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# A Method of Detecting the Fully Cooled State of a Liquid Oxygen Pipeline

*By*

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1961

PRICE 2s 6d NET

U.D.C. No. 53.082.2 : 536.423.2 : 546.21 : 621.643
C.P. No.573

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# A METHOD OF DETECTING THE FULLY COOLED STATE OF A LIQUID OXYGEN PIPELINE

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## SUMMARY

Test sites using liquid oxygen normally rely on visual observation to determine when the pipe system is cooled to liquid oxygen temperature. Test sites for rocket engines of high thrust, however, having considerable distances between control room and test bay, necessitate the use of an automatic "precool" indicator. This note describes a method which has proved to give reliable remote indication when the fully cooled state is reached.

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Previously issued as R.P.E. Tech. Note No.193 - A.R.C.21,734.

## LIST OF CONTENTS



## APPENDIX



## LIST OF ILLUSTRATIONS

## 1 INTRODUCTION

Before liquid oxygen can be allowed to flow through a pipeline the pipe must be chilled to liquid oxygen temperature to prevent boiling owing to heat transfer from the relatively warm pipe. This process of chilling (or "precooling") the pipeline is effected by passing liquid oxygen through the pipe system until there is no trace of evaporation, the oxygen thus used for precooling being discharged from the system through a suitably positioned "precool" pipe.

During development work on a test site for high thrust engines the necessity arose for a suitable method of detecting when the liquid oxygen pipelines were fully precooled. This note describes a detecting system which has been found to provide a reliable indication of the fully precooled state, and should therefore prove useful to other users of liquid oxygen.

## 2 NATURE OF FLOW AND METHOD OF DETECTION

During the precooling operation the flow through the pipe changes from gaseous to liquid; thus on the admission of liquid oxygen the pipe will be warm enough to cause boiling of the initial content; as the pipe temperature falls the evaporation will diminish, and finally liquid oxygen only will be discharged from the pipe. We require, therefore, a method or device which will detect the change from the gaseous to the liquid state. The respective characteristics of gaseous and liquid flow through a convergent divergent nozzle afford a means of detection by measurement of the pressure change at the throat. We therefore mount such a nozzle at the end of the precooling drain pipe, as shown in Fig.1.

Initially, after pressurising the pipe to an extent that ensures that the pressure drop across the nozzle exceeds the critical value, the gas velocity at the throat will be equal to the acoustic velocity, and the prevailing static pressure at the throat, $P_t$, is given by

$$P_t = P_1\left(\frac{2}{\gamma + 1}\right)^{\gamma/\gamma - 1} \approx 0{\cdot}53\ P_1$$

where $P_1$ is the inlet pressure at the nozzle and $\gamma$ is the ratio of specific heat of oxygen at constant pressure to that at constant volume. (For the range of gas temperature obtaining in the nozzle $\gamma \approx 1{\cdot}4$.)

As the pipe temperature falls, the contents approach the liquid state, with considerable reduction in specific volume, which is reflected in a marked fall in throat pressure. When precooling is complete the flow becomes completely liquid and our detector ceases to behave as a supersonic nozzle, but instead operates as a rounded orifice, the total pressure head at the inlet being converted into velocity head at the throat. The static pressure at the throat should be sensibly atmospheric.

The criterion of detection, therefore, is that $P_t$ prevailing at the throat during gaseous flow must be measurably greater than atmospheric pressure, and hence

$$P_1 \nless P_t/\left(\frac{2}{\gamma + 1}\right)^{\gamma/\gamma - 1} .$$

To allow for flow losses in the pipe system the discharge tank must be pressurised to a higher figure.

## 3 TEST RESULTS AND DISCUSSION

There are two pipe systems for liquid oxygen at P2 test site at R.P.E.*, which must be precooled before an engine test can be started. There is a considerable difference in the size of the pipelines of the two systems so that the times necessary to precool them are quite different. For this reason the smaller system is precooled after the larger system has been completely precooled. The two systems are discussed separately.

### 3.1 Main system

This system conveys the main flow of liquid oxygen from the site tank to the engine on test and consists of 50 feet of aluminium alloy pipework of 7 inches bore and 0·6 inch wall thickness. Mounted in the pipeline is a stainless steel flowmeter having an approximate weight of 400 lb, the total weight of metal in the system, including the flowmeter, being approximately 1,450 lb. The line includes 5 right angle bends of some 2 feet 6 inches radius, and is fully lagged from tank to engine.

Before starting to precool, the stop valve at the tank is opened and the tank pressurised to 40 to 50 lb/sq in. gauge to allow liquid oxygen under pressure down to the engine valve.

A "main" valve and two smaller "pilot" valves, situated at the highest point in the system, are provided for precooling, for reasons indicated below.

The main valve is $3\frac{3}{4}$ inches diameter, and is pneumatically operated. Flow through the valve is ducted away from the bay by a $3\frac{3}{4}$ inch bore pipe, at the end of which is mounted a nozzle with a throat diameter of 1 inches, giving a gaseous flow rate of approximately 2·90 lb/sec for precooling. At the base of this main valve are mounted the two small 1 inch diameter pilot valves which are also pneumatically operated. These pilot valves are mounted on the upstream side of the main valve; consequently flow can take place through them independently of the operation of the main valve. Flow through these valves is ducted away from the bay through a $1\frac{1}{4}$ inch bore pipe on the end of which is mounted a nozzle with a throat diameter of $\frac{1}{4}$ inch giving a gaseous flow rate of 0·115 lb/sec. The arrangement is shown in Fig.2.

The flow through the small valves constitutes the pilot flow for the system, the valves being opened at the start of the precooling operation and remaining open until the system is fully precooled.

The main valve is opened intermittently throughout the operation, in order to discharge the large volume of gas which accumulates at the highest point in the system. This valve must be operated economically, to avoid excessive loss of liquid oxygen, and is closed immediately gaseous flow ceases.

It was found necessary to provide a small precool flow of 0.115 lb/sec adjacent to the flowmeter. This was necessitated by the mounting of the flowmeter between two adaptors with a tapered bore allowing a small volume of gas to accumulate between the tapering sections.

The state of the flow through the precooling pipes i.e. whether gaseous or liquid, may be observed by means of pressure gauges connected to the pressure tappings at the throats of the nozzles. On P2 site Bourdon type gauges are used and are observed by means of the periscopes in the control

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*Rocket Propulsion Establishment, Westcott.

room. In addition a pressure switch, connected to the nozzle of the pilot flow system, makes electrical contact when the throat pressure falls to a pre-determined value on reaching the precooled state. The contacts operate an indicator lamp in the control room.

A typical graph showing the variation of throat pressure with pre-cooling time for the nozzle of the pilot system is shown in Fig.3. Also shown is the variation of tank pressure during the precooling operation. It will be seen that at the start the nozzle throat pressure is erratic. This is caused by excessive variation in system pressure (and hence nozzle inlet pressure) during this period, owing to the expansion of gaseous oxygen within the pipeline and the drop in pressure resulting when the main precool valve is operated to relieve it. The control of tank pressure during the initial period can sometimes prove difficult, but pressurisation becomes progressively more stable as the pipeline temperature falls. Experience has shown that it is desirable to increase the pressure in the pipeline after the initial period of bad regulation, resulting in a higher throat pressure at the nozzle during the gaseous phase, and a greater pressure drop between the gaseous and the fully precooled state. An increase in pressure will result in more heat being taken out of the pipeline per pound of liquid oxygen used before it passes into the gaseous state. Also, as the oxygen remains liquid for a longer period, the heat transfer is improved, thus shortening the time for precooling.

It will be seen from Fig.3 that just before the sudden fall in throat pressure, indicating the precooled condition, there is a marked increase in pressure. This is caused by the reduction in specific volume of the pre-cooling gas, which diminishes the drop of pressure along the precool pipe, and so makes a higher pressure apparent at the throat.

It has been stated that the pressure at the throat should be sensibly atmospheric when liquid flow occurs. However, as liquid oxygen readily cavitates in the nozzle at pressures approaching atmospheric, the minimum pressure finally attained at the throat will be the saturation vapour pressure corresponding to the liquid oxygen temperature.

It was found that owing to the high specific volume of the gas during the initial stages of precooling, the ratio of precool pipe area to nozzle throat area should not be less than 20 : 1, in order to avoid excessive pressure drop in the precool pipe.

The time required to precool the system, as likewise the amount of liquid oxygen used for the purpose, will obviously depend to some extent on ambient temperature. As many as four engine tests have been carried out in one day at P2 site, necessitating four separate precooling operations. The variation with precooling time of the amount of liquid oxygen required is shown in Fig.4 for each of these operations.

3.2 Start system

This system conveys liquid oxygen from a special "start" tank to the engine on test for starting purposes. It consists of 65 feet of aluminium alloy pipework of $1\frac{1}{4}$ inches outside diameter by 10 SWG (0·128 inch) wall thickness; the line contains two right angle bends and is fully lagged from tank to engine. The total weight of metal in the system amounts to approximately 45 lb.

Precooling is effected through a 1 inch bore pneumatically operated valve mounted on the pipeline approximately 2 feet from the engine. Flow through the valve is ducted away through 1 inch bore pipe, on the end of which is mounted a nozzle of 0.1 inch throat diameter, giving a gaseous rate of flow of approximately 0·122 lb/sec.

Before starting to precool the line, the stop valve at the tank is opened and the tank pressurised to 450 lb/sq in. gauge to allow liquid oxygen under pressure down to the engine valve. The precool valve is then opened and allowed to remain open until the system is fully precooled.

A graph showing the variation of nozzle throat pressure with precooling time is shown in Fig.5. It will be noticed that the rapid changes in throat pressure during the initial precooling period, occurring with the previous system, are absent. In fact, the tank pressure remains constant during the precooling operation.

On reaching the precooled state, there is a marked fall in throat pressure, which at approximately 90 lb/sq in. operates a pressure switch connected to an indicating light in the control room. After operation of the pressure switch precooling is continued and the throat pressure continues to fall so that by the time the engine is started the pressure is sensibly atmospheric.

The amount of liquid oxygen necessary to precool this system is not known accurately, but is estimated not to exceed 5 gallons.

### 3.3 Disposal of liquid and gaseous oxygen

It is important that all the liquid and gaseous oxygen discharged during precooling is carefully ducted away from structural steelwork, etc., to avoid setting up internal stresses due to contraction. On P2 site the precool flow is ducted into a vertical aluminium pipe of 18 inches diameter situated outside the test bay. The top of the pipe is 6 feet above the bay and is open to atmosphere, allowing gaseous oxygen to escape. Liquid oxygen is ducted away from the bottom of the pipe to a reservoir where it is allowed to boil off freely to atmosphere. As much as 120-150 gallons of liquid oxygen has been collected during the longer precooling operations, most of this being attributed to delay in closing the main precool valve on the main system. Consideration is being given to returning this liquid oxygen into the storage tank.

## 4 METHODS OF INDICATION

The method used in any particular installation to show a visible indication of the precooled state will depend largely on the distance between the control room and the test bay. Visible indication may be effected by one of the following methods:-

(a) Bourdon pressure gauge. This method is suitable only if the control room is situated close to the test bay.

(b) A pressure transducer whose electrical output is fed to a pressure gauge situated in the control room.

(c) A pressure switch connected to an indicator lamp in the control room.

## 5 CONCLUSIONS

A simple and reliable method has been evolved for detecting and remotely indicating when a liquid oxygen pipeline has been cooled to liquid oxygen temperature. The method is based on detecting the change in pressure at the throat of a simple venturi, which occurs when the oxygen flow changes from the gaseous to the liquid phase.

Although the method is sensitive to variations in system pressure during the gaseous phase, it is insensitive during the liquid phase when the fully cooled state is reached.

Each installation will pose its own problems depending on the size and configuration of the pipelines, but the information given in this memorandum on the precooling of two quite separate systems should prove a useful guide.

In addition to rocket engine test sites, this method of detection may prove useful on launching sites, where it is important for missiles taking 'start' liquid oxygen from the ground supplies to have the 'start' pipeline free of gaseous oxygen.

## APPENDIX

## CALCULATION OF NOZZLE THROAT DIAMETER

A graph which enables the nozzle throat diameter to be readily determined is shown in Fig.6. This graph has been drawn by assuming that the minimum gas temperature finally attained during the precooling of a particular pipe system will be that corresponding to the saturation point.

To determine the nozzle throat diameter, the system pressure must be known and a rate of gas flow for precooling must be selected in accordance with the size of the system and the bore of the pipeline. The variation of $W/A_t$ plotted against the nozzle inlet pressure $P_1$ in atmospheres is shown in Fig.6, where W is the precooling gas flow rate in lb/sec and $A_t$ is the nozzle throat area in square inches. The nozzle inlet pressure $P_1$ will be the system pressure less the allowance for the pressure drop occurring in the precool pipe. Having selected the gaseous flow rate, therefore, the graph of Fig.6 provides a rapid method of finding the throat area and diameter of the nozzle. A check should be made however that the ratio of precool pipe area to throat area is not less than 20 : 1 (see section 3.1).

The other dimensions of the nozzle are arbitrary, but it is suggested that the inlet radius to the throat be made equal to half the throat diameter, and that the portion of the nozzle downstream of the pressure tapping be tapered at a divergence of, say, 20° half angle.

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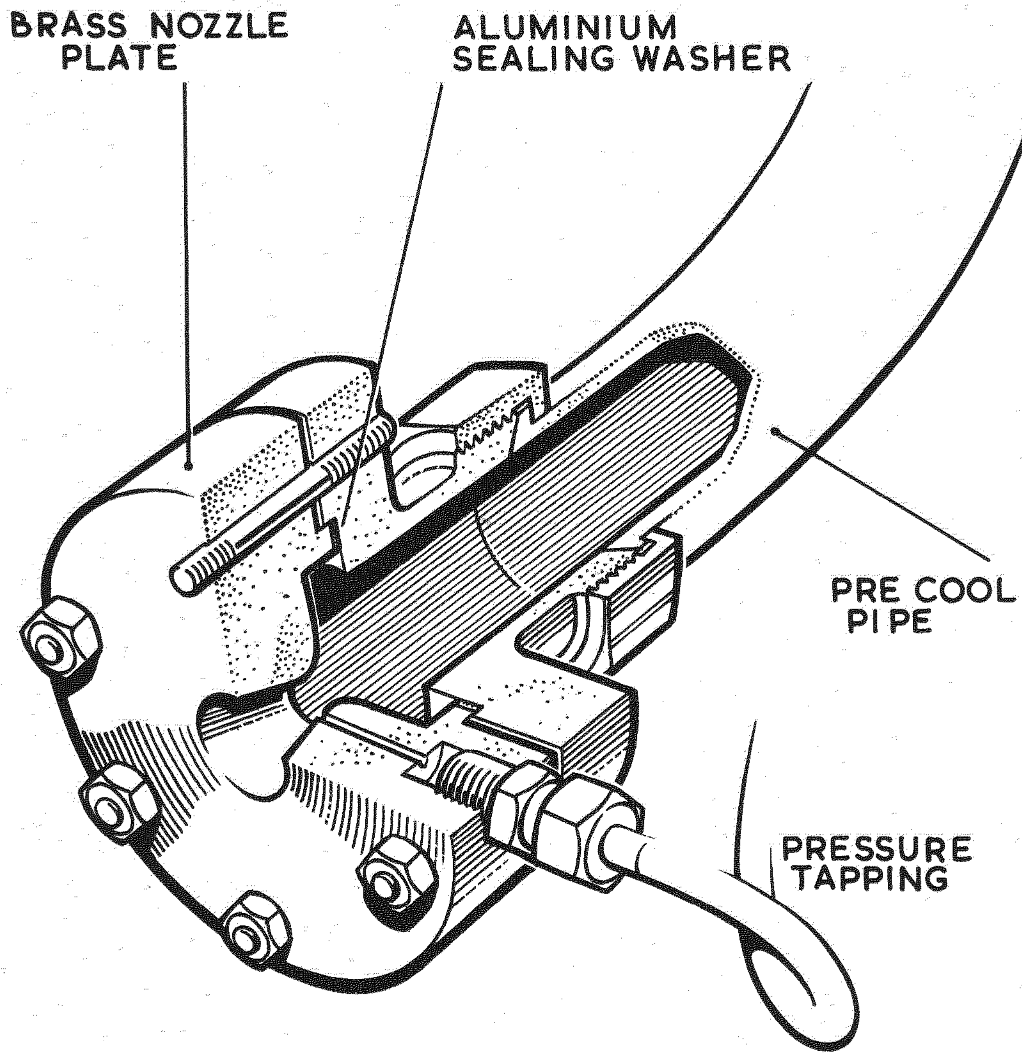
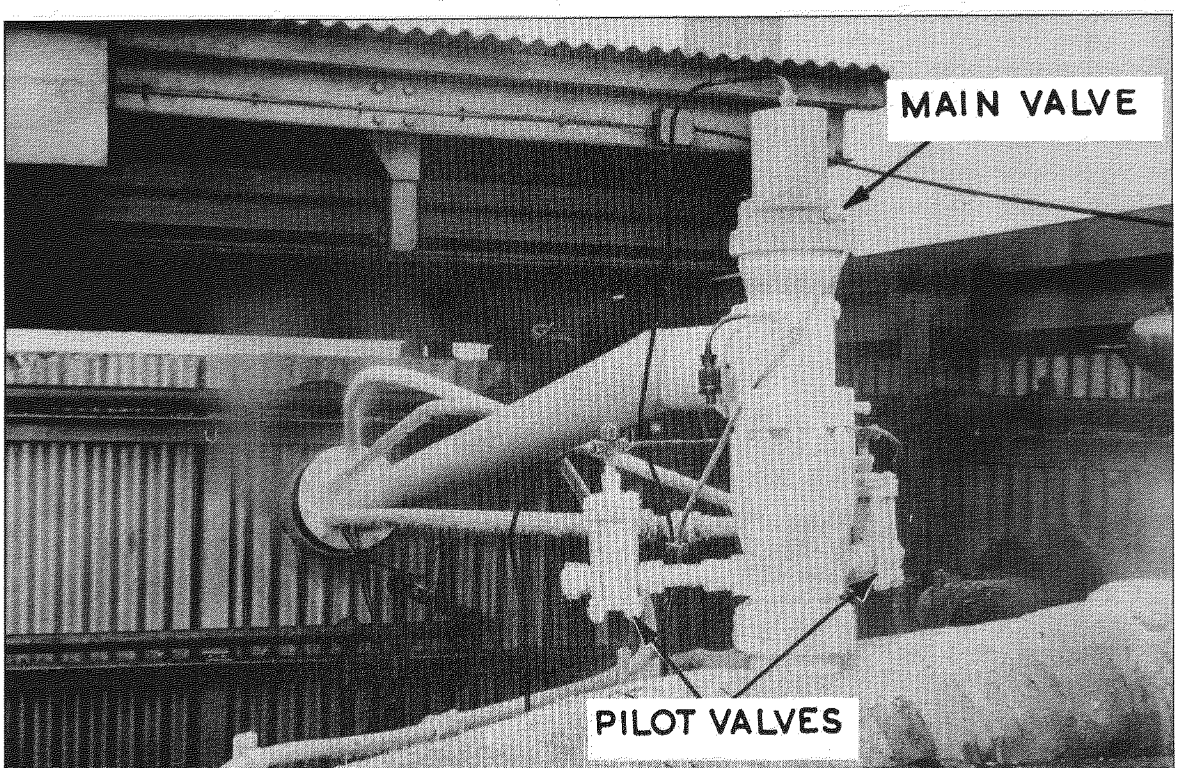



FIG. 1 SECTION THROUGH NOZZLE



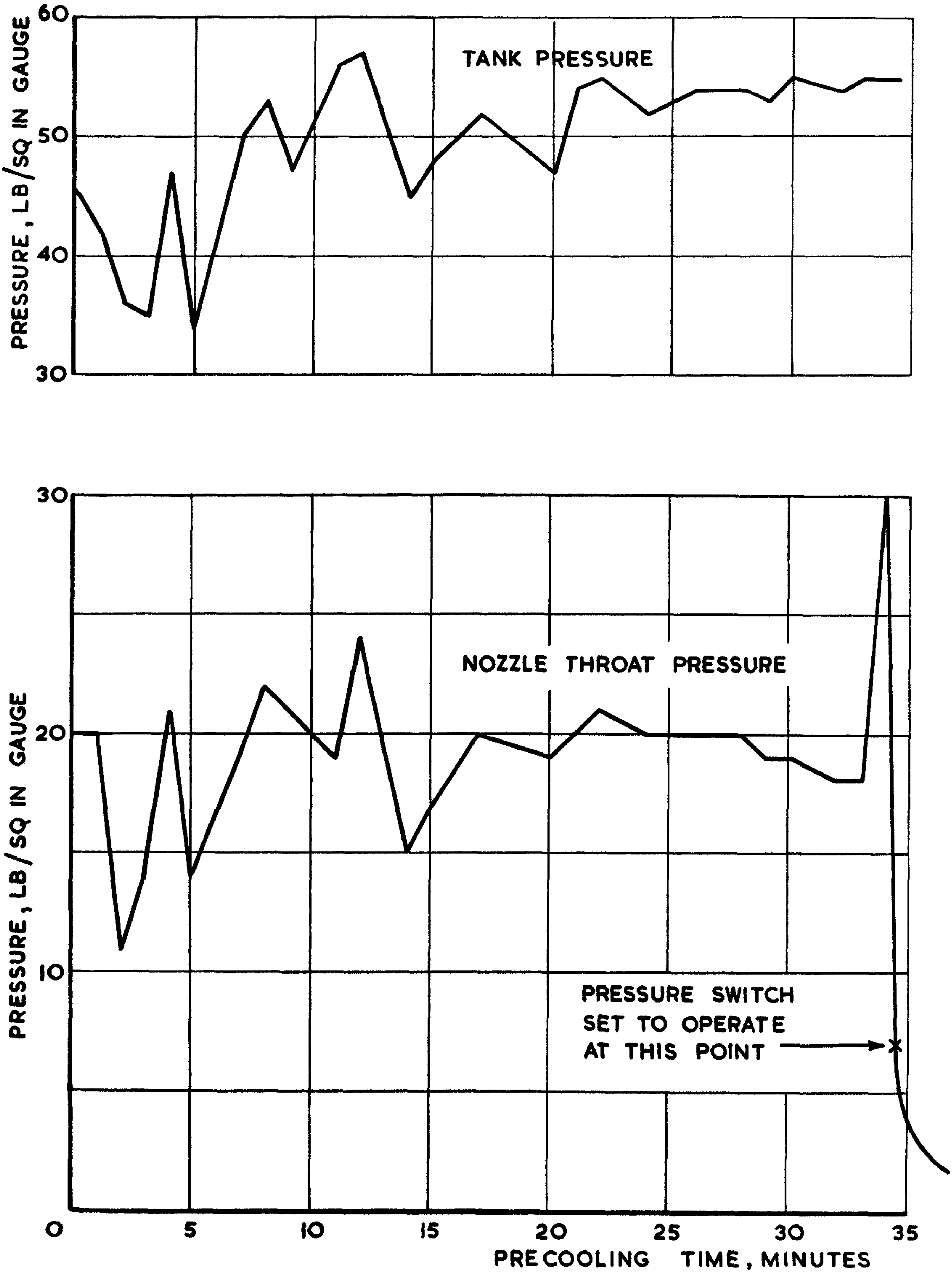



FIG.3 VARIATION OF NOZZLE THROAT PRESSURE AND LIQUID OXYGEN TANK PRESSURE WITH PRECOOLING TIME [FOR MAIN SYSTEM]

| RECORD OF PRECOOLING OPERATIONS ON 9-10-58 | | | | |
|---|---|---|---|---|
| TEST No | TIME AT START OF PRECOOL | AMBIENT TEMP, °F | NOMINAL TANK PRESS, LB/SQ.IN g | TOTAL QUANTITY OF LIQUID OXYGEN USED, GALLON |
| 1 | 10·17HRS | 55 | 45–50 | 351 |
| 2 | 12·53HRS | 57 | 45–50 | 98 |
| 3 | 15·57HRS | 57 | 55–60 | 230 |
| 4 | 17·22HRS | 56 | 55–60 | 196 |

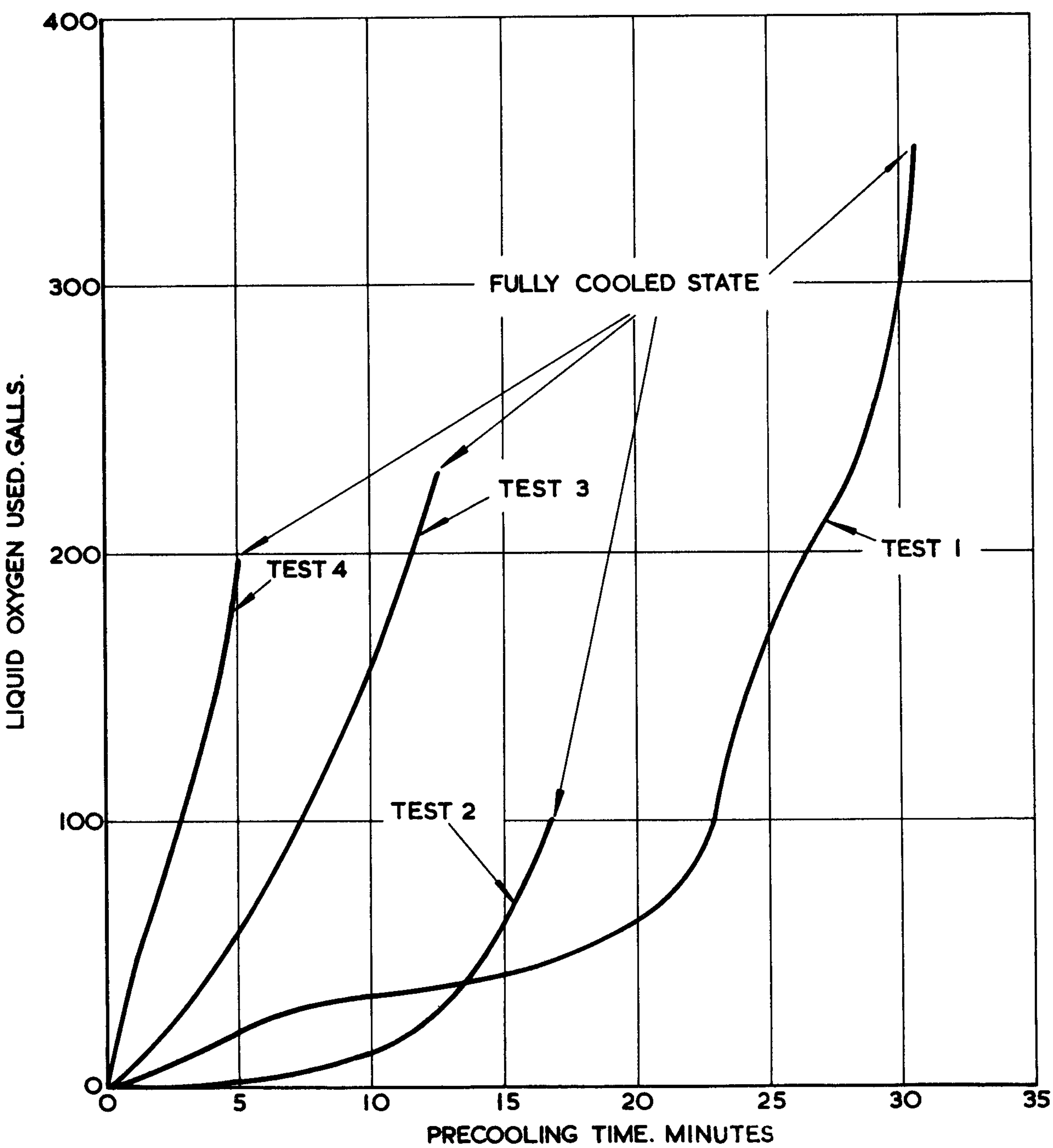



FIG. 4 VARIATION OF QUANTITY OF LIQUID OXYGEN USED WITH PRECOOLING TIME

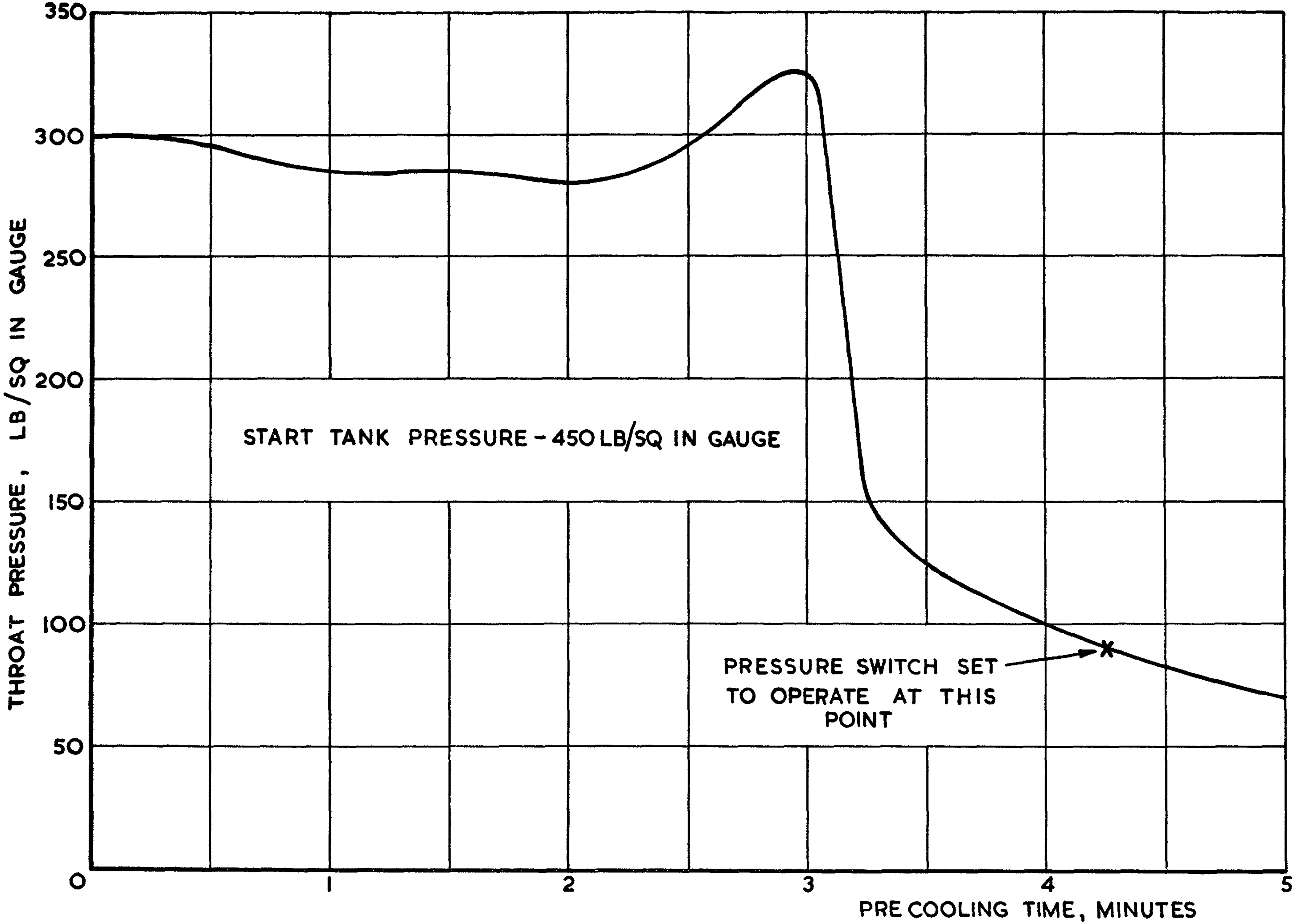



FIG. 5 VARIATION OF NOZZLE THROAT PRESSURE WITH PRECOOLING TIME FOR START SYSTEM

FIG. 5

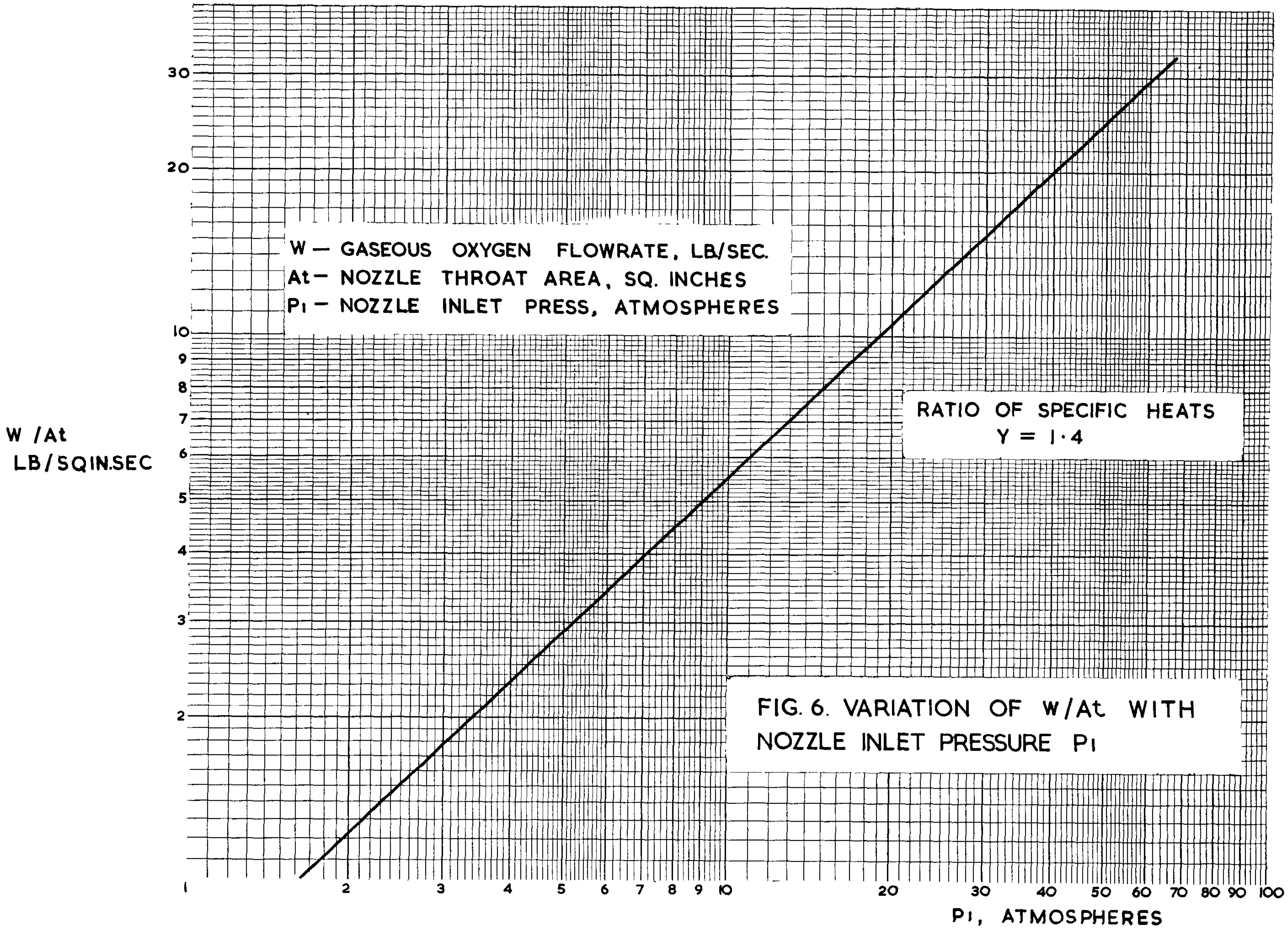



FIG. 6. VARIATION OF W/At WITH NOZZLE INLET PRESSURE P1

FIG.6

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621.643

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Printed and published by
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S.O. Code No. 23-9012-73

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