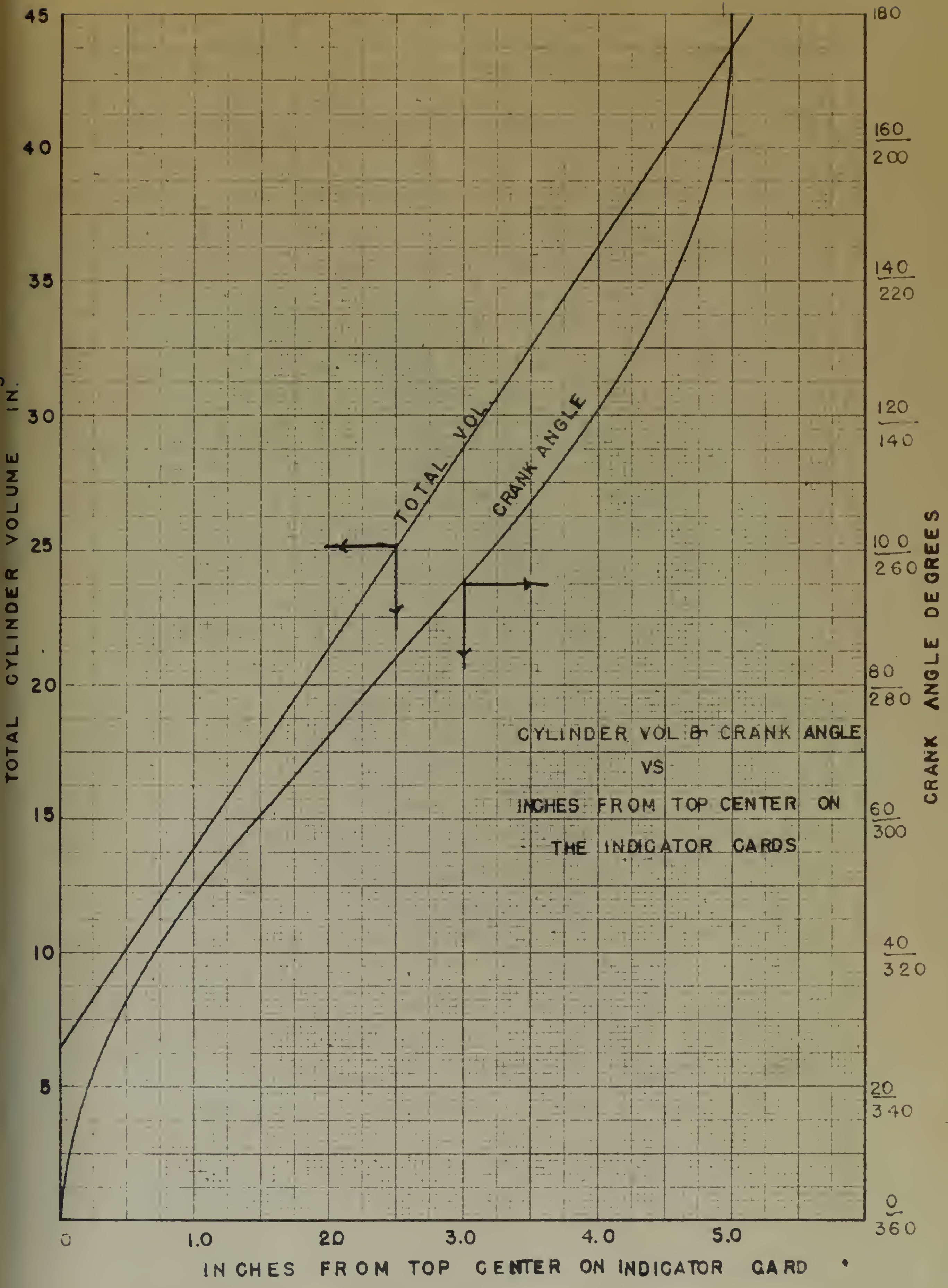
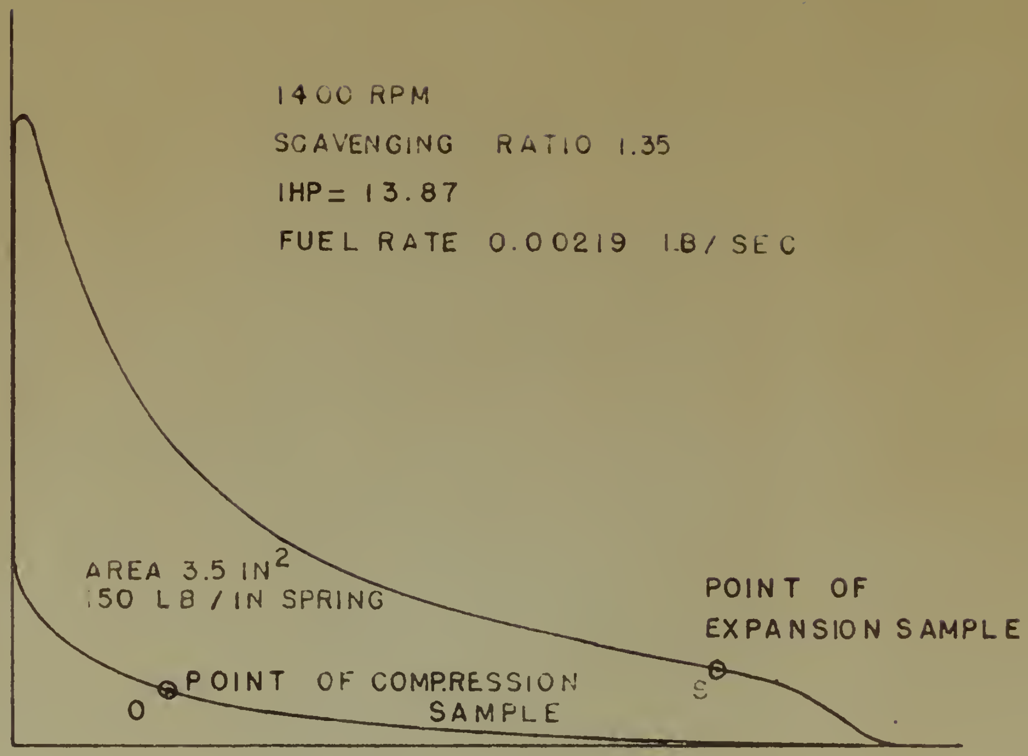

45
40
35
30
25
20
15
10
5
TOTAL CYLINDER VOLUME $IN.^3$
180
160
200
140
220
120
140
100
260
80
280
60
300
40
320
20
340
0
360
CRANK ANGLE DEGREES
TOTAL VOL.
CRANK ANGLE
CYLINDER VOL & CRANK ANGLE
VS
INCHES FROM TOP CENTER ON
THE INDICATOR CARDS
0
1.0
2.0
3.0
4.0
5.0
INCHES FROM TOP CENTER ON INDICATOR CARD

FIG. XVIII

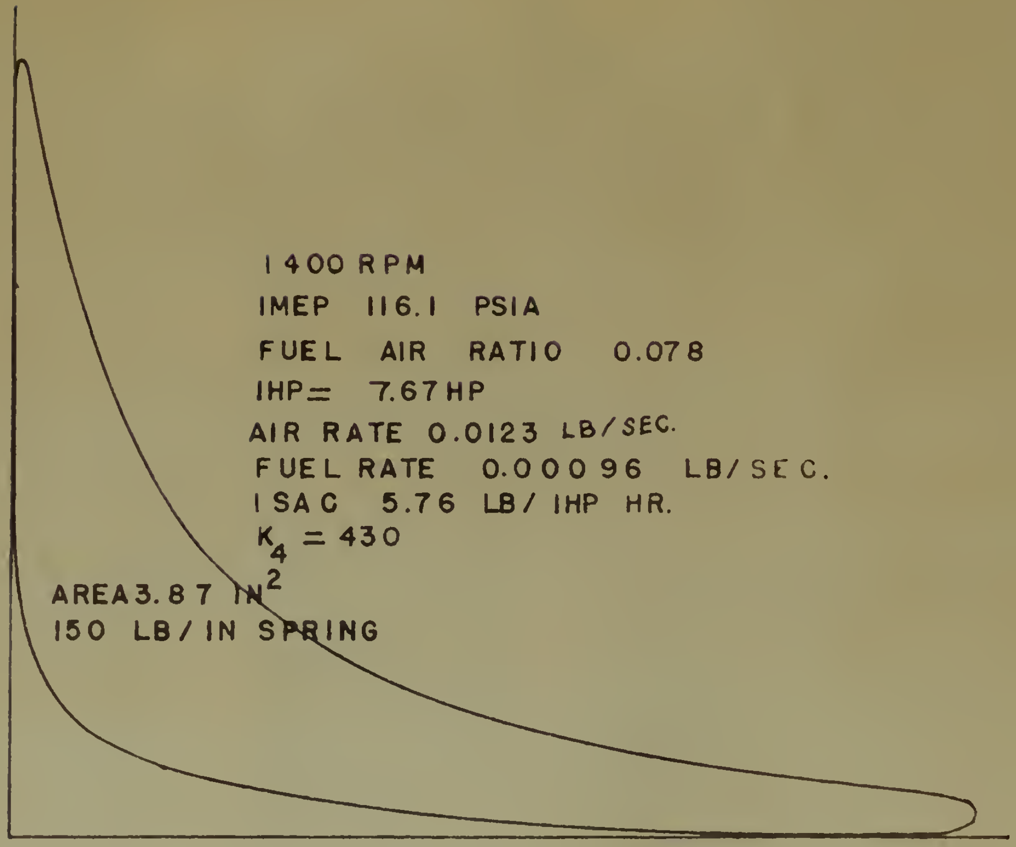
FIG XIX(A) SAMPLING CHECK VALVE (ASSEMBLED)

Fig. XIX (B) Sampling Check Valve (Laid Out)



INDICATOR CARD FOR
TWO STROKE CYCLE

FIG. 20



1400 RPM
IMEP 116.1 PSIA
FUEL AIR RATIO 0.078
IHP= 7.67 HP
AIR RATE 0.0123 LB/SEC.
FUEL RATE 0.00096 LB/SEC.
ISAC 5.76 LB/IHP HR.
$K_4 = 430$
AREA 3.87 IN^2
150 LB/IN SPRING

INDICATOR CARD FOR FOUR STROKE CYCLE

FIG. XXI