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A Study of the MSA Hydrogen Eliminator V to Determine Its Operating Characteristics

by

Franklin S. Thomas

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P. HANNA
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Report
on
A Study of the MSA Hydrogen Eliminator V
to Determine Its Operating Characteristics

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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Work done by
and reported by:

Franklin S. Thomas, Associate Chemist

Reviewed by:

Joseph C. White, Senior Chemist, Chief of Section

P. Borgstrom, Head Chemist, Superintendent, Chemistry Division

Approved by:

H. G. Bowen, Rear Admiral, USN, Director

Distribution: BuShips (15)

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ABSTRACT

The MSA Hydrogen Eliminator V was operated for a total of 367 hours under various conditions at this Laboratory. The thermostat failed near the end of this time but no other depreciation was evident.

Eighteen plates are presented in this report showing the operational characteristics of this equipment and the results to be expected in service.

Suggestions are presented for a method of increasing the capacity of the eliminator for emergency use and for a mode of operation to yield efficient use of the equipment.

An alternative location for the thermostat is suggested for consideration in case the failure of that part is found in service.

[redacted]

I. AUTHORIZATION

This study was authorized by reference (a).

(a) BuShips letter C-SS/S62 (1-29-Mz & Dys) (688) of 31 January 1941.

(b) Coward and Jones, Bureau of Mines, Bulletin 279 (1938), p. 17.

(c) Lewis and Randall, Thermodynamics (1923), p. 478.

(d) NRL letter C-S62-4 of 16 January 1941.

II. STATEMENT OF THE PROBLEM

The problem was to study the MSA Hydrogen Eliminator V to determine its operating characteristics and to establish an experimental basis for oxygen replenishment during its use aboard submarines.

III. KNOWN FACTS BEARING ON THE PROBLEM

Under normal conditions hydrogen forms inflammable mixtures with air when the concentration of the hydrogen is between 4% and 75% by volume (reference b). This fact becomes of importance in relation to submarine operation because hydrogen is produced in the normal operation of the lead-acid storage battery.

The problem here is related to the hydrogen resulting from self-discharge of the battery taking place while the boat is closed. By proper ventilation this gas can be distributed through the atmosphere of the submarine to avoid local points of high concentration. The length of time which any particular boat can remain closed without exceeding the safe limit of hydrogen concentration then depends on the volume of the boat and the rate of hydrogen production. This rate of production is dependent on a number of factors, some of which are: original construction, state of charge, temperature, specific gravity, and age of the battery.

It was found during the last war that in some of the submarines the rate of hydrogen evolution was of such an order that methods for removal were required. At that time the available catalysts were mainly of the platinum group of metals, that is, low temperature catalysts. These could be successfully used for the removal of hydrogen but had the fault that they were readily poisoned by other materials normally present in the submarine atmosphere. At the end of the war the conditions of operation of the submarine were so changed that the removal of hydrogen formed by self-discharge was no longer a problem. The development of a hydrogen eliminator was therefore abandoned.

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Somewhat before the time of the entrance of this nation into the present war one of the steps taken to prepare the submarines for war time service was to raise the specific gravity of the storage battery electrolyte. Closed ship tests carried out after this change showed that the rate of hydrogen production on some of the submarines was of such size that the ships could not remain closed for the time required for normal war time operations.

The problem of developing a practical method for the removal of this excess hydrogen was therefore sent to this laboratory in the latter part of 1940. The known characteristics of a high temperature type of catalyst indicated that it might be suitable for this purpose. This material had not been available at the time of the earlier tests. A hydrogen eliminator was therefore built employing this catalyst as the active material. It was shown in tests aboard a submarine that this apparatus contained a basic solution to the problem. This work was reported at that time (reference c).

The subject equipment, MSA Hydrogen Eliminator V, is a commercial refinement of that original equipment.

IV. THEORETICAL CONSIDERATIONS

A. The Reaction

The fact has been mentioned above that when air contains more than about four percent of hydrogen, the reaction between hydrogen and oxygen may take place in the atmosphere. This reaction will not start spontaneously at any concentration but when the hydrogen-air mixture contains between 4 and 75 percent hydrogen, the presence of an electric spark, flame, or active catalytic surface will start the reaction which will then propagate through the gaseous mixture. When the concentration of hydrogen is outside these limits, the reaction of the hydrogen and oxygen takes place at the spark, flame or active catalytic surface only without propagation.

The reaction which occurs between the hydrogen and oxygen may be written:

$$2\ H_2 + O_2 \longrightarrow 2\ H_2O$$

This means that two molecules of hydrogen combine with one molecule of oxygen to give two molecules of water. Avogadro's rule states that the same number of molecules of different gases will, at the same temperature and pressure, occupy the same volume. Hence, the above reaction also means that two volumes of hydrogen react with one volume of oxygen to give two volumes of gaseous water, when all are at the same temperature and pressure. Since percentages in a particular gas sample are proportional to volumes, the same statement applies when volumes are replaced by percentages. However, the percentage of water vapor formed will be somewhat in error since

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there is some volume change in the system.

This reaction takes place with a large evolution of heat. For each cubic foot (at 0 degrees Centigrade and 762 mm. Hg pressure) of hydrogen which reacts there are 344 BTU's of heat produced. When the hydrogen which reacts is present in an air stream and the heat evolved is not removed, the temperature of the air is increased by about 82 degrees Centigrade for each percent of hydrogen which reacts.

This reaction takes place essentially to completion, reference (c); that is, given sufficient time in the presence of an active catalytic surface with an adequate oxygen supply, the hydrogen reacts almost completely to form water. Conversely, the catalyst in the presence of water vapor will yield no measurable hydrogen and oxygen by decomposition at the temperatures involved in this equipment.

B. The Catalyst

Previous work, reference (d), has shown that the use of a flame or electric spark is unsuited to the problem of hydrogen elimination aboard submarines and that the use of a catalyst to bring about the reaction is the only satisfactory basic method.

The catalyst employed in a hydrogen eliminator should have a high activity, be uneffected by high temperatures, and should not be poisoned by the substances normally found in the atmosphere aboard submarines. A highly active catalyst would be able to bring about the desired reaction to a reasonable degree of completion when the temperature is moderate, the gas concentration is low and the space velocity is of a reasonably high order, that is, the exposure of any particular portion of the gas to the catalyst is of short duration. The property of being uneffected by high temperatures permits the reaction of high concentration gas without the need for temperature control. A high resistance to poisoning substances would make purification of the input gas stream unnecessary.

Various catalyst have been considered for this service and in 1940 experiments were carried out in this laboratory using what was essentially the present catalyst. This catalyst had been developed by the Mine Safety Appliances Co. for another use but appeared to fulfill the requirements for this purpose.

C. The Catalyst Bed

In the design of the eliminator the catalyst bed is the essential unit and the remainder of the equipment is more or less built around it to obtain the required conditions for activity. For a given desired gas flow, the catalyst bed may be varied in two essential dimensions, the frontal area and the thickness. An increase in frontal area or thickness results in a lower space velocity, that

[redacted]

is, longer period of contact between any portion of the gas and the catalyst. This lower space velocity permits the use of lower temperatures to yield the same degree of completion of the reaction. The increase of frontal area decreases the pressure required to achieve a given gas flow rate through the catalyst. On the other hand, the increase of thickness increases the pressure required. An increase in either the frontal area or the thickness increases the quantity of catalyst required to originally fill or to refill the bed. However, this increased amount should permit longer operation under poisoning conditions before a refill is required. The optimum design of the catalyst bed appears to be that having a large frontal area and a medium thickness. This design results in moderate temperature, pressure and catalyst quantity requirements.

D. The Heating System

1. The Heat Interchanger.

The reaction, which is involved here, liberates considerable heat which is mainly removed from the catalyst by the reacted gas. This heat may be partially recovered and used to maintain the desired elevated temperature of the catalyst bed by means of a heat interchanger between the hot reacted gas and the cold input gas. The heat interchanger for this use should be efficient enough to maintain the catalyst at the desiredtemperature without requiring an undue addition of heat. It must be inefficient enough to avoid the occurrence of inordinately high temperatures when the hydrogen concentration input is high. The volume occupied by the heat interchanger must be of a reasonable order.

2. The Electrical Heating Unit.

Since the heat interchanger can only conserve the heat carried by the gas stream, the heat necessary to bring the catalyst to an active state must be supplied by some other source. This is most easily accomplished by the use of an electrical heating unit. This heater may be kept to a minimum size by placing it between the input and output passes of the heat interchanger. Since the catalyst bed is the point at which the highest temperature is desired, the heater should be placed in the gas stream just ahead of the catalyst bed.

3. The Thermostat.

When the heat of reaction is sufficient to maintain the desired temperature, the electric heater can be shut off with resultant use of less electrical energy, production of a smaller heat load and lower maximum temperatures in the catalyst bed and heat interchanger. These desirable results can be attained by the use of a thermostat which will automatically cut off the heater current

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when a predetermined temperature is attained. This thermostat might be located at almost any point in the gas stream after it has passed through a reasonable part of the input pass of the heat interchanger. In the subject eliminator it is located between the electric heating unit and the catalyst bed.

E. The Blower System.

Since the gas must be brought into contact with the catalyst, a unit must be supplied to move the gas. This is accomplished by a small electric motor driving a small multiblade centrifugal fan. This type of device for moving gas is more efficient as a blower than as an exhauster. This blower must be of such size that it will move the gas at the required rate against a back pressure made up of the resistances due to the heat interchanger and the catalyst bed. Since the heat interchanger contains relatively large channels of low resistance, the main part of the blower pressure requirement is fixed by the relation of the dimensions of the catalyst bed to the desired flow rate.

F. The Eliminator.

The various units discussed above have, in the subject apparatus, been built into a single body of cylindrical shape about ten inches in diameter and forty inches in length. The blower is attached to the input end and draws the gas directly from the surrounding atmosphere. This gas is pushed into the end of the eliminator body where it enters the input side of the heat interchanger. The hot gas leaves the heat interchanger, passes over the electric heating coil, the thermostat element, and into the catalyst bed. The hydrogen in the input gas reacts at this point and the hot reacted gas passes to the exhaust side of the heat interchanger. The exhaust gas, cooled by its passage through the heat interchanger, passes out the end of the eliminator opposite the input end.

The eliminator, as it is delivered to the service, may be put into operation by merely attaching an electric lead of 25 amperes capacity to a 125 volt A.C. source. However, this simple setup is desirable only under the most temporary conditions. Since the intake and exhaust ports are separated by only the length of the eliminator body, there is the possibility of more or less recirculation of reacted gas unless the place in which the eliminator is set up is very strongly ventilated. This chance of recirculation can be decreased by the use of a reasonable length of duct on either the intake or exhaust port. Since, normally, the greatest amount of hydrogen to be eliminated will occur when the heat load on the air conditioning system is already high, it would be desirable to pass the hot exhaust gas through some type of heat interchanger, such as an outboard fore and aft ventilating duct, which will allow most of the heat to be interchanged to the surrounding sea water. This interchange would also serve to condense out most of the excess water

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vapor from the exhaust gas before it enters the hull proper.

V. EXPERIMENTAL WORK

A. The Elminator Test Set-up.

1. The Eliminator.

The eliminator was, as received, complete and ready for operation. The subject apparatus was first examined as to construction and operational features. The catalyst was emptied from the catalyst bed and was found to weigh about eight pounds. About two pounds of catalyst was also included in a sack for replenishment use. The catalyst from the bed was packed back into its proper place.

2. Added Equipment for Test Purposes.

(a) Electrical feed system.

The electrical supply for the eliminator was drawn from a 230 volt, 60 cycle A.C. line. A variable transformer was installed to drop this voltage to the desired operating voltage and to permit the use of various voltages to determine the effect of this variable. An accurate voltmeter and ammeter were connected in the circuit to give a measure of the electrical requirements of the eliminator.

In the performance of some preliminary work it was found that the decreased current drawn when the heater was turned off due to thermostat action resulted in an increase of about six volts in the voltage at the eliminator. An adjustable resistance of about fourteen ohms, maximum, was put into one side of the electrical feeder between the transformer and the voltmeter. A magnetic contactor was connected across this resistance so that when the contactor was closed the resistance was shorted out of the circuit. The contactor was in turn controlled indirectly by the thermostat of the eliminator. This setup, when the heater was turned off, placed a resistance in the circuit to absorb the voltage increment.

(b) Temperature measurement system.

The temperatures attained in the inside of the eliminator were measured by means of single junction chromel-alumel thermocouples. One thermocouple was located at the center of the catalyst bed. Another was about a half inch from the bottom edge of the catalyst bed. A third was in the center of the hot reacted gas stream and slightly removed from the catalyst bed. The temperature rise of the gas stream

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was measured by a thermocouple with the hot junction in the exhaust gas and the cold junction in the input gas both located at the ports. These four potentials, and hence, indirectly, the temperatures, were recorded continuously during operation by a six-point potentiometer recorder. The connection of one of these to the recorder was so made that a fifth thermocouple located in the input stream could be manually switched in, in its place. This gave a record of the input gas temperature when desired.

(c) Gas Flow Equipment

The eliminator was so set up that by attaching a two-foot length of four-inch duct to the exhaust, the hot reacted gas was emptied into a fume hood. This avoided any possibility of re-circulation of partially reacted gas.

In order to measure the amount of input gas it appeared best to add a five-foot length of three-inch sheet iron pipe to the intake port. The impact end of a combined pitot-static tube was centered about forty-six inches from the intake end. The dimensions of this pipe were so selected that the gas stream should be free of "end effects" in the zone of the measuring tube. The effect of the air flow on the pitot-static tube was recorded on a zero to one-inch (water) pressure recorder.

The theoretical pressure drop in this added duct work can be calculated as less than 0.05 inches of water at fifty CFM (cubic feet per minute) of gas flow. Since this blower develops a pressure of about 2.5 inches of water, the addition of the pipe should cause only a very small change in gas flow. This was experimentally shown to be true by operating the eliminator at a constant voltage both with and without the duct work. The electrical energy which was put in appears as a temperature rise in the gas and is hence a measure of gas flow. There was no measurable difference in the gas temperature rise between operation with and without the duct.

To obtain hydrogen containing gas for use in the tests of the eliminator, hydrogen was drawn from compressed gas cylinders. The pressure was first dropped by the use of a reducing valve and the flow rate adjusted by a needle valve. The flow rate was manually maintained constant from the indications of a flowmeter in the hydrogen supply system. The actual measure of flow rate was, however, obtained by timing, with a stop watch over a suitable period, the passage of several cubic feet of the hydrogen through a calibrated, displacement type, dry test meter.

Since this hydrogen stream was independent of the action of the eliminator, the possibility existed that any sudden change in the electrical feed to the eliminator or in the mechanism of the eliminator might result in explosive concentrations being attained. A suitable safety system was therefore installed so that a small decrease in either the gas flow rate or the electrical voltage applied to the eliminator would instantaneously and automatically shut off the flow of hydrogen. This system was so designed that when tripped it would not automatically reset.

For one part of these tests it was necessary to admit rather large amounts of nitrogen or carbon dioxide as part of the gas stream. A detachable tee was, for this test, put onto the end of the input duct. The added gas was drawn from compressed gas cylinders, metered roughly by a flowmeter and admitted to the input gas stream from the side arm of the tee.

(d) Gas analysis system.

The hydrogen concentration in the input and exhaust gas streams was determined continuously by the use of thermal conductivity gas analysis. The input gas was sampled between the blower and heat interchanger and the exhaust gas at the eliminator exhaust port. The results of these analyses were recorded as millivoltage, and thus, indirectly, as percent hydrogen on two points of the six-point potentiometer recorder mentioned above. The calibration of the conductivity cells was obtained by the use of samples in which the concentration was determined by slow combustion in an Orsat outfit.

For the experiments with added carbon dioxide, the analysis for that gas was carried out manually on samples of the exhaust gas.

For the experiments with low oxygen, that is, added nitrogen, the analysis was carried out on samples from both the input and the exhaust gas streams. The oxygen values were determined by methods of known accuracy.

(e) Thermostat indicator.

To make the thermostat action available for study a self-starting electric clock was attached across the terminals of the thermostat. This clock would run only when the heater was turned off and totalized the time during which the electric heater was off. As a further aid to this study a recording electric current meter was attached to the eliminator circuit. This gave a record of the thermostat action.

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(f) Auxiliary blower.

For an experiment involving higher flow rates than those normally available, a small laboratory blower was attached temporarily so that its output fed directly into the intake end of the input duct. This blower was in position only during tests involving its use.

B. Tests Carried Out.

1. Normal Operation

The normal operation tests were those made without the use of the thermostat and those with the thermostat and voltage stabilizer. These tests yield the most simple results and will therefore be taken up first in this report. The tests without the use of the thermostat were actually performed near the end of the experiments since it was unknown at that time what effect this type of operation might have on the lower temperature operation of the catalyst which results when the thermostat is used. For these tests the eliminator was started at the desired voltage with no hydrogen admitted. When the temperatures in the eliminator were approaching equilibrium, hydrogen was admitted and its concentration brought to the desired value. After a period of time the entire system came to equilibrium and the various temperatures, flow rates, concentrations, and electrical readings were recorded.

2. Operation Without the Voltage Stabilizer.

Only a little work was done under this condition. It was felt that this operation was not standard and its only value was in a comparison to operation with the voltage stabilizer as indicative of the effect of load line loss. The method of test was the same as in the preceding paragraph and essentially the same data were recorded.

3. Low Oxygen or High Carbon Dioxide Concentration.

Tests were carried out in which, after the eliminator had come to equilibrium with the desired hydrogen concentration in the input, sufficient nitrogen or carbon dioxide was added to the input gas stream to yield the desired concentration of the added gas. Most of these tests were carried out without the use of the thermostat since this condition is less complex and would show the result of the variable introduced more readily.

4. Tests at High Flow Rate.

The possibility exists that the need for a larger hydrogen elimination capacity might arise under conditions when an additional unit could not be obtained or installed. The operation of the eliminator at higher rates than normal was therefore tested. For this pur-

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pose an extra blower was attached to the intake end of the input duct. These tests were all carried out without the use of the thermostat because it had failed prior to that time.

5. Tests on Operating Characteristics.

Several tests were made in which the eliminator, operating without the thermostat, and the hydrogen flow were started almost simultaneously. The lengths of time were determined which were required after the eliminator was turned on for the reaction to start, to become 90% efficient, and to become 100% efficient. Blank tests in which the eliminator heater was not turned on were used to determine the lag in the analysis system. A rough check on the time required to start the reaction was obtained from the recorded temperatures in the eliminator.

VI. DISCUSSION OF DATA AND RESULTS

The data obtained in these eliminator tests are mainly contained in the plates appended. Plates 1 to 12, inclusive, are for normal conditions of operation of the eliminator. Plates 13 to 15, inclusive, cover the higher than normal gas flow rate experiment. Plates 16 to 18, inclusive, give some information on the time required for the eliminator to start the reaction under high hydrogen percent input.

A. Normal Operation

Plates 1 and 2 show the consumption of hydrogen by the eliminator when operating with and without the thermostat at four voltages. Hydrogen consumption is used here to mean the amount actually converted to water in the eliminator. These plates also show the amount of oxygen required for replenishment purposes since the oxygen requirement is exactly one-half of the hydrogen consumption. Therefore, at any point on these curves the oxygen which would be required was equal to the value of the hydrogen consumption for that point divided by two.

These graphs clearly show that an increase of voltage increases the hydrogen consumption. This increase is the difference between two apparent effects resulting from the increase of voltage. The speed of the motor which drives the blower rotor increases as the voltage increases. One measurement of this speed gave the following figures:

Voltage	R.P.M.	Relative Pressure	Relative Capacity	Actual Consumption
100	4250	1.00	1.00	1.00
110	4730	1.24	1.11	1.08
120	5150	1.47	1.21	1.18
130	5630	1.69	1.30	1.27

[redacted]

The relative pressure figures were obtained by the use of one of the fan laws which states that the pressure produced by a blower is proportional to the square of the fan speed when other variables are constant. This increase in pressure should result in an increased gas flow. If the assumption is made that the resistance opposing the flow of gas here has the characteristics of an orifice in which the volume passed is proportional to the square root of the pressure drop, the relative capacity column above should apply. The agreement between the calculated values and the actual consumption values, which are relative figures taken from the values of Plate 1 at 3% hydrogen, indicates that the main part of the increased hydrogen consumption at increased voltage is due to the increased speed of the blower. There also results, however, from the increased voltage, higher temperatures in the eliminator as shown in Plates 7, 10, 11, and 12. This effect of increased temperatures is evident in Plate 4, in which the volume of hydrogen input is plotted against the percent of hydrogen in the input gas. The curves for operations with and without the thermostat should coincide in the graph if there were no effect due to increased temperatures. The fact that operation with the thermostat, which yields lower temperatures, results in higher gas flows means, conversely, here that the increased temperatures should result in decreased gas flow. This, possibly, is due to expansion of the catalyst which somewhat reduces the sizes of the irregular gas passage spaces between the granules. Quite possibly there are other causes which have more or less effect here but which are not apparent from the results of these tests.

Plate 1 also shows, when compared to Plate 4, that the hydrogen consumption drops appreciably below the hydrogen input when the hydrogen concentration in the input is low. This fact is brought out in Plate 5 which shows the eliminator efficiency.

In Plate 1 the fact that the lines of these plots are curves must be at least partly a result of the temperature effect which acts to reduce the total gas flow. Another factor here results from the decreased gas density which reduces the pressure produced by the blower, and hence the total gas flow. This effect is probably small.

Plate 2 shows the effect of the thermostat on the hydrogen consumption. As previously mentioned, the immediate effect of the thermostat is to reduce the eliminator operating temperatures at high hydrogen concentrations. These decreased temperatures then result in greater gas flow and thus increased consumption, as shown in this plate. It should be mentioned that the decreased temperatures also result in a slightly reduced efficiency, as shown in Plate 5, but this effect is overbalanced by the increased gas flow.

The efficiency curves plotted in Plate 5 should not be considered as highly accurate. The data shown here are obtained from a difference between two gas analyses, one of the input gas

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and the other of the exhaust gas. At low percent hydrogen input these values are small so that even a small error in the analysis may introduce disproportionate error as zero percent hydrogen input is approached. The general shape of the curve obtained in Plate 5, Drawing 3, is, however, hardly open to question and the others must be essentially the same in shape. This markedly low efficiency at low hydrogen percentage is also shown by the temperature-percent hydrogen plates, especially Drawing 3 in each of the Plates 7, 10, and 11. The fact that these curves start off from zero hydrogen percent with a portion having a low slope indicates that the hydrogen mostly passes through the eliminator without reacting at these low concentrations.

One further point is of importance relative to Plate 5. It was found in some of the operations at low percent hydrogen input that the eliminator showed a marked instability. This condition was apparent in the temperature measurements and the gas analysis of the exhaust gas. The records of these resembled sine curves in opposite phase. The shape of the efficiency curve indicates that in the region of low hydrogen percent input, the efficiency changes to a large extent, with a very small change in the hydrogen percent input. In this region, therefore, the normally negligible changes in the input hydrogen percent result in greatly amplified changes in the temperature and hydrogen percent output curves due to this change in efficiency.

The data for total gas flow plotted in Plate 6 were obtained by use of the previously mentioned input tube, pitot-static tube, and 0 to 1 inch (water) pressure recorder. This setup does not permit the precision which would be desirable for this measurement but was the best readily available and yielded values which were at least indicative of the actual flow rate. The pressure difference produced by the pitot-static tube for measurement at these flow rates is quite small reaching a maximum value of 0.17 inches of water at 130 volts with no hydrogen in the input. There were available more accurate methods of measurement of these flow rates, but they could not be used, either because they would upset the flow being measured or the degree of stability required was not available here.

The results plotted in Plate 7 show the approach to a straight line relation between the increase in temperature of the reacted gas and the hydrogen percent input. These curves would be more nearly straight if they were plotted as temperature rise against percent hydrogen consumed. This plate, therefore, shows that the temperature rise when operating without the thermostat could be used as a fair measure of hydrogen percent input, or, more accurately, as a measure of hydrogen percent consumed. When, however, the thermostat is used, the values depend on both the hydrogen percent consumed and the electrical energy supplied to the heater.

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It is desirable that the energy consumption of the eliminator be retained at as low a level as possible. Plate 8 shows the energy consumption of the eliminator, both with and without the thermostat. The saving of energy resulting from the use of the thermostat is apparent. The energy consumption is shown in another form in Plate 9. In this plate the energy efficiency is plotted for normal operation. The saving of energy resulting from the use of the thermostat is apparent here as is the inefficiency of the eliminator at low hydrogen percent input.

Plates 10, 11, and 12 show that the temperature attained in the eliminator when operating at 3% hydrogen input may be as high as 550° C, which is a dull red heat. It is of interest to note that hydrogen will react with oxygen on any surface at about this temperature irrespective of the normally considered catalytic character of the surface.

B. Operation Without the Voltage Stabilizer.

The results obtained with this method of operation are not presented as plates since they are closely approximate to the results obtained with the voltage stabilizer. The main difference, in general, results from the fact that the voltage change resulting from the thermostat action caused a change in the total gas flow rate. A variable hydrogen percent input was therefore produced since the hydrogen was introduced at a constant rate. This changing hydrogen percent input resulted in corresponding changes in the other data recorded. The average of these variable values for temperatures, gas flow, hydrogen percent input and electrical energy input are all slightly larger at high hydrogen percent input than the corresponding values for operation with the voltage stabilizer. These differences are small and rendered uncertain by their oscillating character so that they are not considered to be of particular value.

C. Low Oxygen or High Carbon Dioxide Concentration.

The effect of a low oxygen concentration in the input gas was experimentally determined by the addition of cylinder nitrogen to the air input. The figures for the actual gas streams used were: 20.7% oxygen in the air, 19.9% in the input gas containing hydrogen and 16.4% in the input gas containing hydrogen and added nitrogen. To make any effect of the low oxygen concentration readily apparent the eliminator was brought to equilibrium on a hydrogen and air mixture and then part of the air stream was replaced by admitting nitrogen. No significant changes in the eliminator operation resulted from the low oxygen concentration employed.

The effect of a high carbon dioxide concentration was also determined in a manner exactly similar to that used in the

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experiment on low oxygen content above. One of the four tests was carried out during the test of low oxygen concentration and the other three as one each on 1, 2, and 3% hydrogen input. Concentrations of carbon dioxide between 3 and 4% were used. The net result was a decrease of between 2 and 3% in the total gas flow rate with a slight reduction in the temperatures recorded.

D. Tests at High Flow Rate.

The results of tests carried out at high flow rate are contained in Plates 13 to 15, inclusive. These high flow rates were obtained by attaching the output opening of a laboratory blower to the intake end of the input tube. This blower supplied about 1.6 inches of water pressure measured at the intake to the eliminator blower.

Plate 13, Drawing 1, shows the increased consumption of hydrogen attained by use of the extra blower. No test for operation with the thermostat was included. This was because the thermostat had failed before these tests were carried out.

The results contained on Plate 14, Drawing 3, and Plate 15, Drawings 1 and 2, are of the most interest in this test since they show that the increased flow rate has resulted in lower temperatures inside the eliminator except that of the reacted gas at high hydrogen percent input. The significance of this lies in the fact that the eliminator may be overloaded by the application of an auxiliary blower without expecting early failure due to this cause.

E. Tests on Starting Characteristics.

In order to use this eliminator efficiently some knowledge is necessary of the time required after the eliminator is turned on before it becomes effective for the removal of hydrogen. Two tests were carried out to determine this time.

The data obtained from one of these tests are shown in Plate 17, Drawing 1, and Plate 18, Drawing 1. Plate 17, Drawing 1, shows that the reading of the percent hydrogen in the exhaust gas reached a maximum at 3 minutes, had dropped to a reading of 10% of that maximum value at 7.3 minutes, and at the end of 10 minutes a zero reading was obtained. When the lag of the analysis system, as shown in Plate 16, Drawings 1 and 2, is taken into account, the maximum hydrogen concentration was found after about 1 minute, 90% of the hydrogen was being reacted at the end of about 5 minutes and the hydrogen was being completely reacted by the end of about 7 minutes. Plate 18, Drawing 1, shows a sharp break at 2.8 minutes which indicates that the reaction had started to occur at or before that time. The hydrogen percent input was about 1.45 when the reaction started. The increase in the hydrogen percent input after that time was due to the constant hydrogen flow rate used and the decreasing

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total gas flow rate resulting from the increasing temperatures.

A similar test was carried out at a higher hydrogen concentration. The data contained in Plate 17, Drawing 2, show a maximum reading for output hydrogen at 2.9 minutes, 10% of that maximum value at 5.5 minutes, and a zero reading on or before 6.5 minutes. Taking into account the data of Plate 16, Drawings 1 and 2, these values become respectively 1 minute, 3.4 minutes and 4 minutes. Plate 18, Drawing 2, shows that the reaction had started on or before the end of 2.7 minutes. The percent hydrogen input at the time when the reaction started was approximately 2.25.

It is of value to note also that the total gas flow at the time of the start of reaction was about 70 CFM in each case compared to the equilibrium values of 61 CFM and 54 CFM for the two experiments respectively.

F. General Results.

The eliminator was operated for a total of 367 hours during these tests. About 7500 cubic feet of hydrogen were used. This gives an average hydrogen input for the entire period of test of about 0.37 of a cubic foot per minute. From Plate 4 it is seen that this corresponds to operation at about 0.55 percent hydrogen input. A weighted average was also obtained in which the operation at high hydrogen percent was assigned a proportionately greater value. This weighted average gave a value of about 1% hydrogen. The hydrogen percent input was carried as high as 3.6 with the thermostat and 3.5 without the thermostat, without apparently affecting the catalyst for further low percentage use.

Somewhat before 350 hours of operation the thermostat failed. The active element of this thermostat is made of copper tubing with, apparently, a protective plate of some other metal. The tubing of this element at the point of failure had the appearance of having undergone oxidation completely through the metal wall.

Twice during the period of the tests it was necessary to add catalyst to keep the catalyst bed completely filled. This slumping took place despite a careful packing at the time it was placed in the eliminator. It was found that the catalyst tends to bridge across the filling opening, especially when the bed is nearly full, and thus leave void spaces. It appeared from this that a special effort must be made to check the catalyst bed frequently and to pack the catalyst into the less accessible parts of the bed by using a screw driver or other similar tool during the last part of the filling operation.

VII. CONCLUSIONS AND RECOMMENDATIONS

The MSA Hydrogen Eliminator V appears to be a simple and effective method of removing excess hydrogen aboard submarines. Its

[redacted]

design appears satisfactory from the theoretical considerations outlined in section IV.

The rated capacity of this equipment is 30 CFM of gas mixture at all percentages of hydrogen input. The above data, however, show that its actual capacity is between about 42 and 75 CFM depending mainly on the voltage, percent hydrogen input, and whether the thermostat is being used. The data contained in Plate 3 may be used to obtain an approximate figure for the hydrogen consumption under any set of normal conditions. It must be remembered in using these values that they were obtained on a single sample of the eliminator operating without any essential outside interfering effects. If any appreciable change is made in the conditions under which the eliminator was set up and run in these tests, then the data obtained here can not be applied.

It probably would be possible, for use where the conditions under which the eliminator is to operate are either variable or different from the normal here, to develop enough measuring equipment to permit the determination of hydrogen consumption during actual use. This measuring equipment would comprise two parts; one to measure the gas flow and the other to measure hydrogen percent consumed. A venturi tube or orifice plate could be applied to the intake port and equipped with a pressure measuring device directly calibrated as total gas flow. A differential temperature measurement between the input gas and the exhaust gas would, when corrected for temperature rise due to the electric heater, give a direct measure of the hydrogen percent consumed. The product, then, of the total gas flow and the percent hydrogen consumed would give the rate of hydrogen consumption at the time of measurement. This measuring equipment would, of course, be unnecessary if a suitable method for the determination of oxygen concentration were available for use aboard submarines.

The results obtained with the high flow rate indicate that in case of necessity an auxiliary blower could be attached to the intake port to increase the flow rate and hence the hydrogen consumption, without causing damage to the eliminator. It should be remarked relative to this method of obtaining increased capacity that the flow rate increases approximately as the square root of the increase in pressure head employed. Therefore, a large increase in flow rate can only be expected when a proportionately much higher pressure head is available.

There is, also, a method by which it might be possible to obtain higher flow rates without the use of a higher pressure blower. This method would be to increase the particle size of the catalyst employed. This would result in larger flow but would undoubtedly decrease the efficiency at low hydrogen percent input and possibly even at high hydrogen percent input. However, the increase in flow rate probably would more than overbalance the loss in efficiency and yield an increase in the hydrogen consumption rate at high percentages.

[redacted]

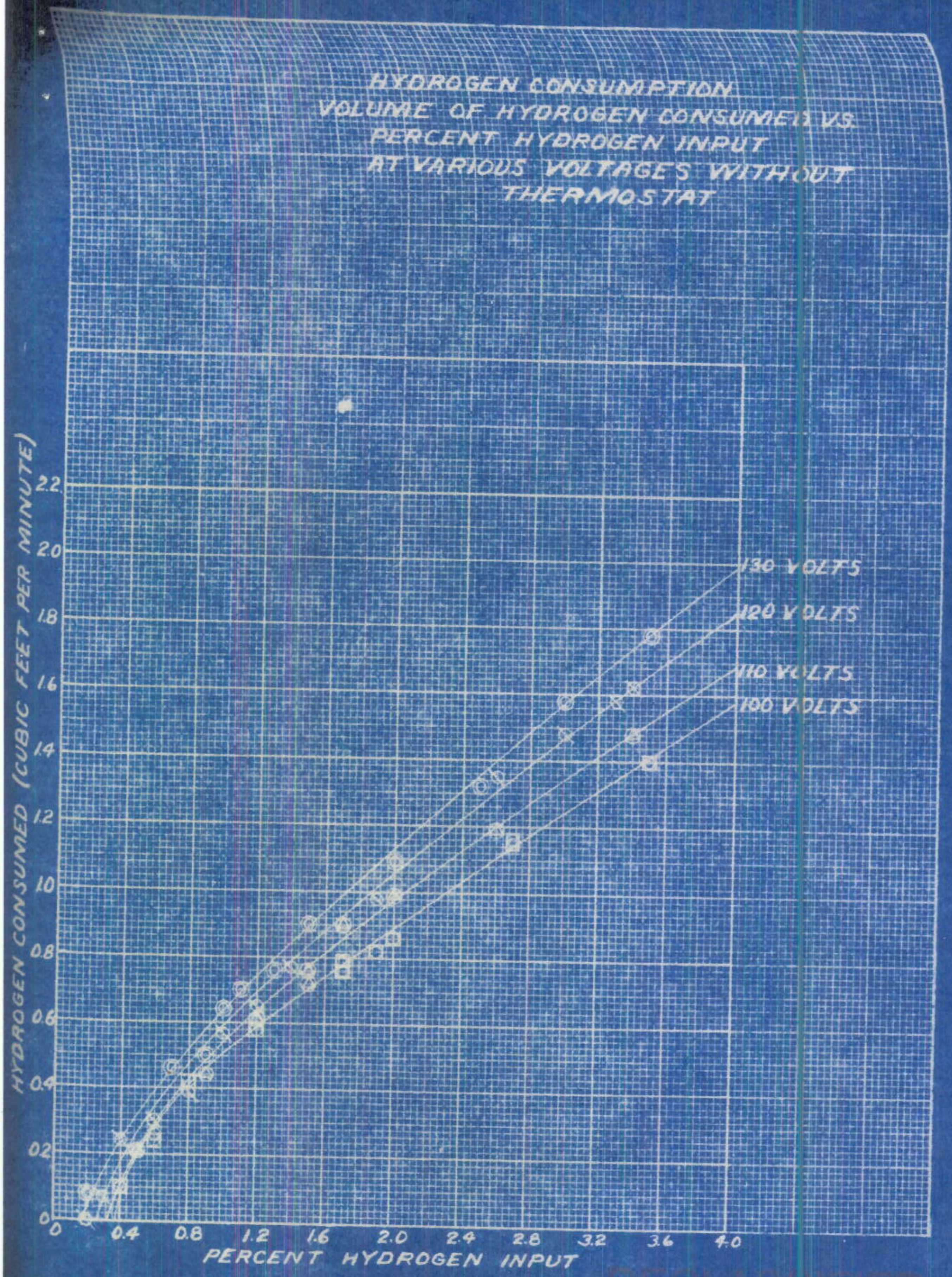
Where the full capacity of the eliminator is not required or where one eliminator cannot handle the entire hydrogen evolution and a second one provides more than the needed capacity, a material saving in the electrical energy consumption and heat output could be achieved by intermittent operation of the eliminator. By this mode of operation the eliminator would not be started when the submarine was closed for the dive but instead would be turned on when some appreciable percent, such as 2%, of hydrogen had been reached. The experiments on the starting characteristics of the eliminator reported above show that the eliminator will attain its full operating efficiency in a very few minutes after starting. In fact, since the eliminator is at low temperatures for some time after being turned on, the flow will be higher than normal at the start and gradually drop to the equilibrium value. This would partially compensate for the delay in starting the eliminator. The eliminator would then be operated until the hydrogen content of the atmosphere had dropped to 1.5% or until the boat could be ventilated outboard. This cyclic or intermittent method of operation has several advantages. The eliminator is not operated at low percentages of hydrogen where it is inefficient in hydrogen consumption and where the electrical energy requirement is high but instead is operated at high hydrogen concentrations where the reaction furnishes most of the energy required and the hydrogen consumption is high. The energy efficiency of this method of operation is obvious from Plate 9.

The failure of the thermostat which occurred in this eliminator will possibly be found to also occur in the service use. This failure may have been the result of the severe testing conditions employed here or to an imperfect protective coating or to other unknown causes. However, if the thermostats show failure under service conditions, consideration should be given to the possibility of moving the thermostat from its present location to some point of lower operating temperature and, preferably, some point in the exhaust gas stream. A location just before the exhaust port with a setting of 100° to 150° C might yield satisfactory results. This move, of course, would completely upset the present reported data for eliminator operation with the thermostat.

The length of time the eliminator will operate under service conditions before the catalyst will become ineffective due to poisoning is unpredictable from laboratory tests and will probably be found to be extremely variable if it occurs at all.

The effect of a low oxygen concentration in the input gas has been found to be negligible. High carbon dioxide concentration in the input gas has been found to have a small effect on the eliminator which is probably inappreciable compared to the effect of other variables.

[redacted]



HYDROGEN CONSUMPTION
VOLUME OF HYDROGEN CONSUMED VS.
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES WITHOUT
THERMOSTAT

PLATE I

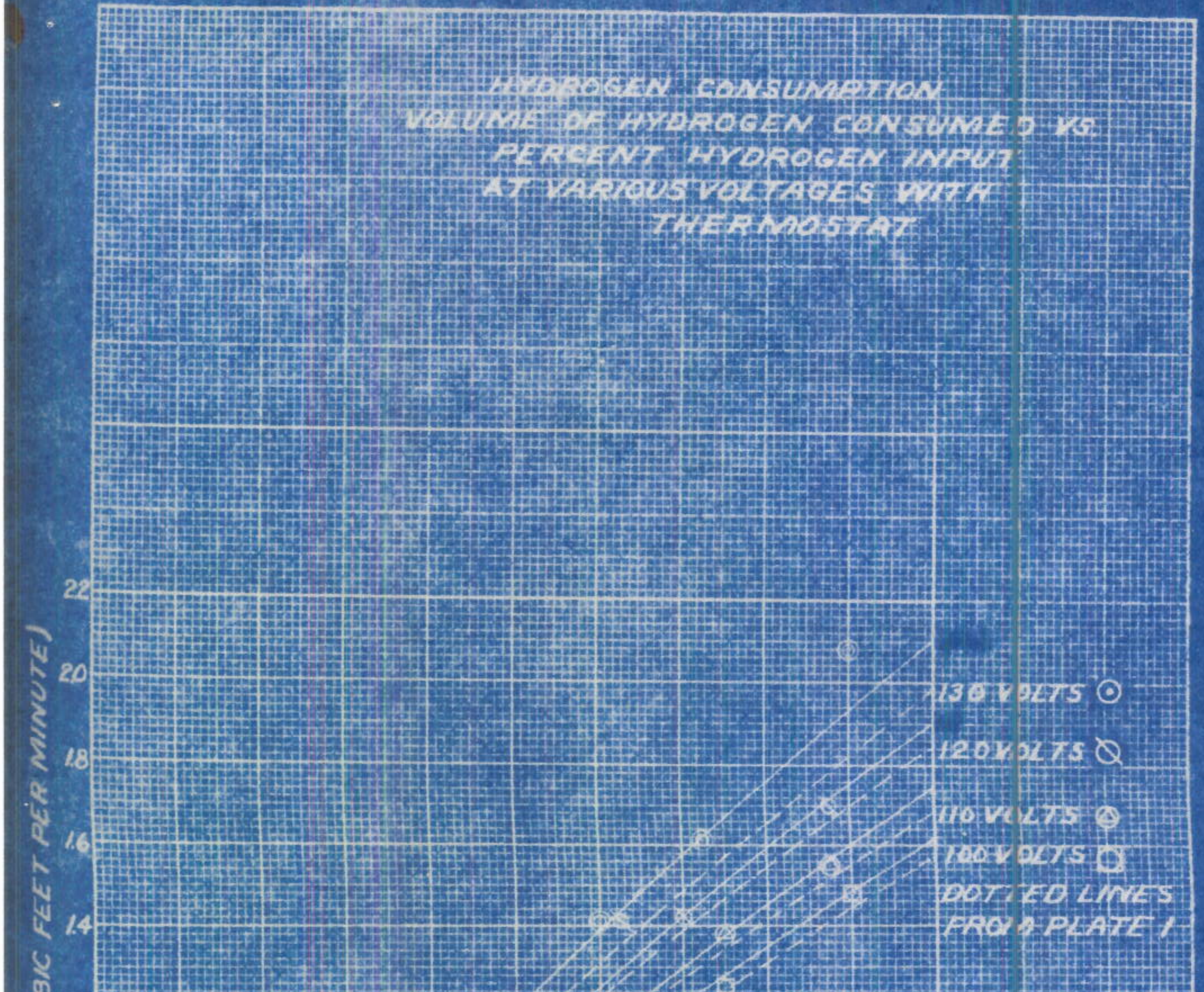

HYDROGEN CONSUMPTION
VOLUME OF HYDROGEN CONSUMED VS.
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES WITH
THERMOSTAT
130 VOLTS ⊙
120 VOLTS ⌀
110 VOLTS ⊛
100 VOLTS ▣
DOTTED LINES
FROM PLATE 1
HYDROGEN CONSUMED (CUBIC FEET PER MINUTE)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
PERCENT HYDROGEN INPUT

PLATE 2

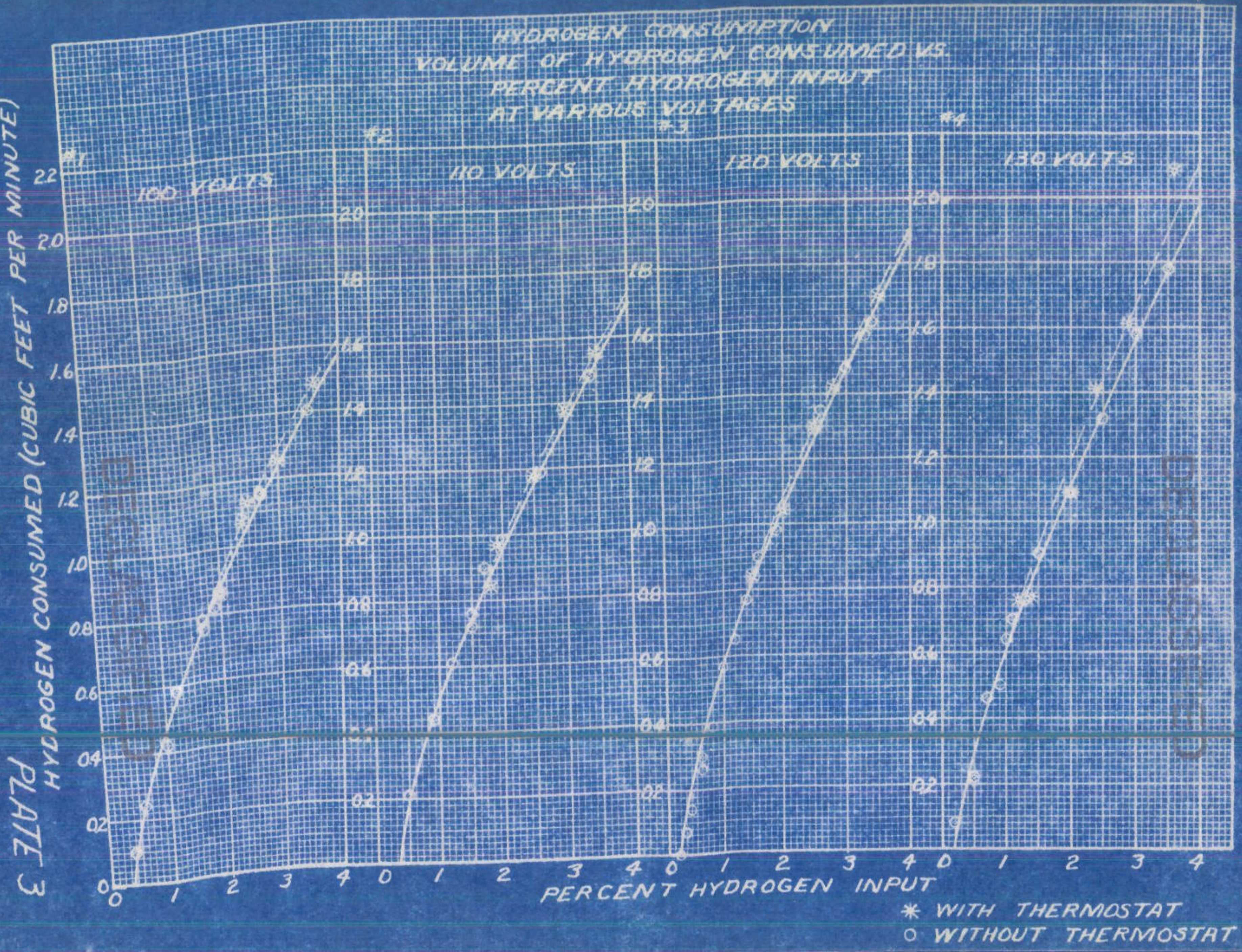

HYDROGEN CONSUMPTION
VOLUME OF HYDROGEN CONSUMED VS.
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES
#1
100 VOLTS
#2
110 VOLTS
#3
120 VOLTS
#4
130 VOLTS
HYDROGEN CONSUMED (CUBIC FEET PER MINUTE)
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
0 1 2 3 4
PERCENT HYDROGEN INPUT
✳ WITH THERMOSTAT
○ WITHOUT THERMOSTAT

PLATE 3

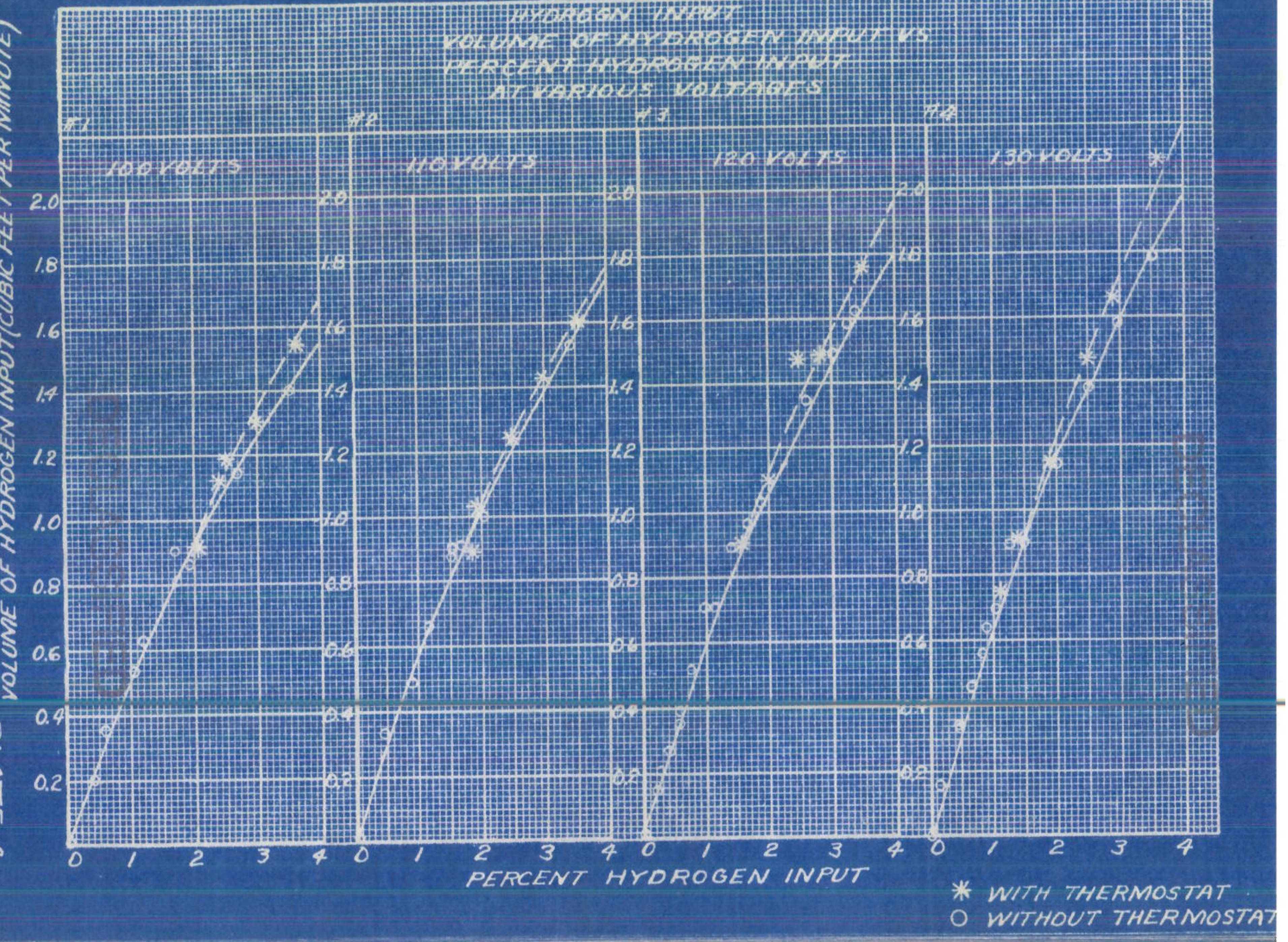
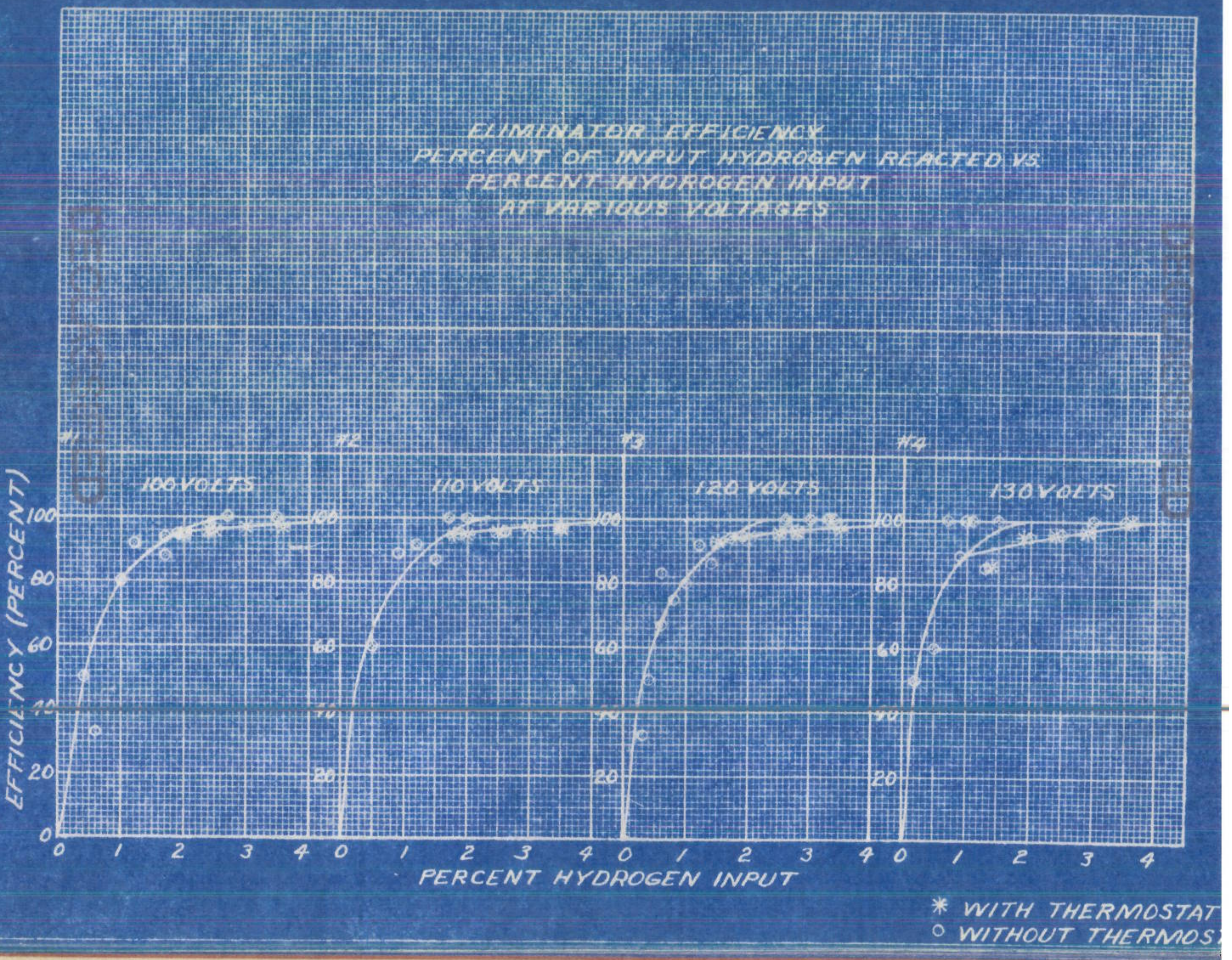

HYDROGEN INPUT
VOLUME OF HYDROGEN INPUT VS
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES
#1
100 VOLTS
#2
110 VOLTS
#3
120 VOLTS
#4
130 VOLTS
VOLUME OF HYDROGEN INPUT (CUBIC FEET PER MINUTE)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
1
2
3
4
PERCENT HYDROGEN INPUT
✱ WITH THERMOSTAT
○ WITHOUT THERMOSTAT

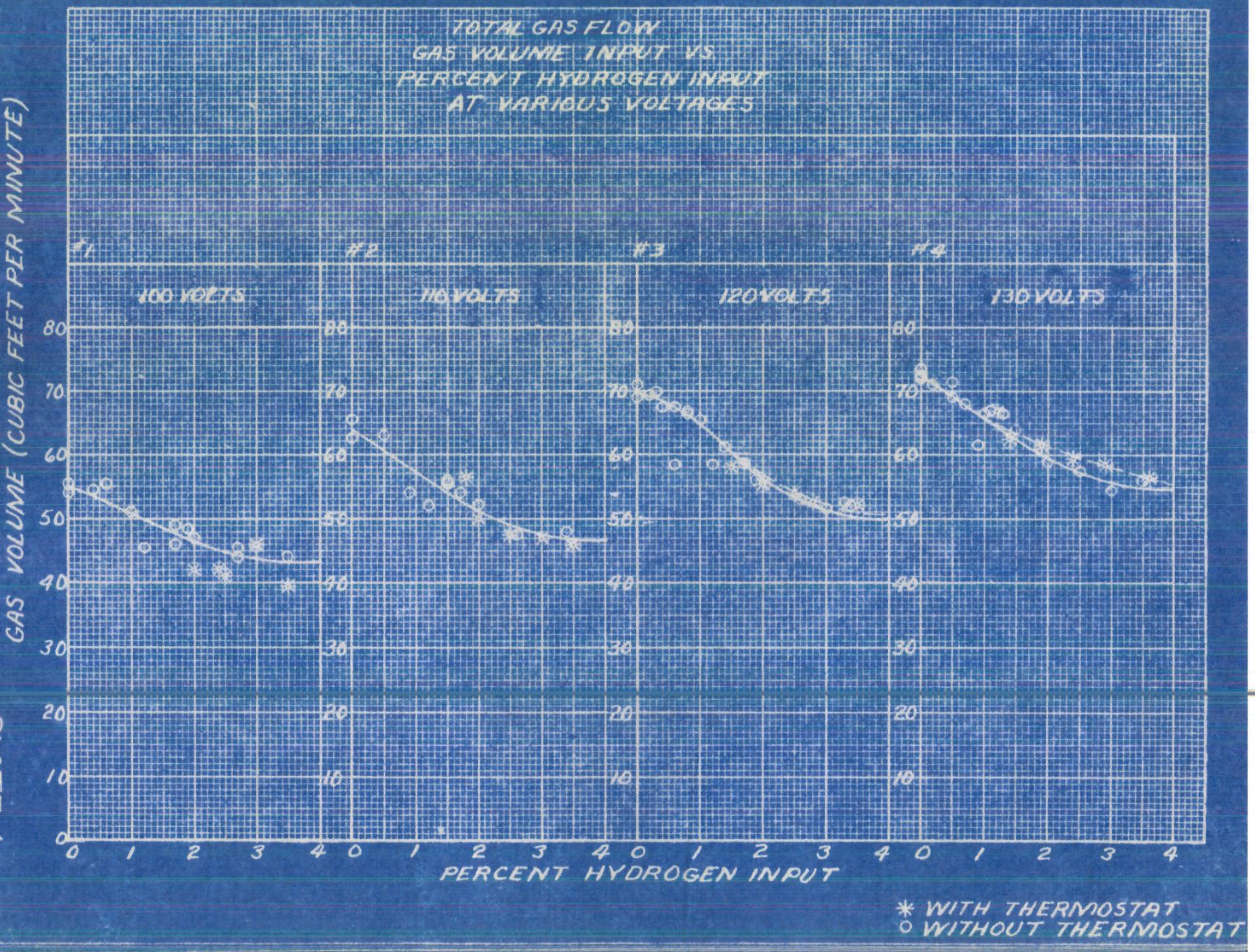
PLATE 4



ELIMINATOR EFFICIENCY
PERCENT OF INPUT HYDROGEN REACTED VS.
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES

PLATE 5

PLATE 6



TOTAL GAS FLOW
GAS VOLUME INPUT VS
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES

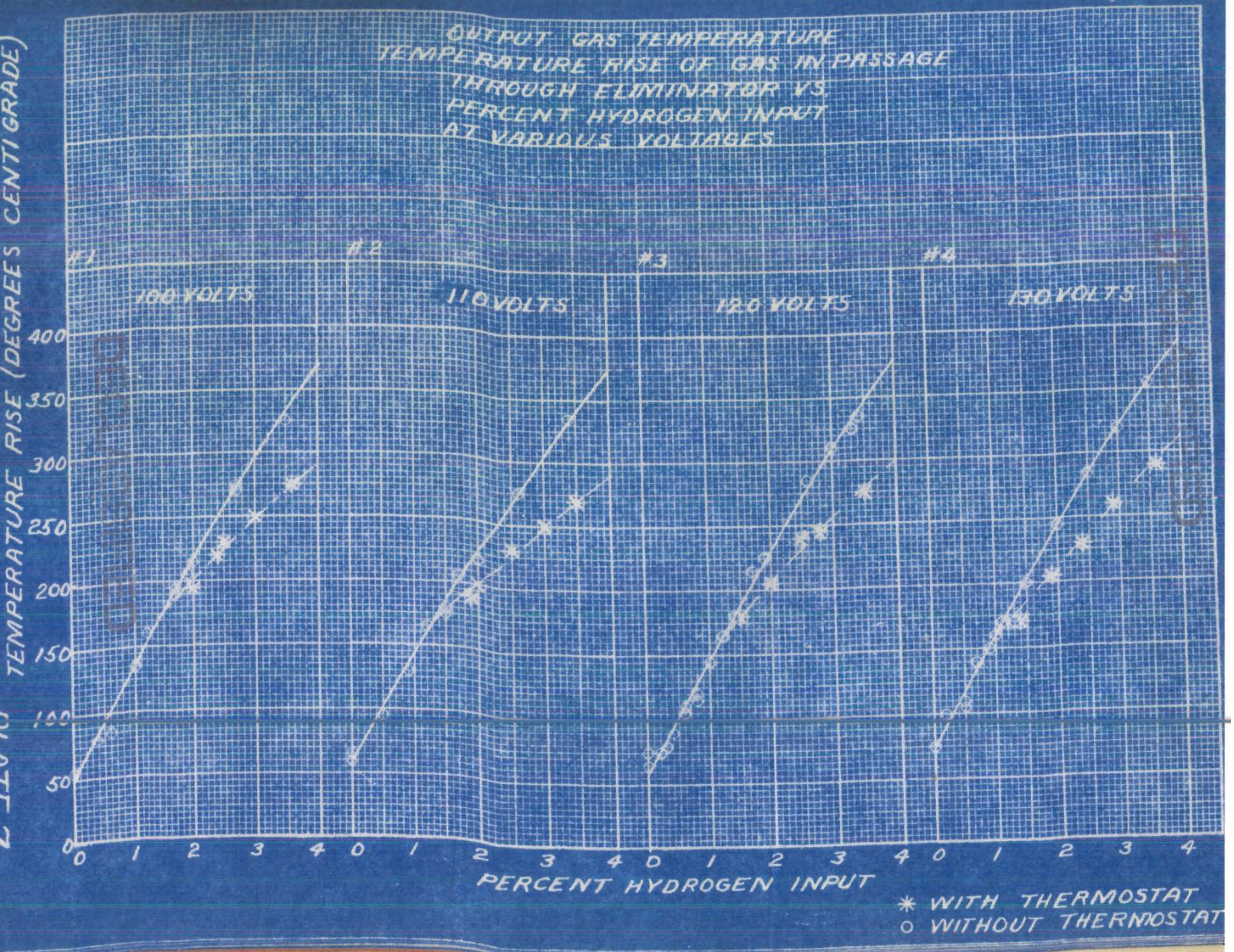

OUTPUT GAS TEMPERATURE
TEMPERATURE RISE OF GAS IN PASSAGE
THROUGH ELIMINATOR VS
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES
#1
100 VOLTS
#2
110 VOLTS
#3
120 VOLTS
#4
130 VOLTS
TEMPERATURE RISE (DEGREES CENTIGRADE)
0
50
100
150
200
250
300
350
400
0
1
2
3
4
PERCENT HYDROGEN INPUT
* WITH THERMOSTAT
○ WITHOUT THERMOSTAT

PLATE 7

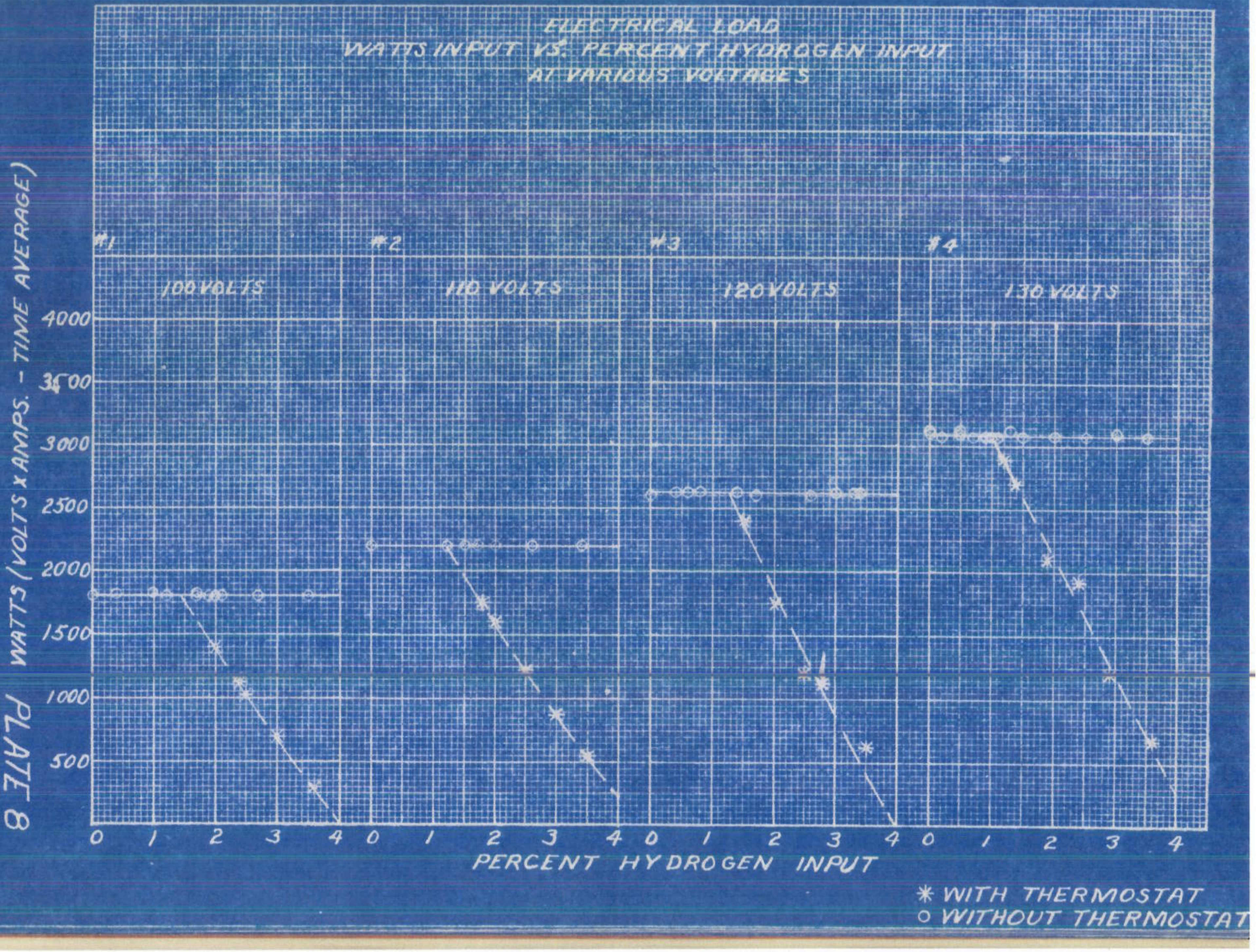

ELECTRICAL LOAD
WATTS INPUT VS. PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES
#1
100 VOLTS
#2
110 VOLTS
#3
120 VOLTS
#4
130 VOLTS
WATTS (VOLTS x AMPS. - TIME AVERAGE)
4000
3500
3000
2500
2000
1500
1000
500
0
1
2
3
4
PERCENT HYDROGEN INPUT
* WITH THERMOSTAT
○ WITHOUT THERMOSTAT

PLATE 8

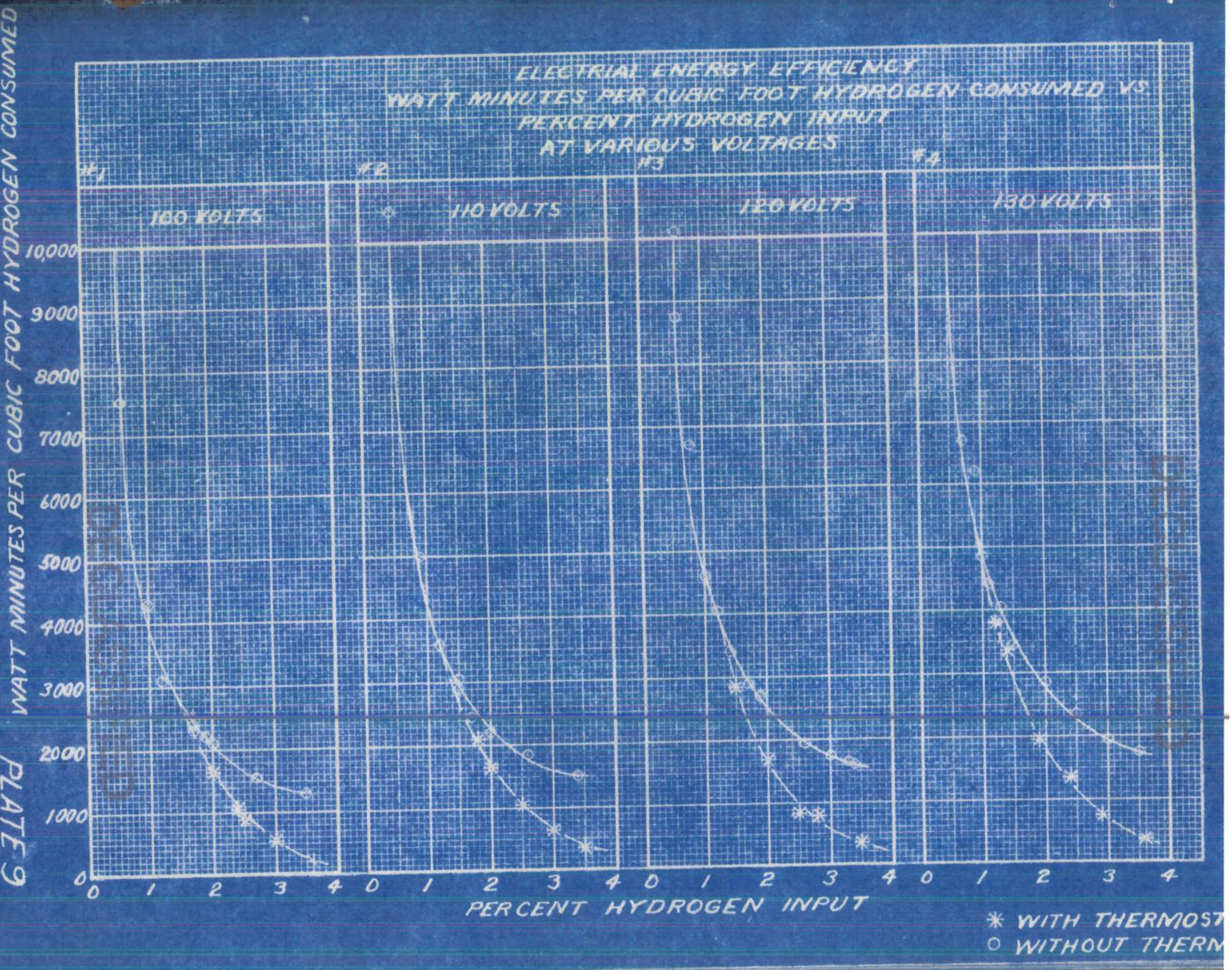
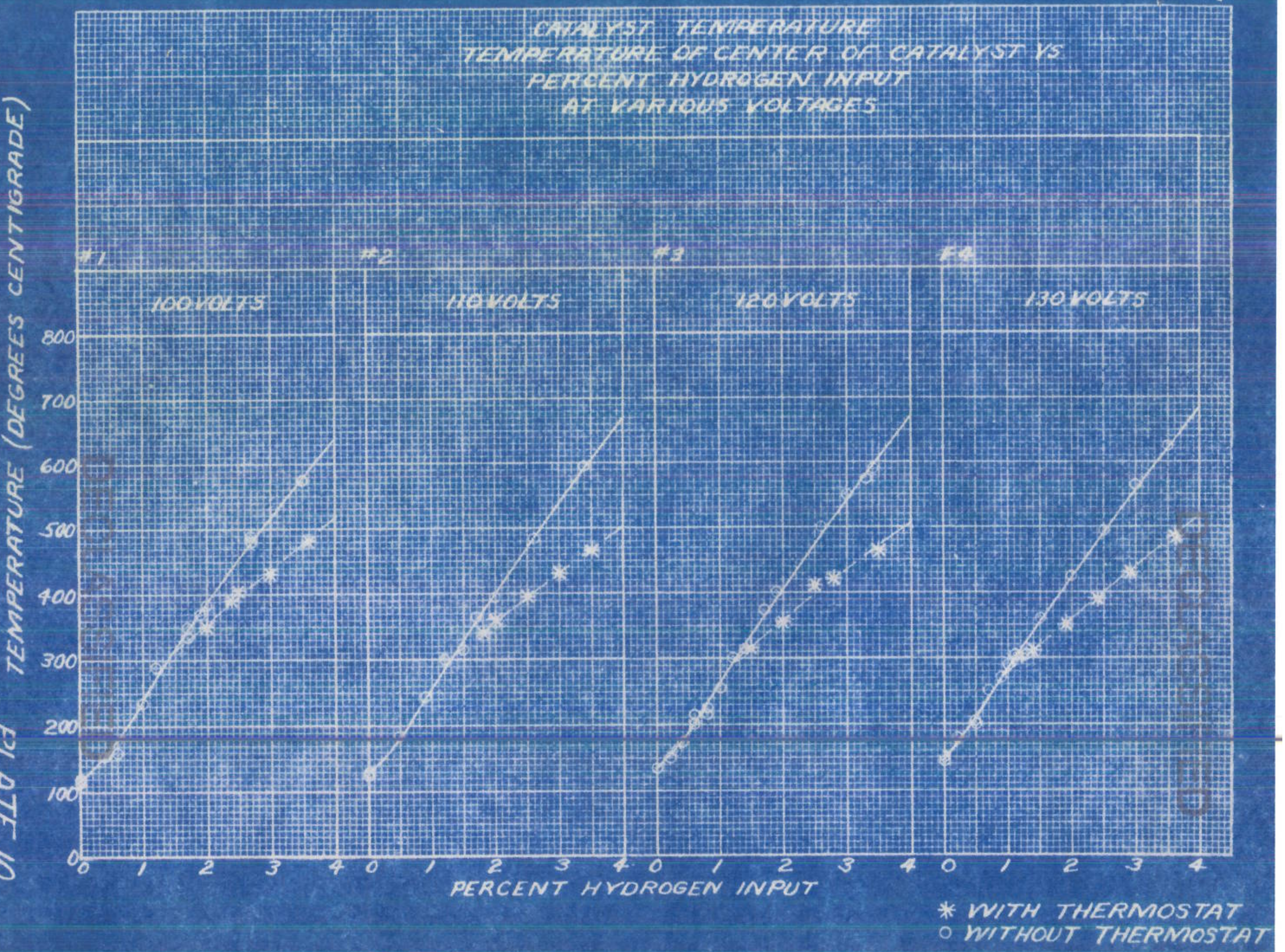
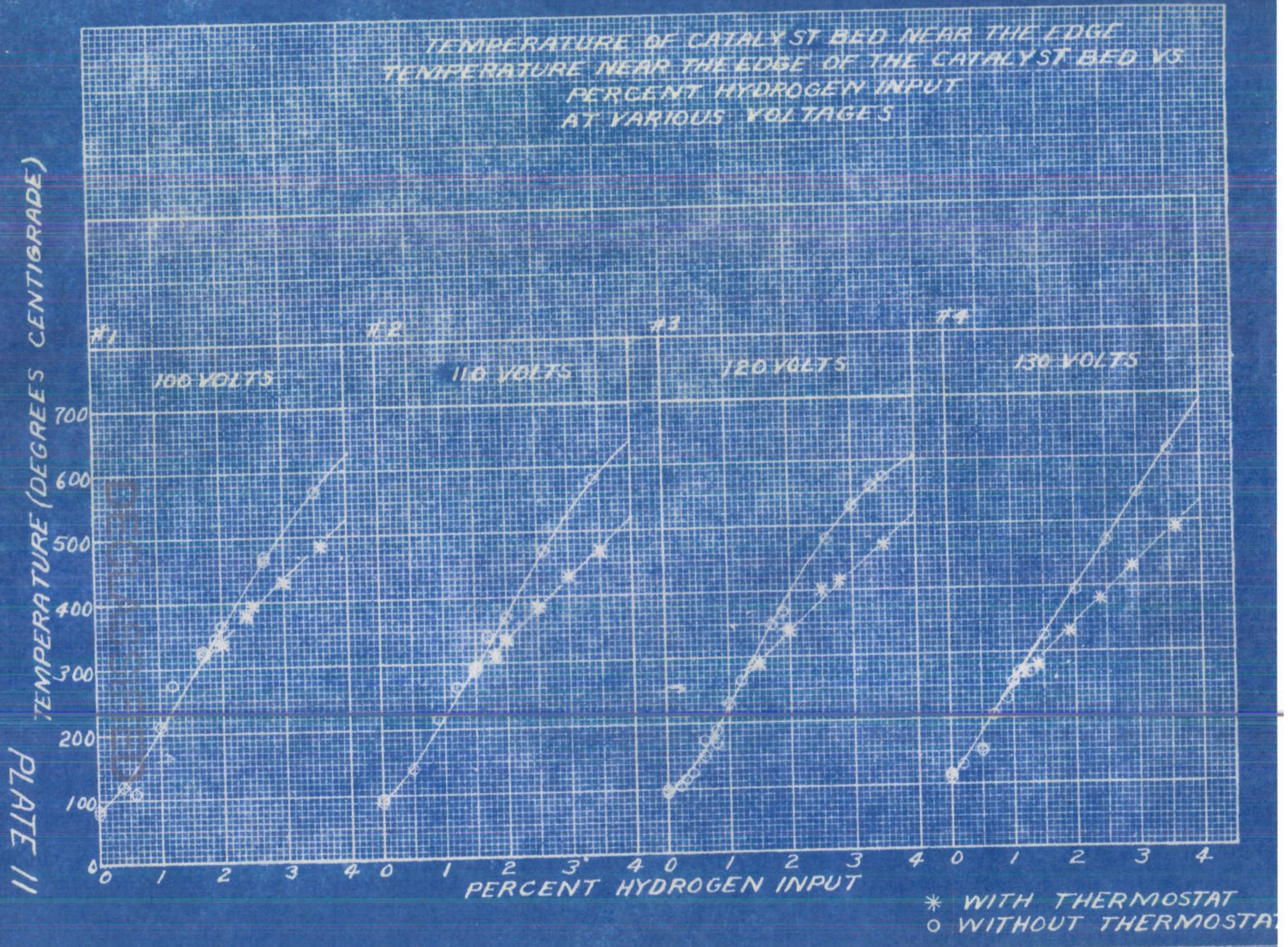

ELECTRIAL ENERGY EFFICIENCY
WATT MINUTES PER CUBIC FOOT HYDROGEN CONSUMED VS
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES
#1
100 VOLTS
#2
110 VOLTS
#3
120 VOLTS
#4
130 VOLTS
WATT MINUTES PER CUBIC FOOT HYDROGEN CONSUMED
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0 1 2 3 4
0 1 2 3 4
0 1 2 3 4
0 1 2 3 4
PERCENT HYDROGEN INPUT
* WITH THERMOST
○ WITHOUT THERM

PLATE 9



CATALYST TEMPERATURE
TEMPERATURE OF CENTER OF CATALYST VS
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES

PLATE 10



TEMPERATURE OF CATALYST BED NEAR THE EDGE
TEMPERATURE NEAR THE EDGE OF THE CATALYST BED VS
PERCENT HYDROGEN INPUT
AT VARIOUS VOLTAGES

PLATE 11

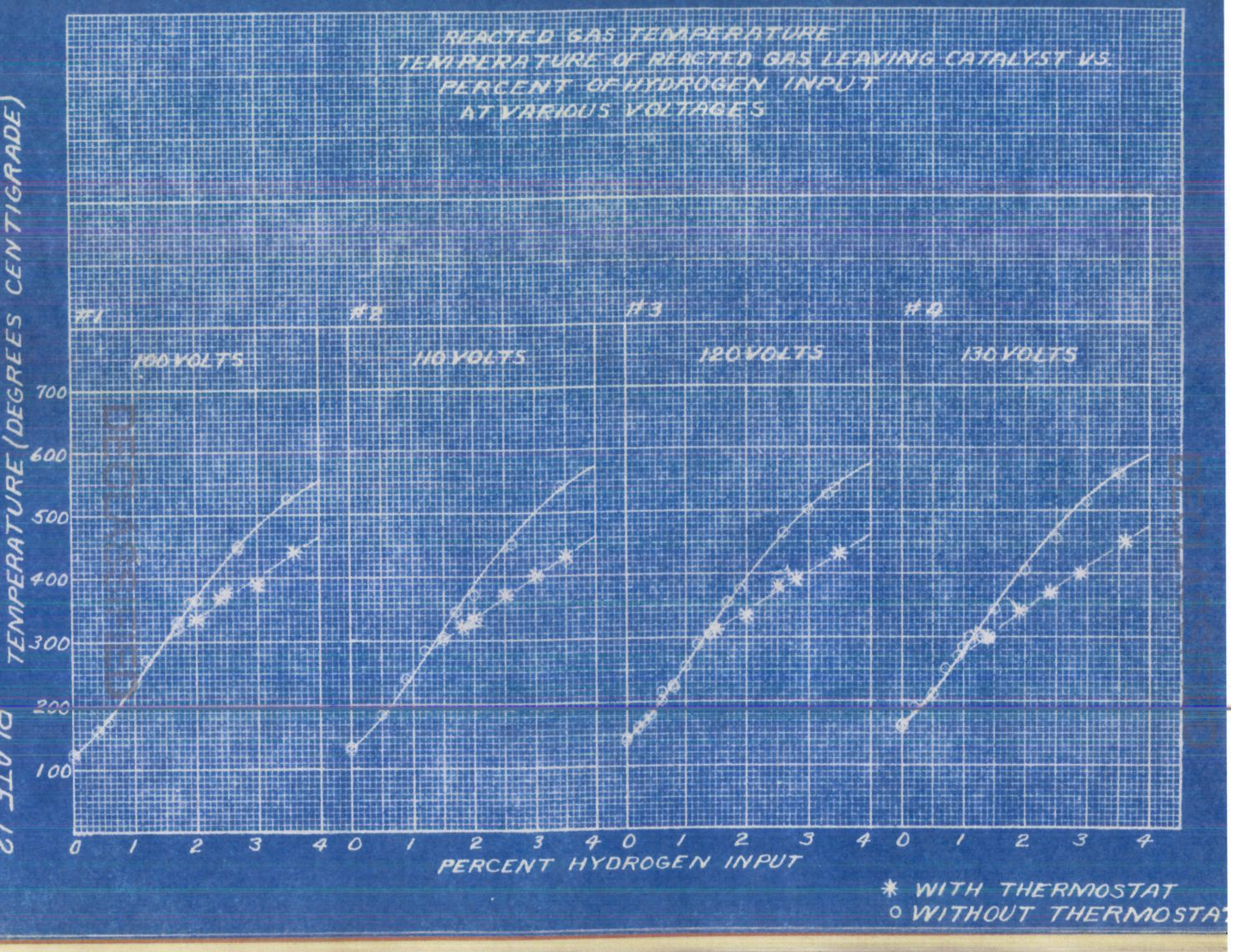
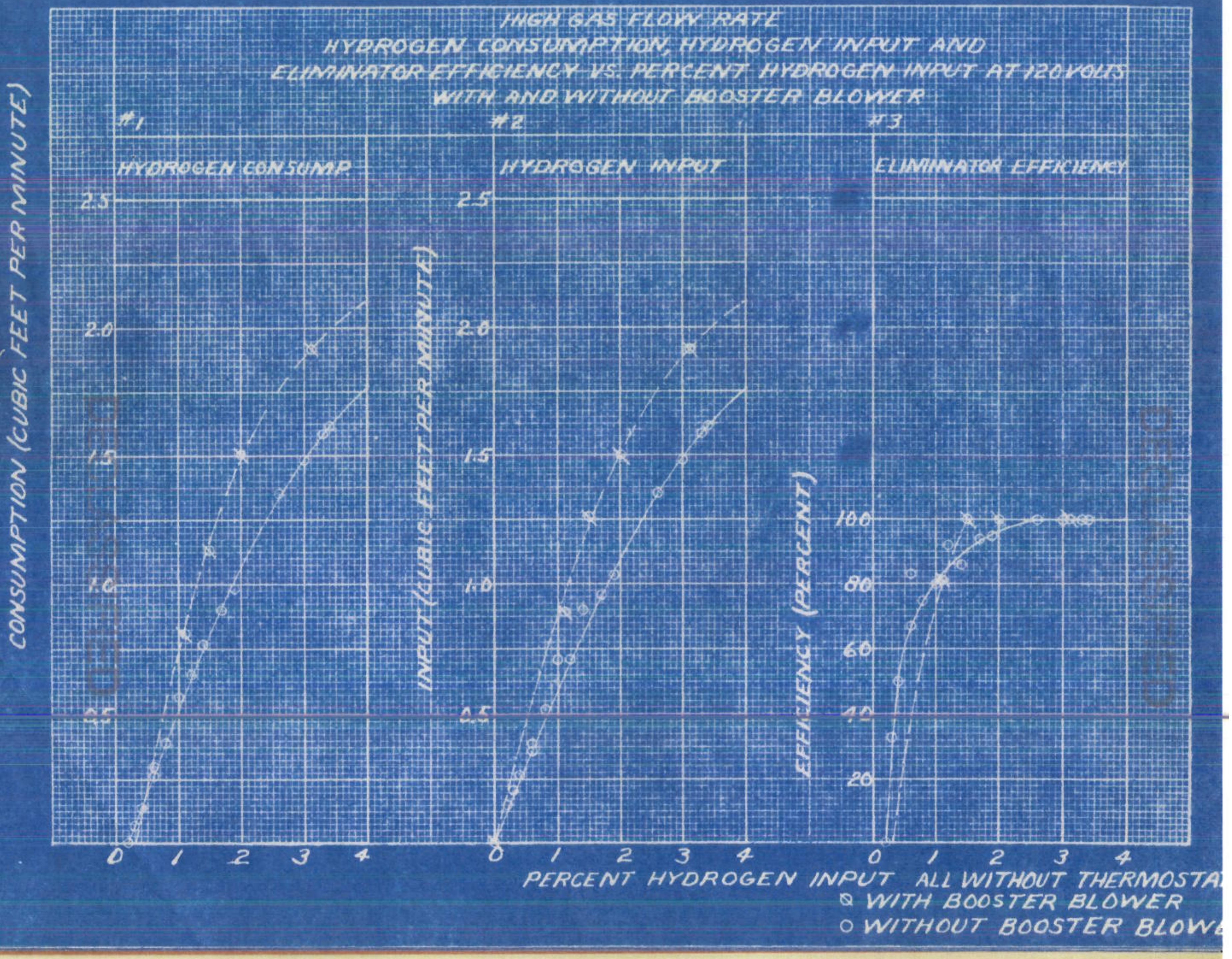

REACTED GAS TEMPERATURE
TEMPERATURE OF REACTED GAS LEAVING CATALYST VS.
PERCENT OF HYDROGEN INPUT
AT VARIOUS VOLTAGES
#1
100 VOLTS
#2
110 VOLTS
#3
120 VOLTS
#4
130 VOLTS
TEMPERATURE (DEGREES CENTIGRADE)
700
600
500
400
300
200
100
0
1
2
3
4
PERCENT HYDROGEN INPUT
✱ WITH THERMOSTAT
○ WITHOUT THERMOSTA

PLATE 12



HIGH GAS FLOW RATE
HYDROGEN CONSUMPTION, HYDROGEN INPUT AND
ELIMINATOR EFFICIENCY VS. PERCENT HYDROGEN INPUT AT 120 VOLTS
WITH AND WITHOUT BOOSTER BLOWER

PLATE 13

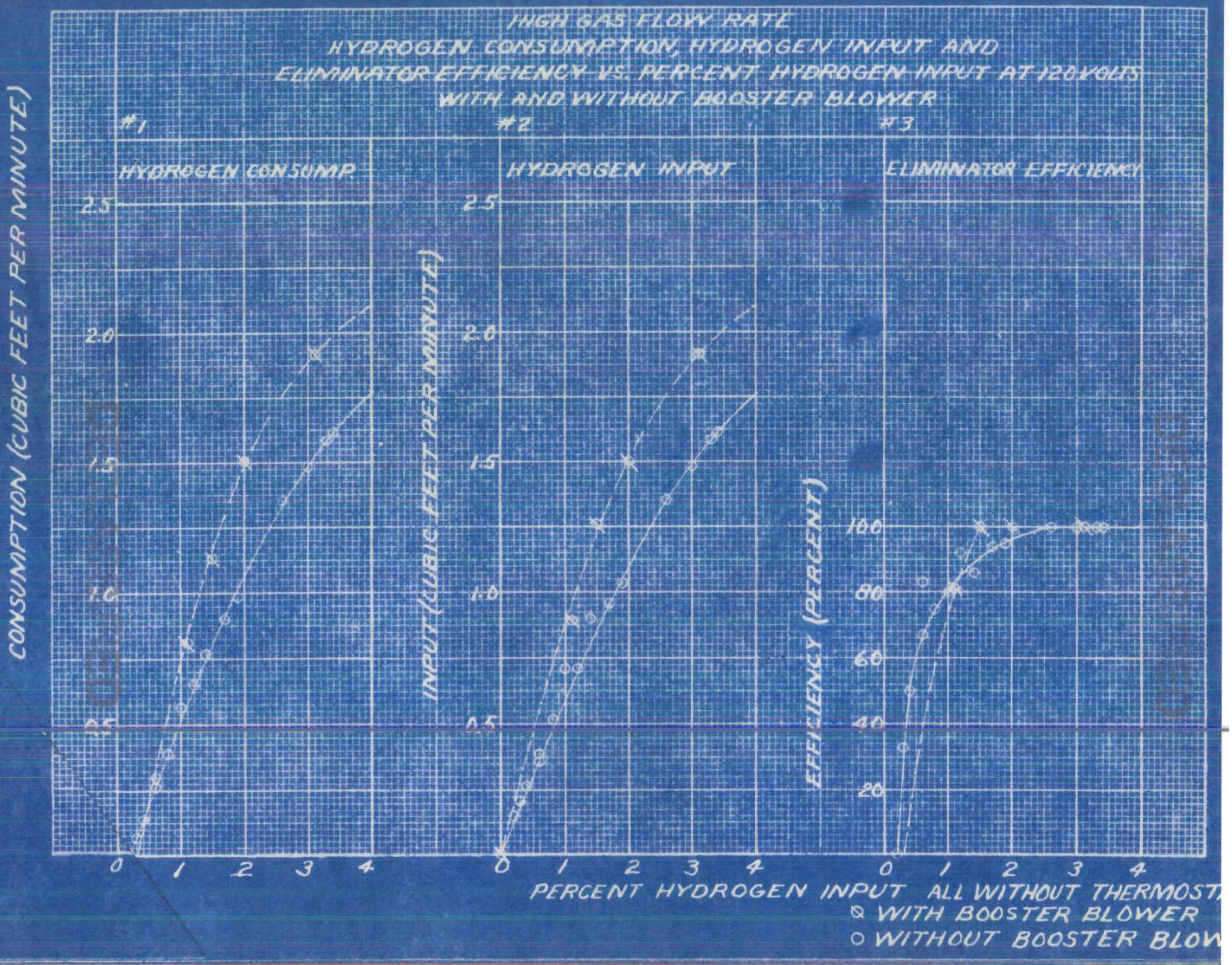
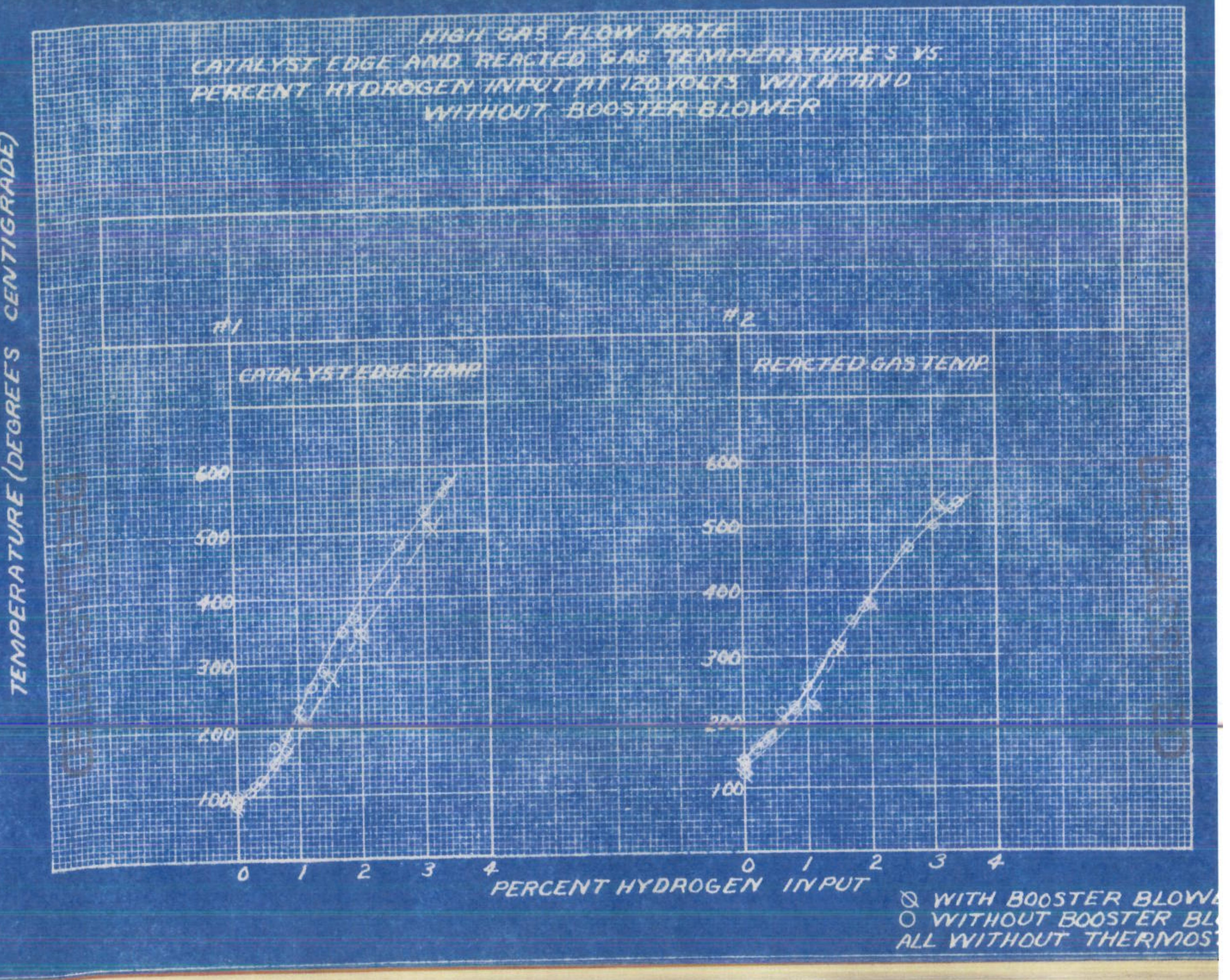
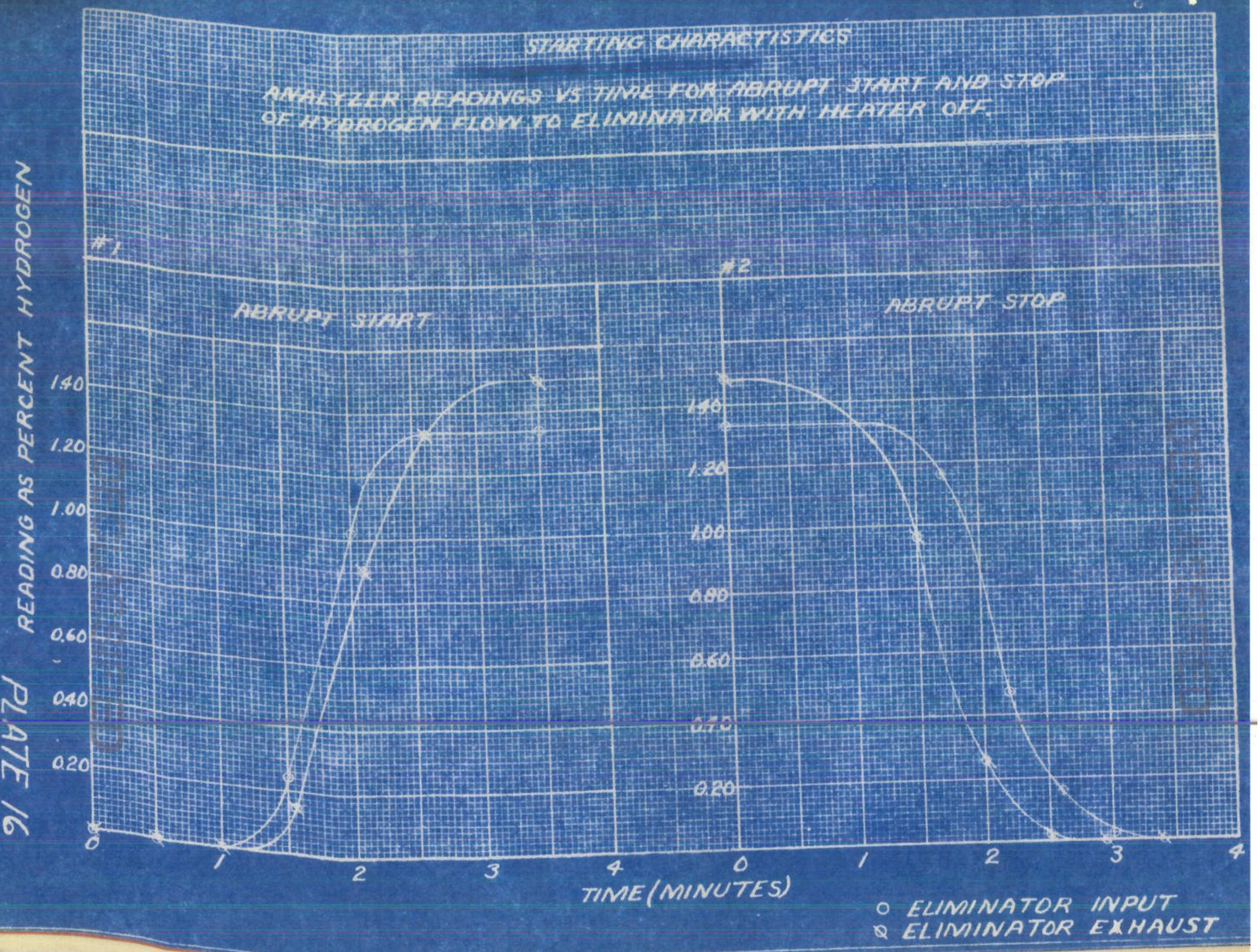
HIGH GAS FLOW RATE
HYDROGEN CONSUMPTION, HYDROGEN INPUT AND
ELIMINATOR EFFICIENCY VS. PERCENT HYDROGEN INPUT AT 120 VOLTS
WITH AND WITHOUT BOOSTER BLOWER
#1
HYDROGEN CONSUMP.
#2
HYDROGEN INPUT
#3
ELIMINATOR EFFICIENCY
CONSUMPTION (CUBIC FEET PER MINUTE)
2.5
2.0
1.5
1.0
0.5
INPUT (CUBIC FEET PER MINUTE)
2.5
2.0
1.5
1.0
0.5
EFFICIENCY (PERCENT)
100
80
60
40
20
0
1
2
3
4
0
1
2
3
4
0
1
2
3
4
PERCENT HYDROGEN INPUT ALL WITHOUT THERMOST
⊗ WITH BOOSTER BLOWER
○ WITHOUT BOOSTER BLOW

PLATE 14



HIGH GAS FLOW RATE
CATALYST EDGE AND REACTED GAS TEMPERATURES VS.
PERCENT HYDROGEN INPUT AT 120 VOLTS WITH AND
WITHOUT BOOSTER BLOWER

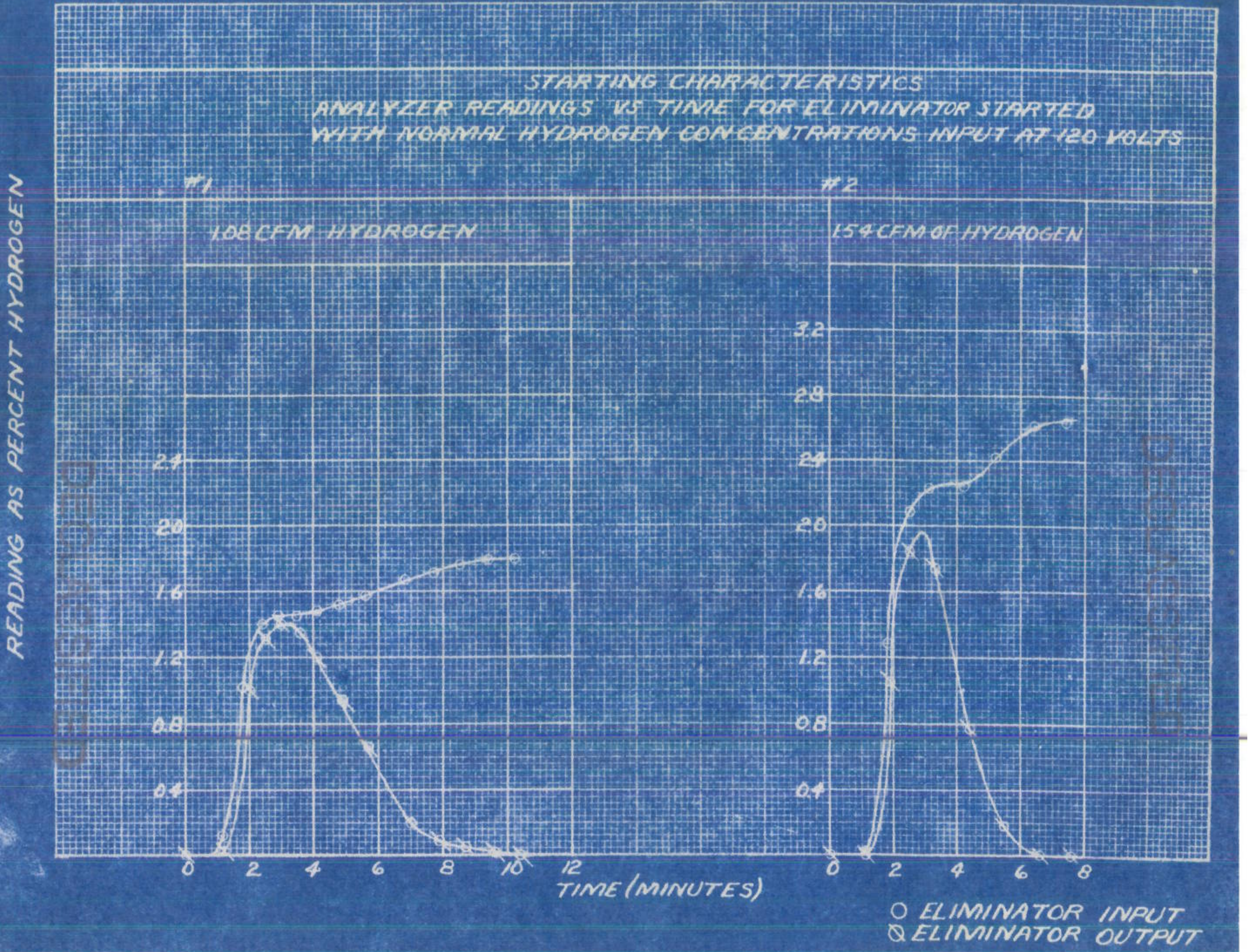
PLATE 15



STARTING CHARACTISTICS

ANALYZER READINGS VS TIME FOR ABRUPT START AND STOP OF HYDROGEN FLOW TO ELIMINATOR WITH HEATER OFF.

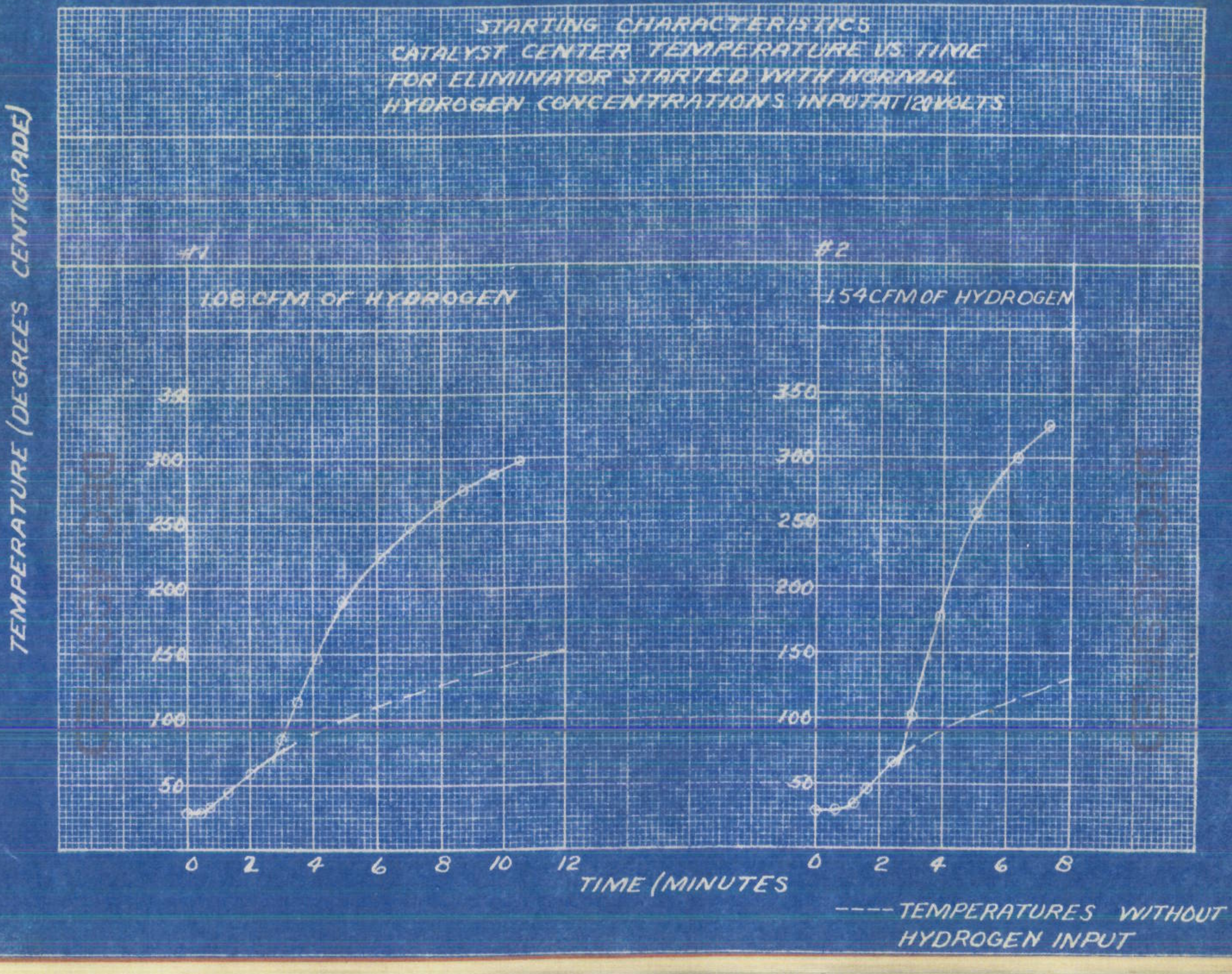
PLATE 16



STARTING CHARACTERISTICS
ANALYZER READINGS VS TIME FOR ELIMINATOR STARTED
WITH NORMAL HYDROGEN CONCENTRATIONS INPUT AT 120 VOLTS

PLATE 17

PLATE 18



STARTING CHARACTERISTICS
CATALYST CENTER TEMPERATURE VS TIME
FOR ELIMINATOR STARTED WITH NORMAL
HYDROGEN CONCENTRATIONS INPUT AT 120 VOLTS