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FLAME SPREADING ACROSS LIQUID FUELS AT
SUB-FLASH POINT TEMPERATURES: MEASUREMENTS
AND TECHNIQUES (THE FUEL SURFACE TENSION,
VAPOR PRESSURE, FLASH POINT, VISCOSITY
AND FLAME SPREAD RATE)

by

R. MacKinven, J. G. Hansel and I. Glassman

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Approved by

I. Glassman

I. Glassman
Professor
Principal Investigator

Guggenheim Laboratories for the Aerospace Propulsion Sciences
Department of Aerospace and Mechanical Sciences
PRINCETON UNIVERSITY
Princeton, New Jersey

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I. INTRODUCTION

The purpose of this brief report is to describe the various experimental techniques which are utilized to measure the fundamental properties of the fuels in the Physics of Flames research program at Princeton. Much of the material presented herein has been accumulated over the past two years and generally has not been documented elsewhere (except for brief references to the work in the Monthly Progress Reports (Technical) to the U. S. Army, Ballistic Research Laboratories (Aberdeen), the sponsor of the overall research effort).

The fuel properties which are known to effect the flame spreading rate (1,2*) and which are included in this report are: surface tension, vapor pressure, flash point and viscosity. (The bulk thermal expansion coefficient is not included in the measurements.) Much of the data which have been obtained to date are included in this report. Whenever possible these data are compared with existing literature values. In several instances measurements were taken with n-decane and n-decane which had been thickened (to any desired degree) with very small percentages of polyisobutylene. Comparisons are made between these data.

* Numbers in parentheses refer to the references at the end of this report.

The most important guiding principles which were used in the selection of the measurement techniques are (not necessarily in order of importance):

1. simplicity of operation
2. accuracy
3. precision
4. adaptability to operation in a controlled temperature water bath

The last item is considered important to the program in effect and is the reason for eliminating many measurement techniques from serious consideration. The water bath used in these experiments consisted of an approximately 7 gallon cylindrical glass jar with an open top. The water, which was stirred constantly, was heated with a 1000 watt electric heater, and the temperature was controlled to better than $\pm \frac{1}{4}^{\circ}\text{C}$ with a mercury column thermostat.

II. SURFACE TENSION

In this report, the negligible difference between the surface tension of a liquid at an air interface and at a vapor interface is neglected. The most common methods of measuring surface tension depend on one of the following: the force required to tear a wetted ring from a surface, the size of drops of a liquid flowing from a capillary, the vapor pressure of small droplets, the oscillations in suspended drops, the bubble pressure and the rise of a liquid in a

capillary tube (3). In general, the first and last techniques, namely, the wetted ring and the capillary rise methods are the simplest and are capable of high accuracy and precision (within about one per cent). However, the capillary rise instrument can be immersed in a constant temperature bath (in contrast to the wetted ring method); furthermore, the technique is quick and the apparatus is easy to calibrate.

The particular capillary rise apparatus selected was a Fisher Catalog Number 14-817 (Ref. 4). The principle of operation is described in Reference 3. The assumption was made that the contact angle θ between the liquid and the capillary wall was zero. Calibration was accomplished by utilizing liquids whose surface tensions are known, measuring the heights of the capillary rise and solving for the capillary bore radius. Using reagent grade acetone, hexane, methanol, carbon tetrachloride and n-decane at 20°C the bore radius was found to be .0196 cm (using 980 cm/sec² as the acceleration due to gravity). It is interesting to note that when distilled water was used to calibrate the instrument the bore radius was found to be .0191 cm. This repeatable difference probably was caused by the relatively large difference between the surface tension of water (about 70 dynes/cm) and the other six organic liquids (about 18 to 27 dynes/cm) and by the assumption that θ was zero.

The accuracy and precision of the capillary rise surface tensiometer are very strongly dependent upon two factors, namely, the cleanliness of the bore (through the ability of the liquid to wet the surface) and the reading of the capillary rise with the associated menisci. The cleaning procedure and the standardized method of reading the menisci are presented in Appendix B.

The surface tensions of n-decane (viscosity, 0.92 centipoise at 20°C) and thickened n-decane (viscosity, 64.8 centipoise at 20°C) were measured at 20, 30, 40, and 50°C. The data*, shown in Figure 1, are identical, and more importantly, from the point of view of a model of the flame spreading process (1), $d\sigma/dT$ (the rate of change of the surface tension with temperature) is unchanged. The measured values of surface tension of n-decane agree well with the literature. Summarizing, the surface tension (and $d\sigma/dT$ of n-decane is unaffected by the presence of a thickening agent.

Another important aspect of the surface tension measurements concerns the possible effect of surface tension agents (surfactants) on the surface tension of n-decane. In this regard, the Armour Industrial Chemical Company (5) reported that, because the surface tensions of hydrocarbons

* Each datum point represents the average of at least three trials.

are quite low, it is difficult to find an agent to reduce the surface tensions further. (Armour had no additives to alter $d\sigma/dT$ and noted that this is an industry-wide problem). For trial purposes the following twelve chemicals were supplied by Armour:

Aromox C/12-50%	Ethomeen 18/12
Aromox DMC-40%	Arquad ZC-75
Aromox DMHT-40%	Arquad ZHT-75
Aromox 18/12-50%	Arquad ZS-75
Ethomeen C/12	Kessco Isopropylmyristate
Ethomeen T/12	Kessco Isopropylpalmitate

At the suggestion of Armour, approximately 1% of each of these possible agents was added to n-decane. None had any measurable influence on the surface tension.

More recently, the 3M Corporation provided these laboratories with a new surfactant which is still in the research stage and not available in large quantities commercially. This surfactant is a fluorinated hydrocarbon and has the 3M Corporation designation FC176. An addition of approximately 1.32% of this compound in n-decane reduces the surface tension of n-decane from 24 dynes/cm to 19 dynes/cm at 20°C. Moreover, FC176 altered the $d\sigma/dT$ of n-decane. These results are shown in Figure 1A.

III. VAPOR PRESSURE

There are a surprisingly large number of available methods for determining the vapor pressure of a liquid. Generally, they may be divided into two broad classes, namely, the static and dynamic methods (6). The dynamic methods are usually more complex, but have the distinct advantage over the static methods in that they are continuous flowing; thus, the air which is dissolved in the test liquid can be removed easily prior to the taking of the data. The outgassing of dissolved air from the test liquid can introduce significant errors when measurements are being made in the vicinity of a few torr pressure.

The static, classic isoteniscope method of the Smith and Menzies type (7) was selected for the measurements with n-decane and thickened n-decane. Some difficulty was encountered in removing the dissolved air from the n-decane in the instrument. Probably as a result of this, the data had more scatter than desired, and since the operating range was from about 1 to 10 torr, a dynamic method (e.g., Ramsay and Young method (6)) would probably have been a better choice. The data for n-decane and thickened n-decane are shown in Figure 2*.

* Each datum point represents a single trial.

As may be noted from the data in Figure 2, the vapor pressure of thickened n-decane does not appear to differ in a consistent manner from that of pure n-decane. Also, the data scatter amounts to about $\pm 10\%$, which is large. The scatter cannot be attributed entirely to dissolved air in the liquid, for this would cause the data to be higher than literature values. Linder (9) has noted though that the literature values of the vapor pressure may be high due to dissolved air.

IV. FLASH POINT

The flash point temperature of a liquid fuel has a significance which is somewhat distinct from the other properties of a fuel in that the flash point is often used for government regulatory purposes, particularly in the commercial shipping of fuels. Perhaps more importantly, the flash point is defined rather arbitrarily in comparison to other fuel properties, and the definition is dependent upon the apparatus utilized to measure it.

The Tag open-cup flash point apparatus was selected for use in this laboratory. The apparatus and the measurement technique conform to the ASTM (American Society for Testing and Materials) Designation D-1310-67 (Ref. 10). The apparatus was similar to a Fisher Catalog Number 13-512-1V2 (Ref. 11).

Most of the operating procedure for the Tag open-cup tester is straightforward. Extra precaution must be exercised to prevent drafts in the room. Also, the prescribed heating rate can be maintained only after some trial and error practice. The instrument was calibrated according to the ASTM specification using p-Xylene. The correction factor was found to be + 1°C.

The flash point of pure n-decane (viscosity, 0.92 centipoise at 20°C) was found to be 56°C. The flash point of thickened n-decane (viscosity, 43.8 centipoise at 20°C) was found to be 55°C. According to the ASTM specification, these two temperatures are not distinguishable.

Thus, the flash points of pure and thickened n-decane are essentially the same. The only literature value of the flash point of n-decane is 46°C for a closed-cup tester. This value, which is reported extensively (12) but apparently not referenced to any investigator, is consistent with the value of 56°C in that closed-cup values are usually lower than open-cup values.

Although the determination of the fire point is not specified for the Tag open-cup tester¹, and is rather difficult to carry out, some measurements were accomplished. It was determined that the fire point of pure n-decane is about 5°C above the flash point and this is to be expected.

* The fire point is defined for the Cleveland open-cup tester. However, this tester is not the proper one for the flash point range of n-decane.

It is interesting to note that in the case of n-butanol the measured flash point was identical to the measured fire point in all of the runs, (within the resolution of the instrument or 1°C) with an average value of 43°C . The reason for the close agreement between the two points probably is due to its low heat of vaporization. It may be noted that consistent with this result, the flame spreads across a n-butanol surface in a steady manner with a steady flame front. This steady propagation should occur when the flash point is close to the fire point. In contrast to this, the flame spreading across n-decane was observed to be nonsteady; the existence of a precursor flame (1) has been attributed to the difference between the flash and fire points.

V. VISCOSITY

A number of different methods exist for measuring the absolute viscosity (μ) or the dynamic viscosity (γ) of liquids. These include the Saybolt, Zahn, Falling Ball, Stormer (both cylindrical rotor and paddle rotor) in the case of absolute viscosity and the Ubbelonde and Cannon-Fenske in the case of kinematic viscosity (3). In a manner similar to the flash point, the measurement of viscosity is closely related to ASTM standards (ASTM Designation No. D445).

Relatively early in the research program, a number of measurements were taken with a student falling ball viscosimeter. This instrument later proved to be inaccurate and its use was discontinued. The bulk of the viscosity measurements were taken with ASTM approved and calibrated Ubbelohde viscosimeter tubes which were obtained from Scientific Glass Apparatus, Catalog No. V-7050 (Ref. 13). These tubes, which are made with various capillary bore diameters to accommodate specific viscosity ranges, were suspended in the constant temperature water bath.

The viscosity data* for pure n-decane and thickened n-decane are shown in Figure 3, along with the literature values (see Appendix A). The data for n-decane were obtained with two different calibrated Ubbelohde viscosimeters on the two different dates. Some of the data scatter probably can be attributed to not maintaining the viscosimeters in an absolutely vertical direction; the water currents created by the stirring motor tend to make this a difficult task.

* Each datum point represents the average of at least two trials.

VI. FLAME SPREADING

The velocity of flame spread over liquid fuels is highly dependent on the laboratory conditions under which the measurements are made. Because of this, well defined initial conditions are essential in order to give data which can be meaningfully correlated. As a direct result of an extensive series of tests carried out at Princeton, the conditions and procedures necessary to give flame spreading data have been defined. The choices made are described below.

A. BASIC APPARATUS REQUIREMENTS

B.1. Test Cell

The test cell should be a room sufficiently large to perform the burning tests. (25 foot long by 9 feet wide by 11 feet high has been adequate at Princeton). Flammable material should be absent from the test cell (i.e., a wooden building is considered totally unsuitable).

The test cell should be fitted with an exhaust fan in order that the room can be ventilated after each run.

Other requirements of the room are that it should have adequate temperature control (i.e., a heater and perhaps an air conditioner) and it should have a water supply.

B.2 The Experiment Table

A table on which to perform the flame spreading experiments is essential; this should be constructed of non-flammable material (metal). A top size of approximately 8 ft. by 4 ft. has been found adequate.

B.3. The Trays

Extensive testing at Princeton has indicated that the ideal size of the fuel container is 72 inches long by 8 inches wide. When the wall material is glass (or metal lined with glass), heat losses from the fuel are unimportant in this size tray.

Pyrex glass can be supplied to order from:

F. J. Gray & Co.
182 S. Portland Ave.
Brooklyn, New York

and the sheet Pyrex can be bonded together using Epoxy resin.

Alternatively the fuel tray can be fabricated from 1/16" aluminum and the long walls lined inside with plate glass (1/10" thick is adequate). It has been found convenient to clip the glass in position (using aluminum clips). The aluminum trays have a much longer lifetime than the Pyrex trays and are preferred for this reason. However, the glass liners do break and have to be replaced periodically.

A drainage hole should be provided for rapid emptying of the tray after use.

B.4. Ignition Systems

Research at Princeton has indicated that fuels below their flash point cannot be ignited by merely applying a source of energy (such as a propane torch) and that the use of wicks is not a satisfactory method of ignition.

Two different modes of ignition have been used at Princeton; both are equally convenient. The first uses an aluminum barrier to segment a small (approx. 2-3 cm wide) section at the end of the tray which is ignited with a Bernz-O-Matic propane torch. When the flame is fully established in this section, the barrier is removed and the flame is allowed to spread.

In the second mode of ignition, a small volume (approx. 1 cc) of a volatile fuel, usually hexane, is poured onto the fuel at one end of the tray and is spark ignited.

These two methods give excellent agreement, provided, of course, the measurements of the flame spreading velocity are sufficiently downstream (~ 14 inches) to be unaffected by the ignition process. (See Run Procedure later.)

B.5. Extinguishment System

By far the most convenient method of extinguishment is to cover the fuel (and flames) with a non-flammable board ('Transite' Sheet has been used at Princeton) and, hence, cut off the supply of oxygen. Manual manipulation of these "snuffer boards has been found satisfactory in work at Princeton.

Of course, elementary fire precautions require that fire extinguishers should be close at hand in case of accident. (It should also be noted here that the use of fire extinguishers directly on uncovered, and relatively large, areas of burning

fuel is not a good method of extinguishment since it serves only to "blow" the burning fuel throughout the test area).

B.6. Instrumentation

The basic instrumentation required to measure the flame spreading velocities is very simple since all that is required is instantaneous knowledge of the position of the flame and the time. A stopwatch and a scale is all that is required theoretically, but it has been found in practice that the flame spreading velocities measured in this manner are quite variable (up to $\pm 10\%$ scatter of results).

A better method is that which has been developed at Princeton. This employs a series of photo-transistors (L14B) which are set at known positions along the length of the tray, and the outputs from which are displayed on a Visicorder. (The prints for construction of the flame detector assembly are included with this report.)

A secondary system using a movie camera to record the progress of the flame along the length of the tray could also be considered. This has the advantage that it also gives a record of the flame height, but has the marked disadvantage that it is very time consuming to obtain the data from the filmed record.

B.7. Miscellaneous

A certain amount of miscellaneous apparatus is necessary.

- (a) Carbon dioxide fire extinguishers.
- (b) Flame-proof coats - for the protection of the operator.
- (c) Breathing apparatus - either compressed air supply or a filtration system (gas-mask-type). This is required for working in the smoke filled test area.
- (d) Thermostatted water bath - this is required to control the temperature of the fuel (and water if the fuel is floated on a layer of water). This requires a large volume tank (~ 30 gallons), a heating element, a temperature control unit and a stirrer.
- (e) Graduated measuring cylinders - to measure the exact quantities of fuel (and water) required for each run.
- (f) Thermometers - to measure the fuel temperature and the ambient air temperature.

B. STANDARDIZED RUN PROCEDURE

The pamphlet, "Operating and Safety Procedures for the Flame Spreading Apparatus",^{*} July 1969 is included with this report. All of the procedures will not be relevant to operations other than at Princeton and also some of the precautions necessary to obtain reproducible data are not mentioned explicitly and these are given below.

^{*} Appendix C

- (a) Exact control of the initial conditions of each test (fuel temperature and fuel depth) is essential in order to give reproducible results. It is also necessary to repeat each run two or three times and take mean values in order to minimize the errors.
- (b) Both the barrier/propane torch and the hexane/spark ignition methods perturb the flame spreading velocity in the early moments of flame spread. For this reason the first measurement on the flame should be at least 35 cm (14 inches) downstream of the ignition end of the tray, (i.e., if the photo-transistor method is used to measure flame spreading velocity, the first detector must be at least 14 inches from the ignition end).
- (c) Flame spreading is not a totally steady process. but more an oscillatory motion about a steady velocity. For this reason the measured value of flame spreading velocity is more accurate the further apart the measuring stations are positioned. It is suggested that the photo-transistors are at least 100 cm. apart to give the most accurate results.

D. PROGRAM OF TESTS

The suggested program of tests is to measure the flame spreading velocity of commercial fuels over a range of temperatures (ambient temperature to the flash temperature) and over a range of fuel depths (the smallest depth that will support a propagating flame to 50 mm deep layer).

VII. REFERENCES

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APPENDIX A: Some Physical and Chemical Properties of n-Decane

Sources: 1. API Technical Data Book-Petroleum Refining,
American Petroleum Institute, 1966

2. Other sources (as noted)

Formula: $C_{10}H_{22}$

Molecular Weight: 142.276

Boiling Point (at 1 atm): $174.12^{\circ}C$.

Fusion Point (in air at 1 atm): $-29.66^{\circ}C$

Note: There are 75 isomers of $C_{10}H_{22}$, the lowest
boiling point is $147^{\circ}C$; the highest boiling
point is $169.7^{\circ}C$.

Density of the Liquid: See Figure 4

Density of the Gas: (Note: The density of the gas may be
calculated at any given temperature and pressure using
a procedure outlined on page 6-53 of the API, Technical
Data Book-Petroleum Refining, American Petroleum
Institute (1966).

Absolute Viscosity of the Liquid: See Figure 5

Surface Tension (with air): See Figure 4

Specific Heat of the Liquid: See Figure 6

Specific Heat of the Gas: See Figure 6

Note: The specific heat of the gas can be calculated
at any given temperature and pressure using a
procedure outlined on page 7-155 of the API
Technical Data Book-Petroleum Refining, American
Petroleum Institute (1966).

Thermal Conductivity of the Liquid: See Figure 7

Thermal Conductivity of the Gas: See Figure 7

Heat of Vaporization: See Figure 6

Heat of Formation of the Liquid (at 25°C): -80 kcal/mole

Heat of Formation of the Gas (at 25°C): -59.6 kcal/mole

Free Energy of Formation of the Liquid (at 25°C): 4.13 kcal/mole

Free Energy of Formation of the Gas (at 25°C): 7.94 kcal/mole

Heat of Combustion of the Liquid at Constant Pressure (at 25°C):

Gross: 1620 kcal/mole or 11,387 cal/gm

Net: 1504 kcal/mole or 10,573 cal/gm

APPENDIX B: Procedure for Cleaning Glassware

All glassware was soaked overnight in a 50-50 mixture of 20% sulfuric acid and 20% nitric acid solution, and rinsed with distilled water and finally dried with dry N_2 . Once cleaned in this manner it was only necessary to rinse with acetone and dry with N_2 when changing samples or when changing from one organic liquid to another. The acid cleaning was only necessary when changing from an organic liquid to water or vice versa.

Procedure for Reading Meniscuses

The Fisher surface tensiometer is equipped with a millimeter scale which is affixed to the glass capillary tube. The top meniscus was read with little difficulty using the bottom of this meniscus. The lower meniscus in the reservoir (in which the capillary tube is immersed) was somewhat more difficult to read; however, the following procedure was standardized.

When viewed from below the relatively large reservoir surface reflects light. By raising one's eyes in a vertical direction the angle at which the surface is viewed gradually decreases until the eye level is reached such that the reflection is zero. At this height, the eye is in perfect alignment with the level reservoir surface and the reading on the millimeter scale may be made. Using this procedure, measurement errors of less than 1% were accomplished.

APPENDIX C: Operating and Safety Procedures for the Flame Spreading Apparatus*

I. General Precautions

1. Safety glasses and a fire-proof (orange) lab coat are to be worn during all operations where heated fuel, fire or pressures are involved.
2. Air filter masks (2) and compressed air breathing masks (2) are available and should be used when deemed necessary for the experiment. For this purpose, any area of fuel to be burned greater than 288 square inches (48 inches by 6 inches) is considered to give hazardous breathing conditions and breathing equipment MUST be used by the experimenters.
3. There must be at least one person in the vicinity (i.e., in the test cell building) during all operations specified in section (1) above. In addition, two operators must be in the test cell when fuel areas greater than 288 sq. inches are to be burned.
4. All volatile fuels (i.e., with flash point below 90°F) must be removed from the burning area before any flame spreading experiments are conducted.

* These procedures were prepared by R. MacKinven and A. Bozowski and approved by A. Beach for the Guggenheim Laboratories Safety Board.

5. All fuels except those to be burned within 24 hours are to be stored in the FUEL STORAGE SHED.
6. The safety-trash-can is to be emptied into the 'BURNABLE BIN' each morning before 8:30 A.M. Oily rags (which are deemed to be particularly hazardous) should not be left in the test area, but should be laid over the edge of the waste basket outside the cell.
7. The flashing warning lights must be in operation when fuel is being burned.
8. No fuel should be burned without first checking the Handbook values of flash point and toxicity. Flash points below 90°F are deemed hazardous for experimental purposes.

II. Start-Up Procedure

1. Switch on heater/cooler and stirrer in temperature controlled water bath first thing in the morning.
2. Switch on electronic counter and reset to zero. Switch on circulating fan.
3. Immerse the required volume of the required fuel in the temperature controlled water bath (at T_0 °C) to equilibrate the fuel exactly to the required temperature.
4. Rinse the tray required for the test with water (at T_0 °C), dry and align in front of the phototransistor detector unit.
5. Check the air temperature and make any necessary changes

with the heaters or the air conditioners. Check the temperature of the tray by placing a thermometer in it for five minutes.

III. Run Procedure

1. If the fuel is to be floated on water, measure out the required volume of water (at T_0 °C).
2. Check the temperature of the water and pour into the tray.
3. Switch off circulating fan and heating or air conditioning and allow the air currents to die away.
4. Remove fuel from temperature controlled water bath, check temperature and pour into the tray.
5. Refill measuring cylinder with the required volume of the required fuel in readiness for the next run and immerse in the constant temperature water bath. [This also allows time for the currents in the fuel which has been poured into the tray to die away].
6. Refill water bath to the mark.
7. Check the temperature of the fluid in the pan.
8. Close all doors and turn on the flashing yellow warning lights.
9. Check air temperature.
10. Ignite the pool of fuel, caused by immersing the appropriate metal barrier one inch from the right hand end of the tray, with the Bernz-O-Matic torch. (an orange fire-proof coat MUST be worn).

11. Allow the pool to become fully ignited and then lift the barrier and allow the flame to propagate.
12. Shut off torch and place in area away from fuels or rags whilst the torch flame dies away.
[N.B. Ignition may also be accomplished by placing a small amount of hexane at the end of the tray and lighting it with the spark ignitor.]
13. Extinguish the fire, after all the required observations have been made, by placing the "smother boards" directly on the tray.
14. Switch on the circulating fan and the extractor fan (and the air conditioning, if necessary), open external door and switch off warning lights.
15. Empty the burned fuel and water into the collecting jar and rinse tray with water at T_0 °C.
16. Dry the tray.
17. Transfer all data from the run into the laboratory notebook.
18. Switch off extractor fan and close external door.
19. Repeat operations (1) through (18) for the next run.

IV. Emergency Procedures

1. Three CO₂ fire extinguishers are located inside the test cell for rapid fire extinguishment. Three more CO₂ fire extinguishers are located just outside the cell door.

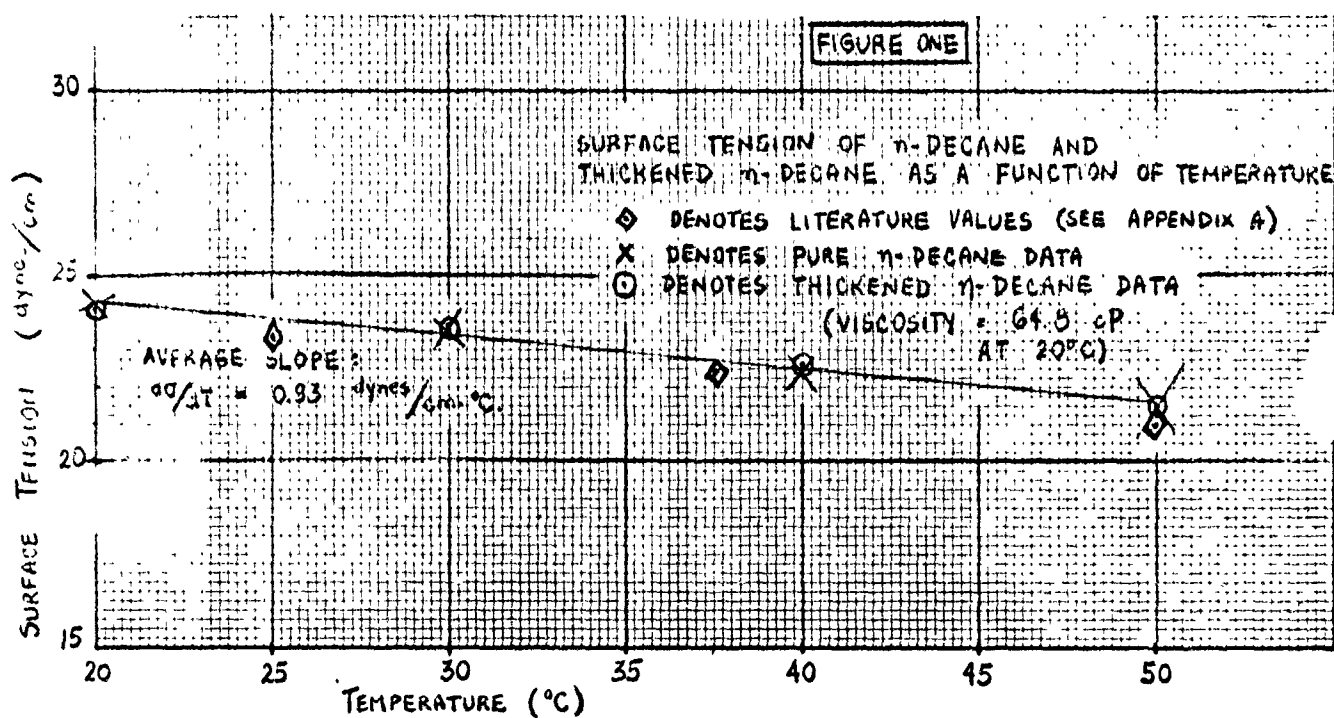
2. Should burning fuel be splashed on the lab coat, the coat should be quickly abandoned or if this is impossible, the overhead shower or fire blanket, both located in the cell, should be used to extinguish the fire.
3. Summon help with short, quick blasts on the siren.

V. Shut-down Procedures

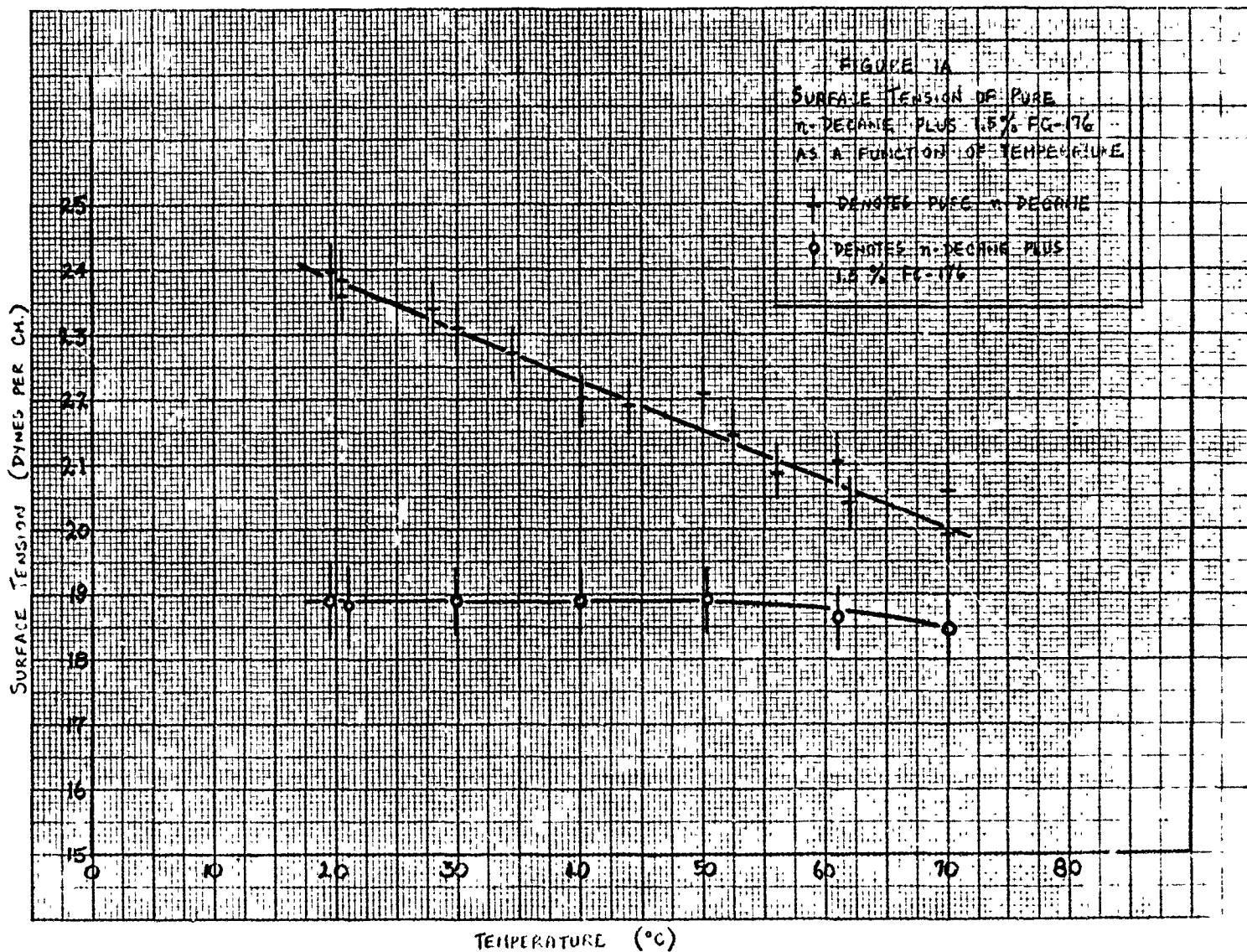
1. After completing the desired number of runs, fill the water tank.
2. The thermostat should be set and the circulating fan switched on to maintain the required room air temperature overnight.
3. Bring sufficient fuel from the storage shed for the runs which are projected to be completed the next day.
4. Switch off all apparatus not mentioned above, close the door and switch off the lights.

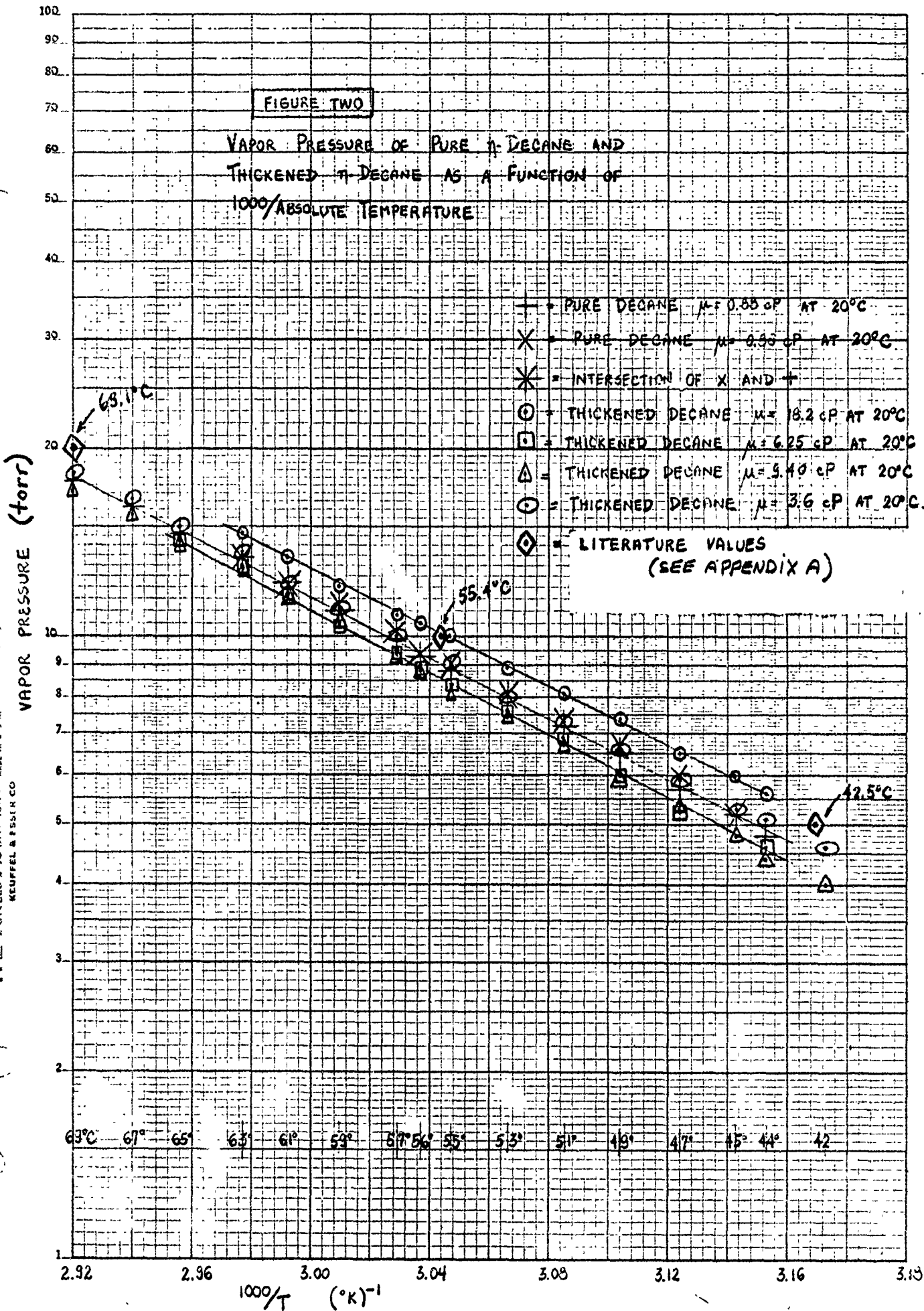
VI. Fuel Retention

1. Expensive fuels are to be retained and processed for further use. The fuels are separated from the water by decanting or siphoning. The contaminated fuel is then distilled and the appropriate boiling fraction stored for future use.
2. Care should be taken in order not to waste fuel.



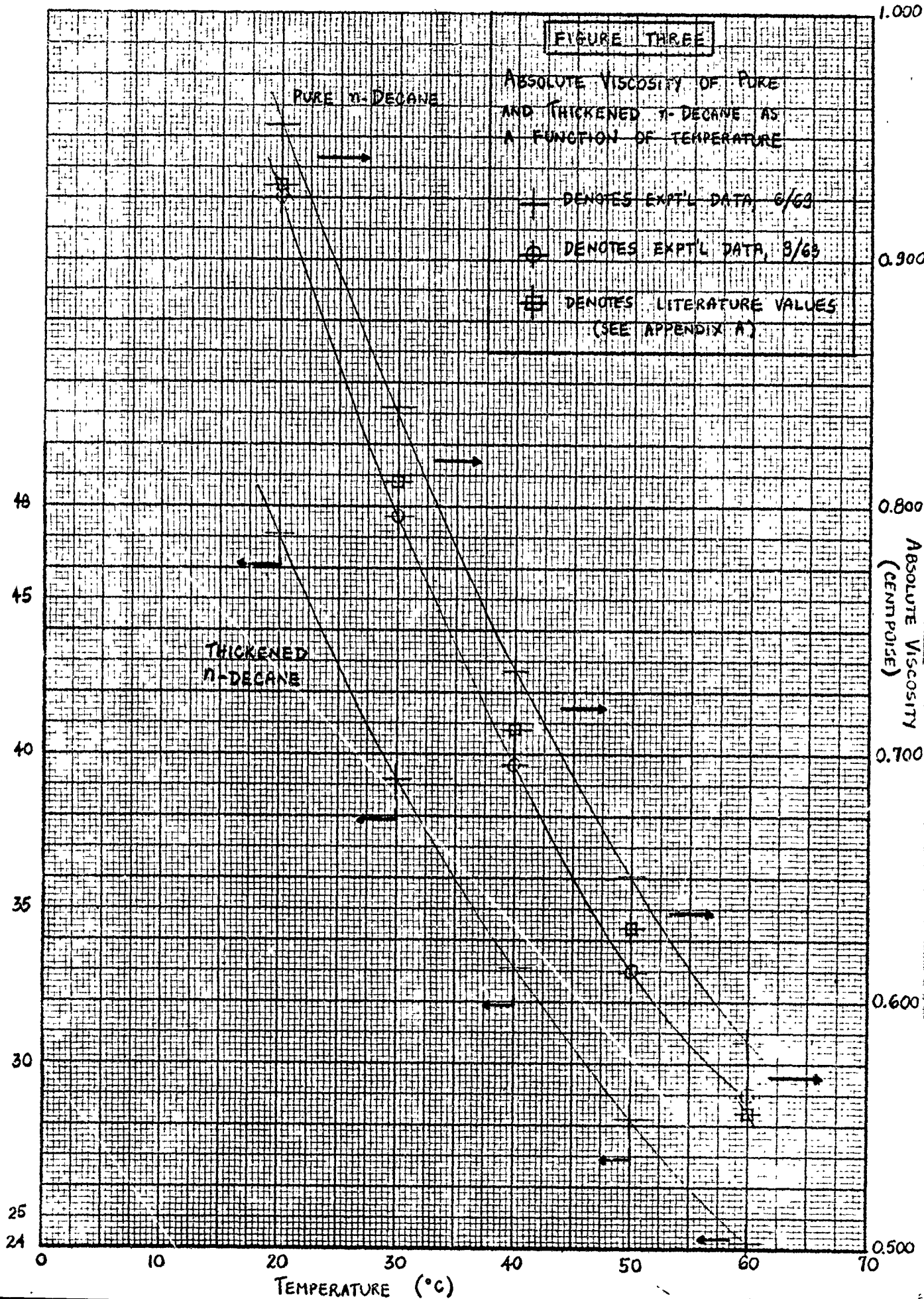
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7 X 10 INCHES 43M IN 9 S A
KEUFFEL & ESSER CO.





ABSOLUTE VISCOSITY
(CENTIPOISE)

K&E 10 X 10 TO 1/2 INCH 46 1320
7 X 10 INCHES
KEUFFEL & ESSER CO



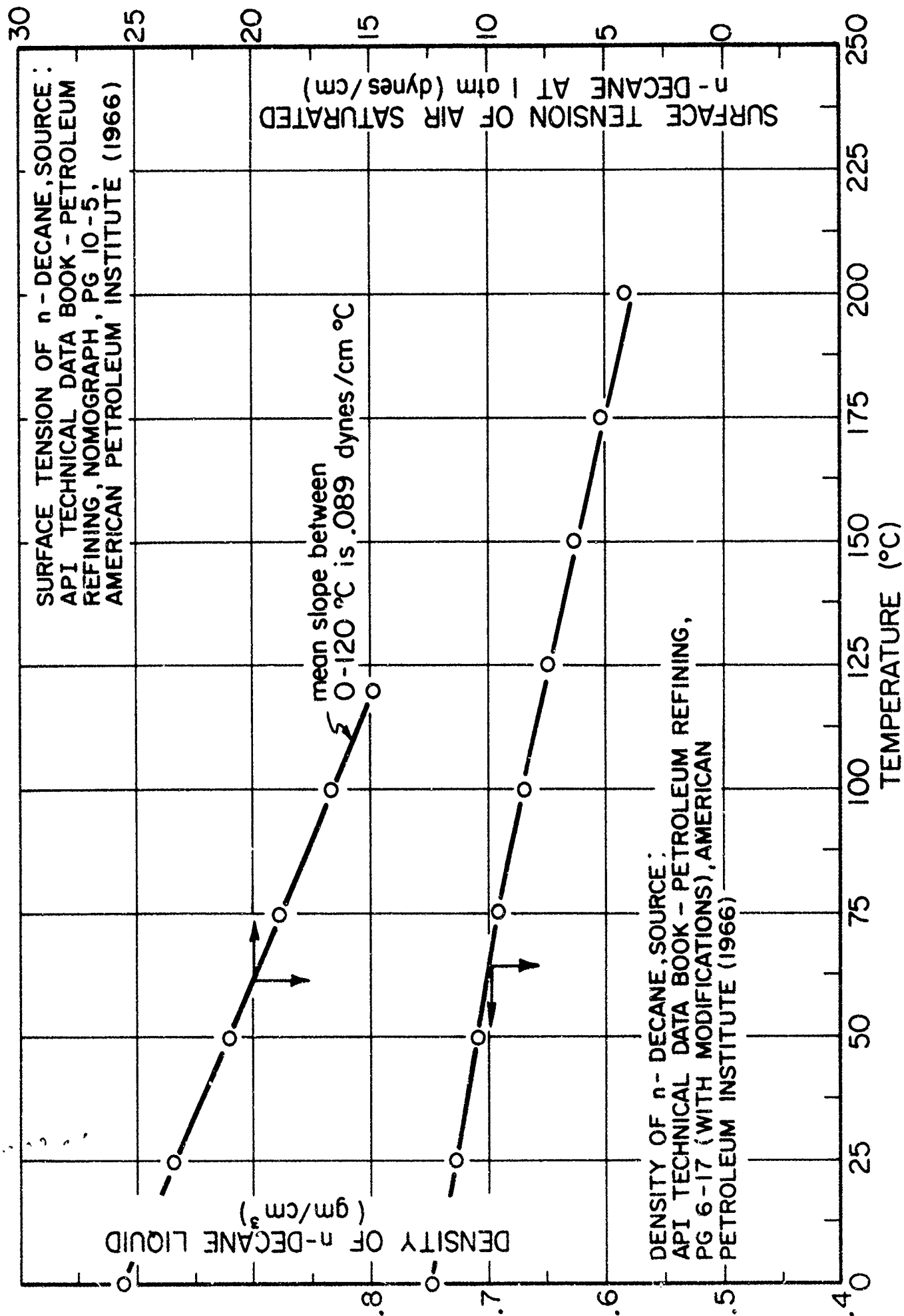


FIGURE 4

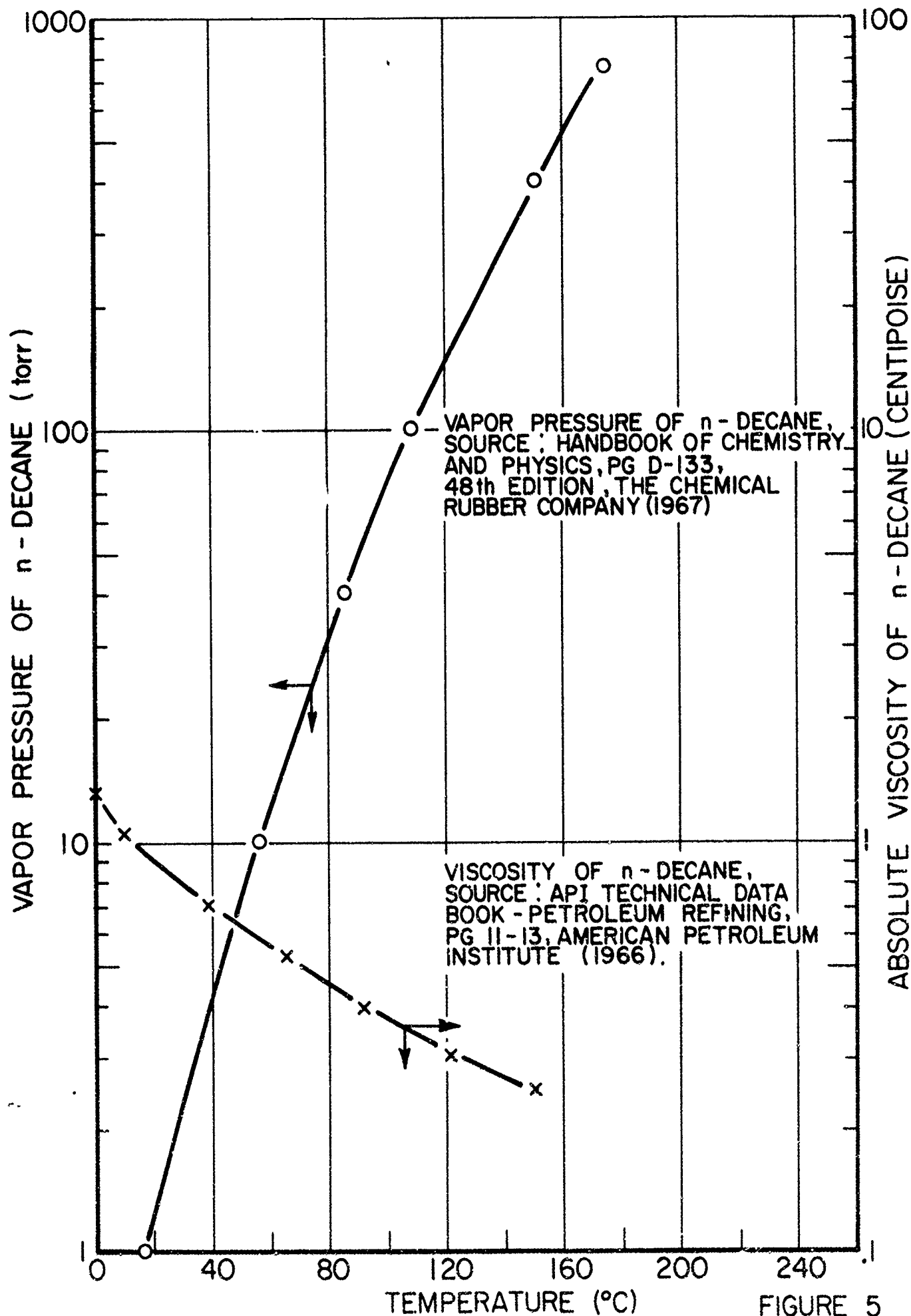


FIGURE 5

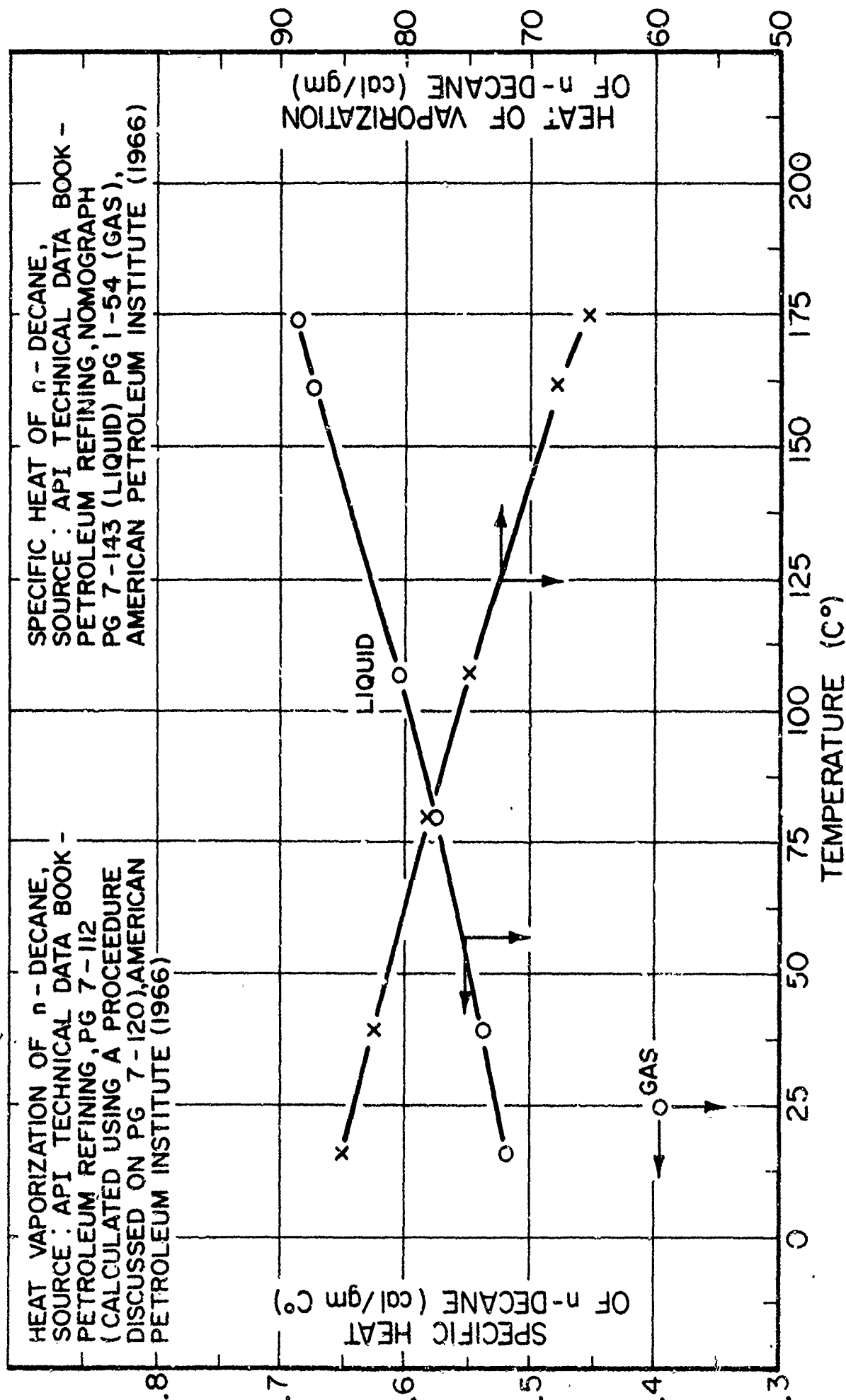


FIGURE 6

THERMAL CONDUCTIVITY OF n-DECANE LIQUID,
SOURCE: API TECHNICAL DATA BOOK -
PETROLEUM REFINING, PG 12-13, AMERICAN
PETROLEUM INSTITUTE (1966). (THIS SOURCE
LISTS THE TWO VALUES AND RECOMMENDS
LINEAR INTERPOLATION BETWEEN THESE VALUES.)

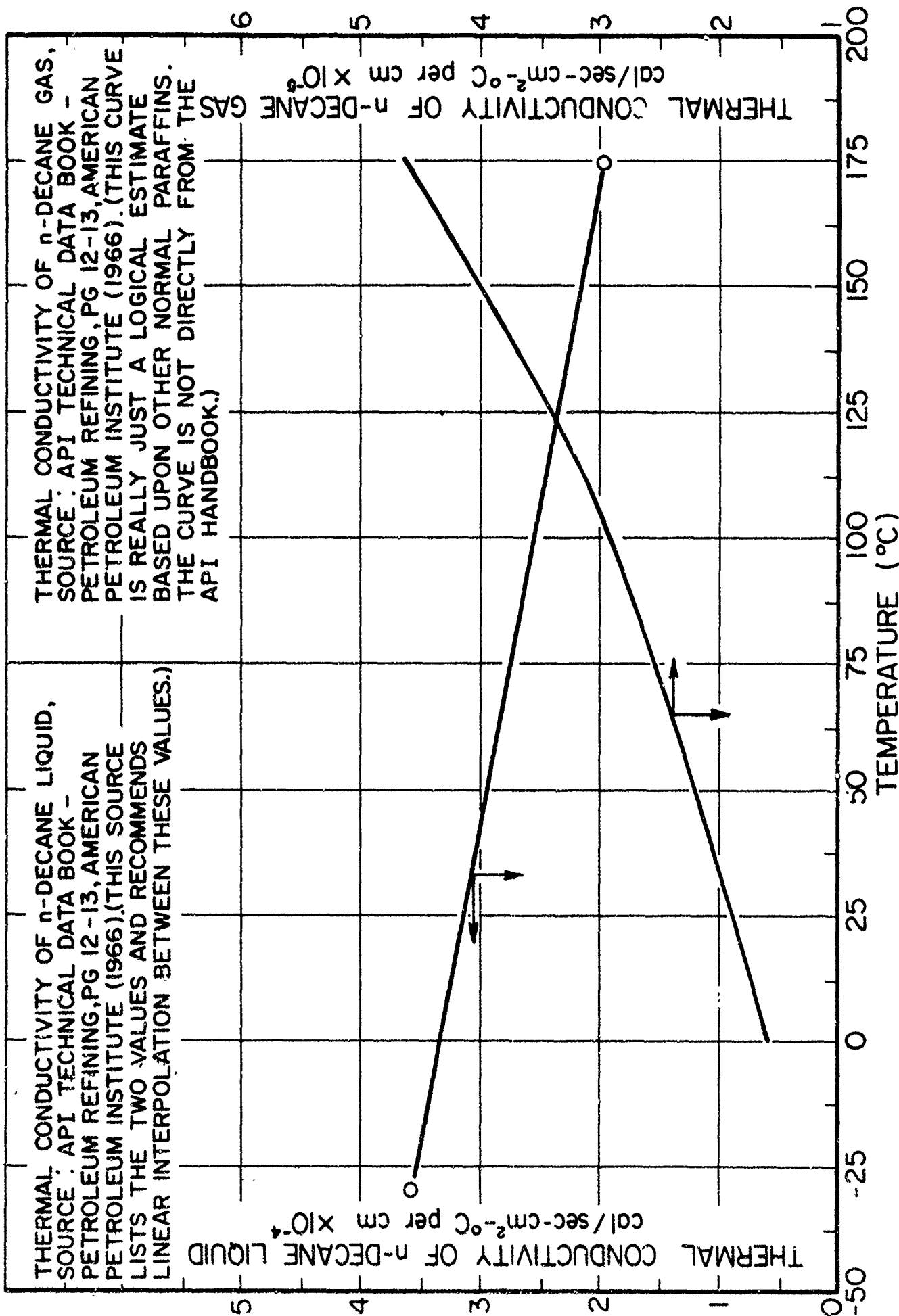
THERMAL CONDUCTIVITY OF n-DECANE GAS,
SOURCE: API TECHNICAL DATA BOOK -
PETROLEUM REFINING, PG 12-13, AMERICAN
PETROLEUM INSTITUTE (1966). (THIS CURVE
IS REALLY JUST A LOGICAL ESTIMATE
BASED UPON OTHER NORMAL PARAFFINS.
THE CURVE IS NOT DIRECTLY FROM THE
API HANDBOOK.)

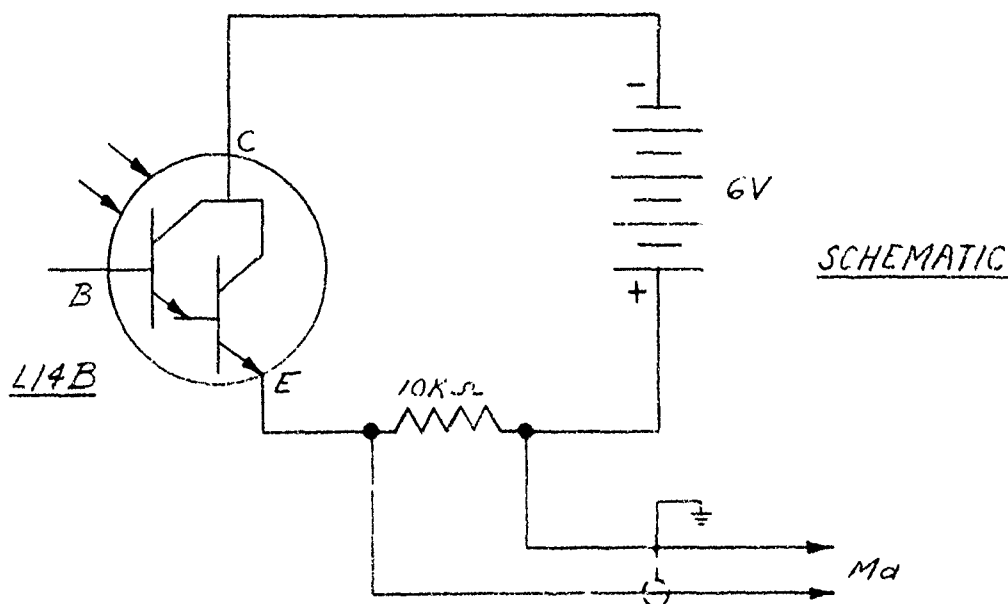
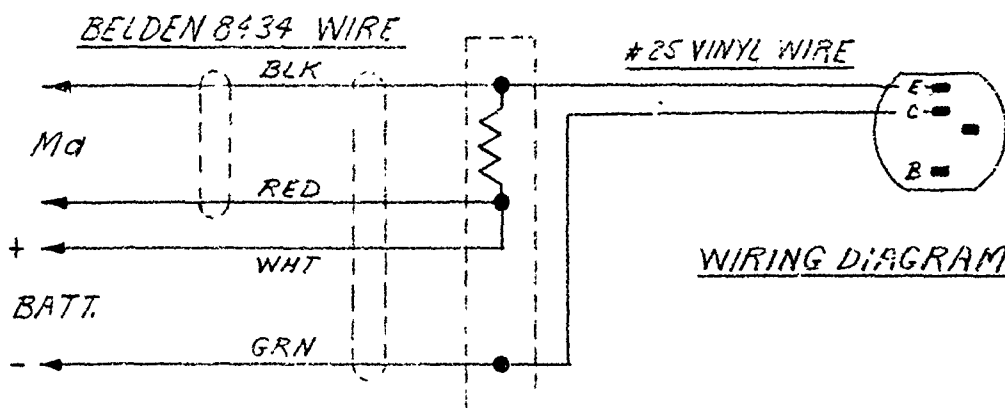
THERMAL CONDUCTIVITY OF n-DECANE LIQUID
cal/sec-cm²-°C per cm x 10⁻⁴

THERMAL CONDUCTIVITY OF n-DECANE GAS
cal/sec-cm²-°C per cm x 10⁻⁴

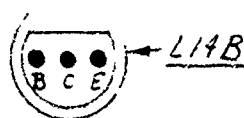
TEMPERATURE (°C)

FIGURE 7





LOOKING DOWN
ON RECEPTACLE



LOOKING DOWN
ON SENSOR

SCALE: NONE	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)	NO.	CHANGE	BY	APP.
DATE: 11-9-65		NO. REQ'D:			
DESIGNED:	.XXX = $\pm .002$ "	MAT'L:			
DRAWN: J.J.	.XX = $\pm .005$ "	FINISH UNLESS NOTED:			
CHECKED:	FRACTIONS = $\pm 1/32$ "	TITLE:	WIRING DIAGRAM - FLAME DETECTOR		
APP'D:	ANGLES = $\pm 1^\circ$	DWG. NO.	61055-002A		
GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY					

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PRINCETON UNIVERSITY

Form No. 5C

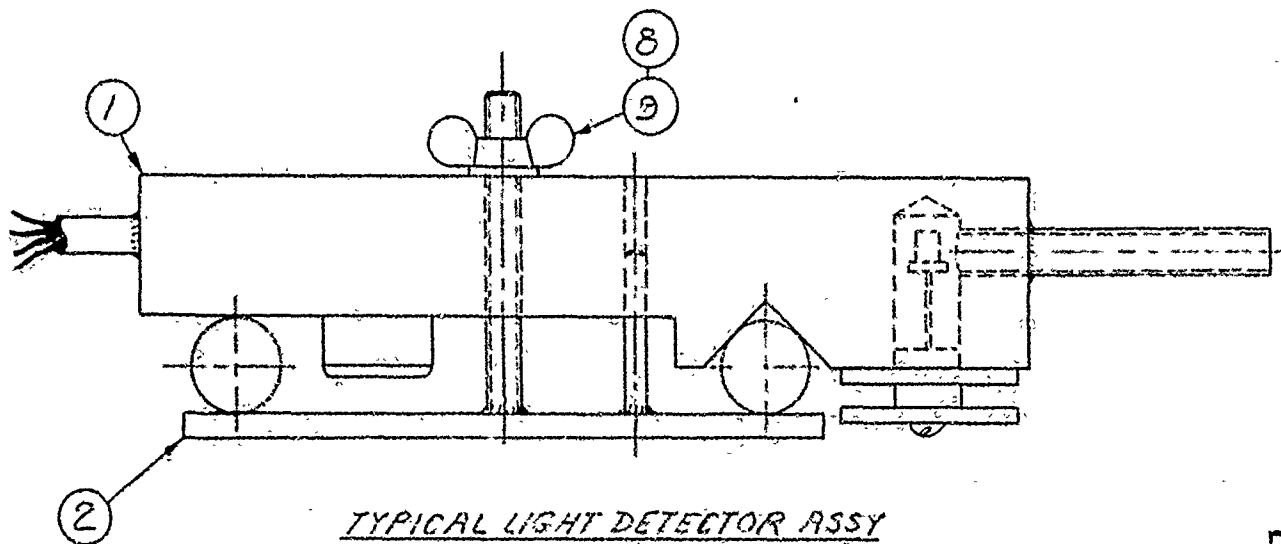
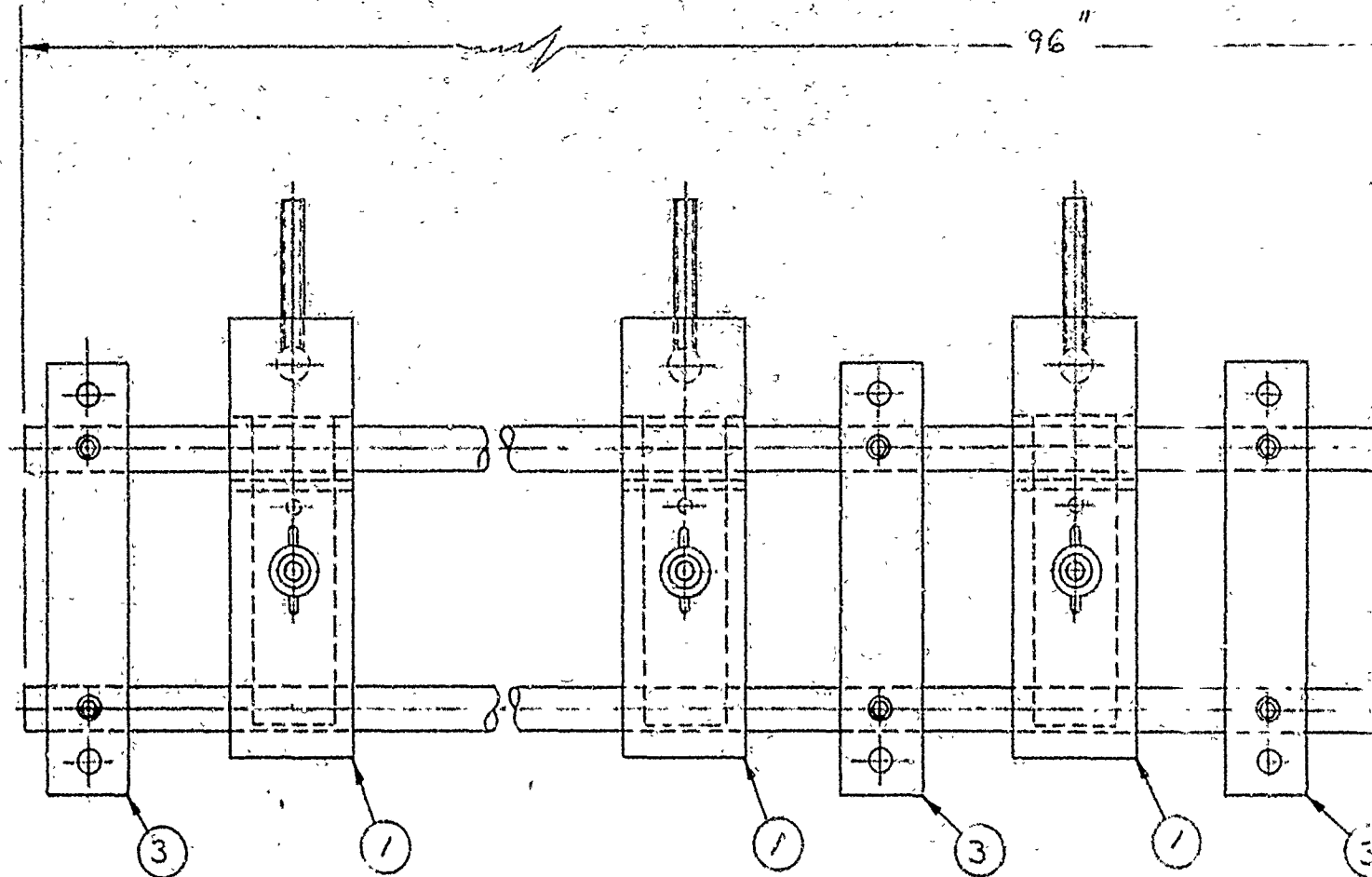
Sheet 1 of 1

BILL OF MATERIALS For Drawing FLAME DETECTOR ASSY

6175M003A

Date 11-5-68

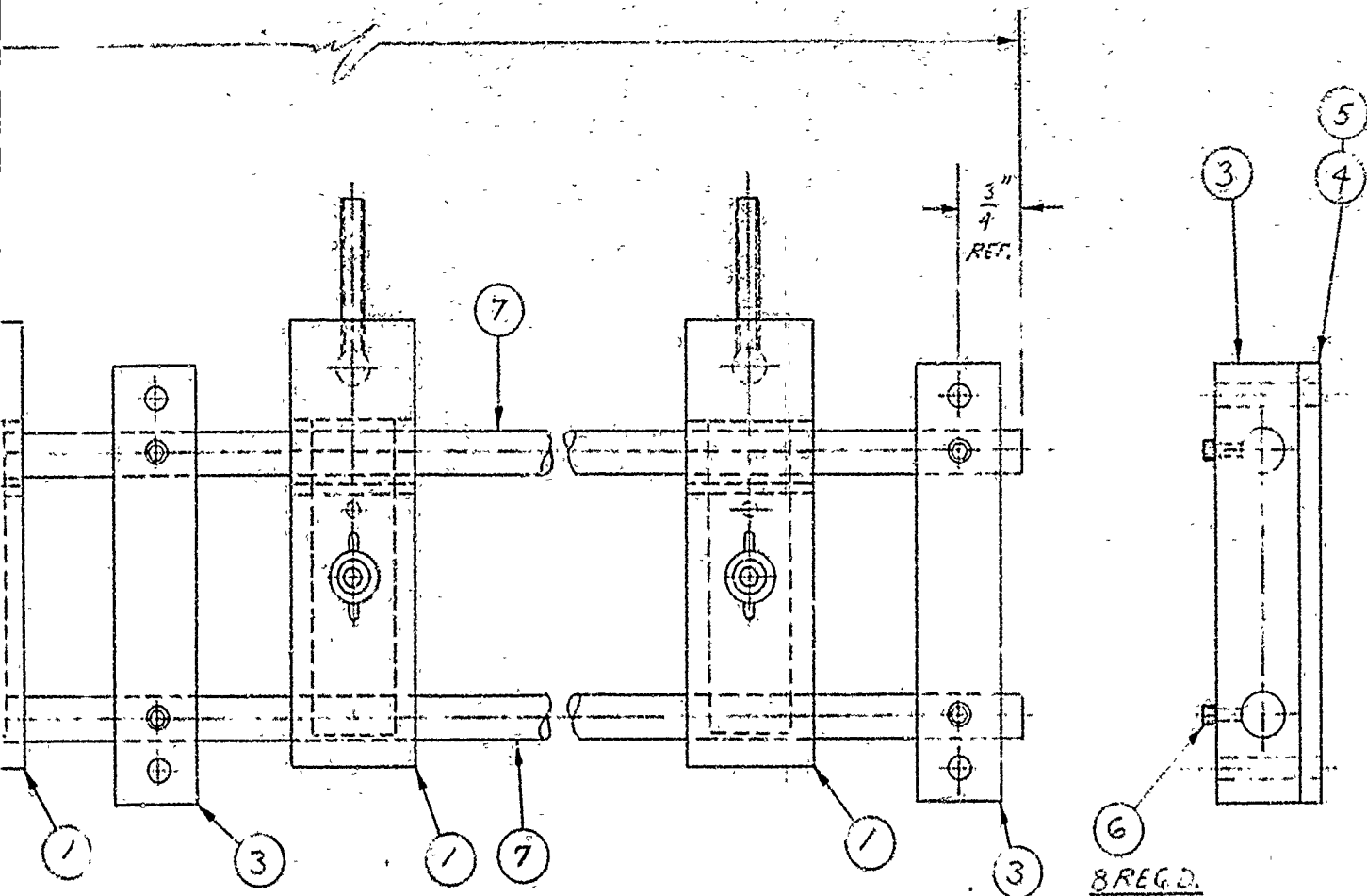
Dash No.	Description	Material	Size	Qun.	G. I. Drawing Number
1	ELECTRICAL ASSY	—	—	5	61055 005A
2	HOUSING RETAINER	—	—	5	61055 004A
3	BLOCK	BRASS	1" SQ. BAR X $5\frac{1}{8}$ "	4	61055 003B
4	SHIM	BRASS	$\frac{1}{8}$ " X 1" BAR X $5\frac{1}{8}$ "	4	61055 003C
5	SHIM	BRASS	$\frac{1}{4}$ " X 1" BAR X $5\frac{1}{8}$ "	12	61055 003C
6	500 HD SCREWS	STEEL	#8-32 X $\frac{3}{8}$ LG	8	
7	RAILS	ACCURACY STOCK ROUND	RYEASON & #13 $\frac{1}{2}$ " DIA X 3 FT. LG	2	
8	WING NUT	STEEL	#10-24 THREAD	5	
9	WASHER	STEEL	#10	5	



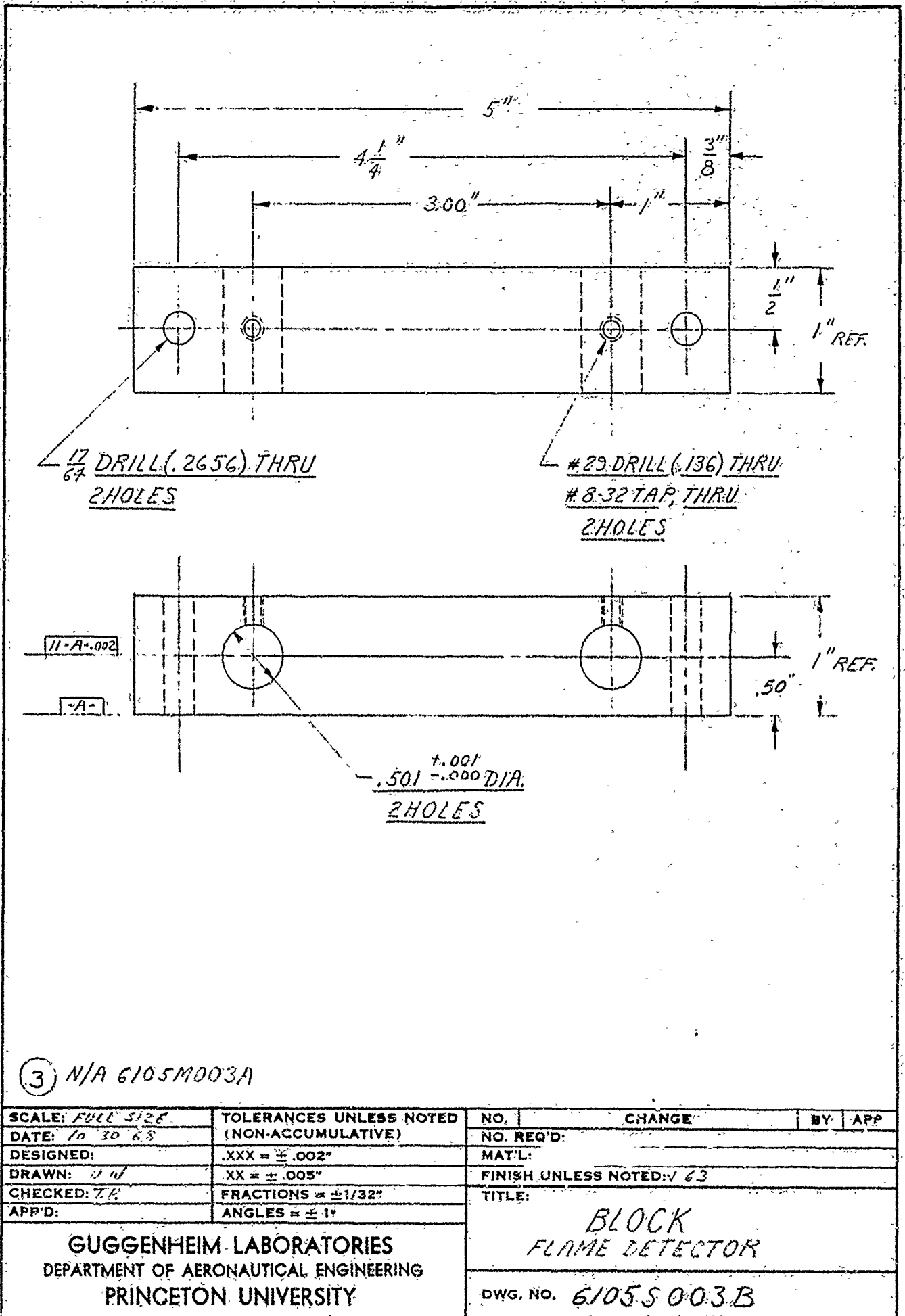
TYPICAL LIGHT DETECTOR ASSY
5REQD

SCALE
DATE:
DESIG
DRAW
CHECK
APP'D:

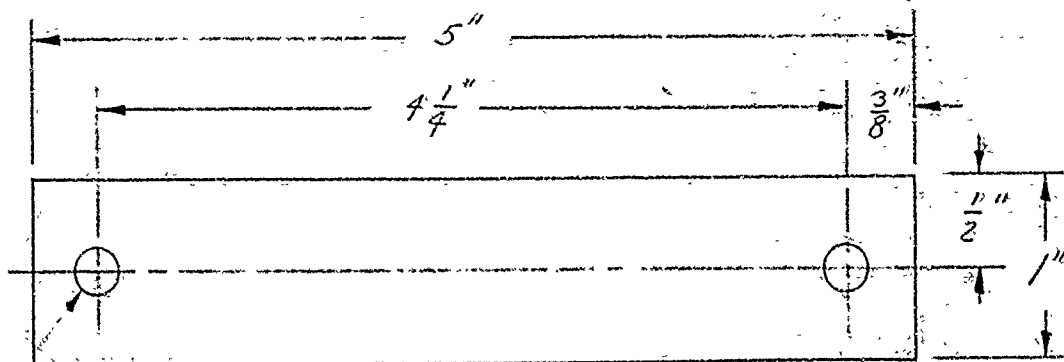
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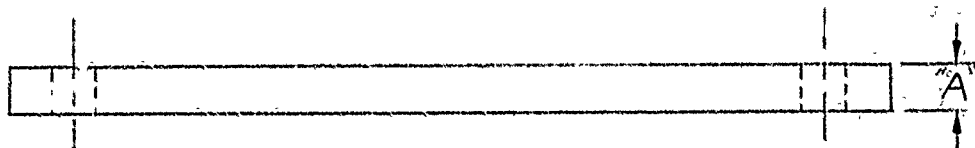
SCALE: $\frac{1}{4}$ SIZE & NOTED	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)	NO.	CHANGE	BY	APP
DATE: 11-5-68		NO. REQ'D:			
DESIGNED:	.XXX = $\pm .002$ "	MAT'L:			
DRAWN: U.W.	.XX = $\pm .005$ "	FINISH UNLESS NOTED: V			
CHECKED: Z.P.	FRACTIONS = $\pm 1/32$ "	TITLE:			
APP'D: Z.P.	ANGLES = $\pm 1^\circ$	FLAME DETECTOR ASSY			
GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY		DWG. NO.	6105M003A		



SCALE: FULL SIZE	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)	NO.	CHANGE	BY	APP
DATE: 10 30 68		NO. REQ'D:			
DESIGNED:	.XXX = $\pm .002"$	MAT'L:			
DRAWN: J W	.XX = $\pm .005"$	FINISH UNLESS NOTED: V 63			
CHECKED: T P	FRACTIONS = $\pm 1/32"$	TITLE:			
APP'D:	ANGLES = $\pm 1^\circ$				
GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY		BLOCK FLAME DETECTOR			
		DWG. NO. 6105S003B			



17
69 DRILL (.2656) THRU
2 HOLES TO MATCH (3) 6105S003B



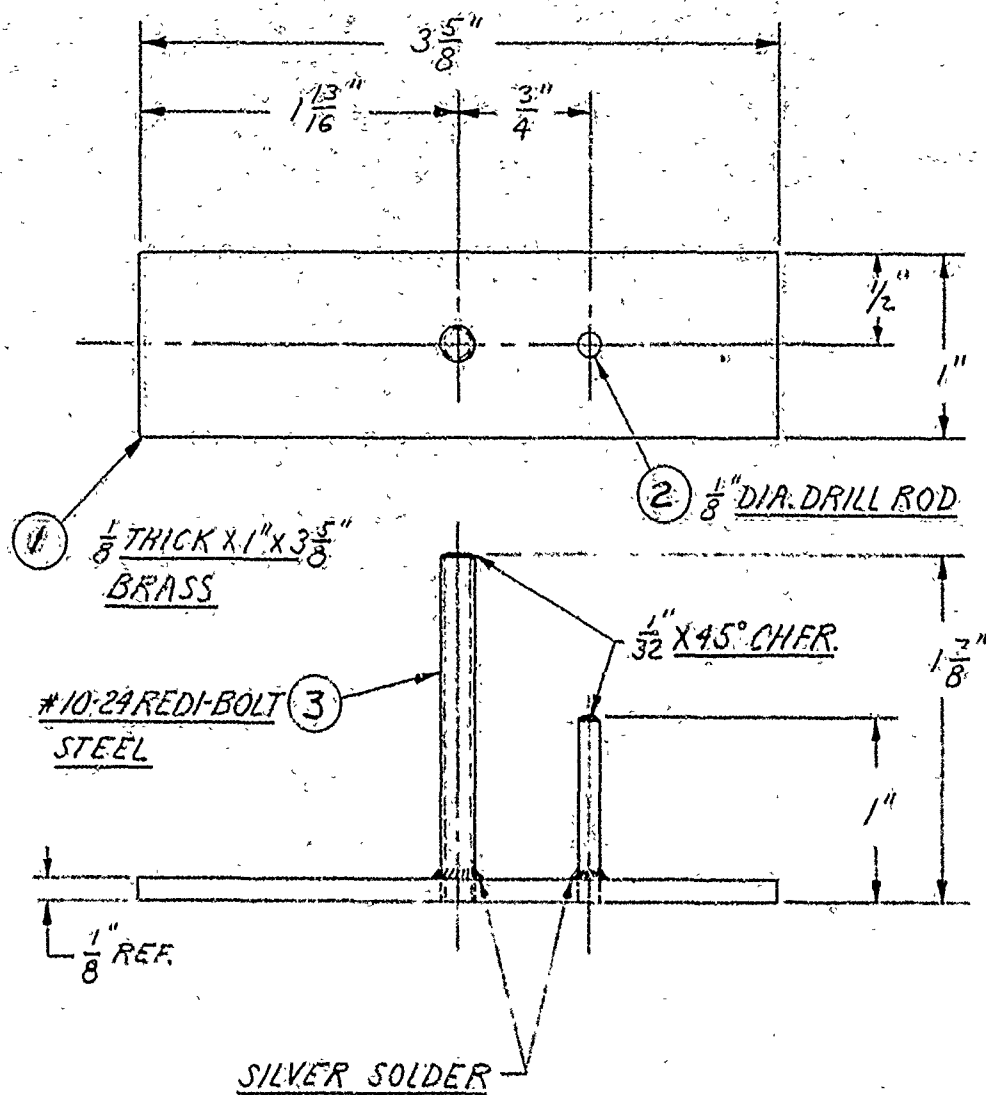
(5) "A" = $\frac{1}{4}$ " 12 REQD.

(4) "A" = $\frac{1}{8}$ " 4 REQD.

(5)

(4) N/A 6105M003A

SCALE: <u>FULL SIZE</u>	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)	NO.	CHANGE	BY	APP.
DATE: <u>10-31-68</u>		NO. REQ'D			
DESIGNED:	.XXX = $\pm .002$ "	MAT'L:			
DRAWN: <u>U.W.</u>	.XX = $\pm .003$ "	FINISH UNLESS NOTED: <u>V 6.3</u>			
CHECKED: <u>T.R.</u>	FRACTIONS = $\pm 1/32$ "	TITLE:			
APP'D:	ANGLES = $\pm 1^\circ$	<u>SHIMS</u> <u>FLAME DETECTOR</u>			
GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY		DWG. NO. <u>6105S003C</u>			



② N/A 6105M003A

SCALE: FULL SIZE	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)	NO. CHANGE	BY	APP.
DATE: 10-31-68		NO. REQ'D:		
DESIGNED:	.XXX = $\pm .002$ "	MAT'L:		
DRAWN: U.N.	.XX = $\pm .005$ "	FINISH UNLESS NOTED: V.63 & STOCK AS IS		
CHECKED: T.R.	FRACTIONS = $\pm 1/32$ "	TITLE:		
APP'D:	ANGLES = $\pm 1^\circ$	HOUSING RETAINER FLAME DETECTOR		
GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY		DWG. NO. 61055 004A		

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DEPARTMENT OF AERONAUTICAL ENGINEERING
PRINCETON UNIVERSITY

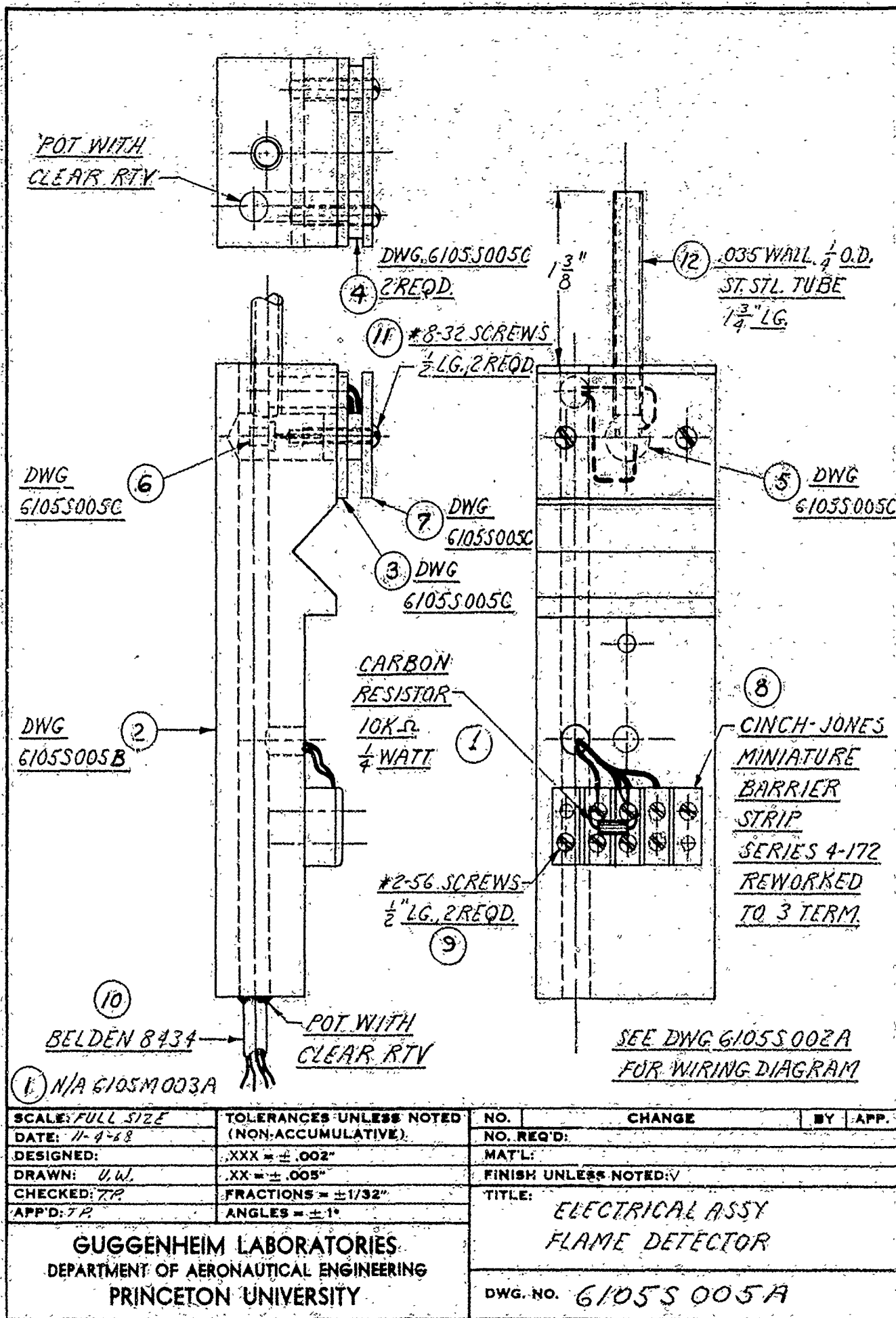
Form No. 5C

Sheet 7 of 7

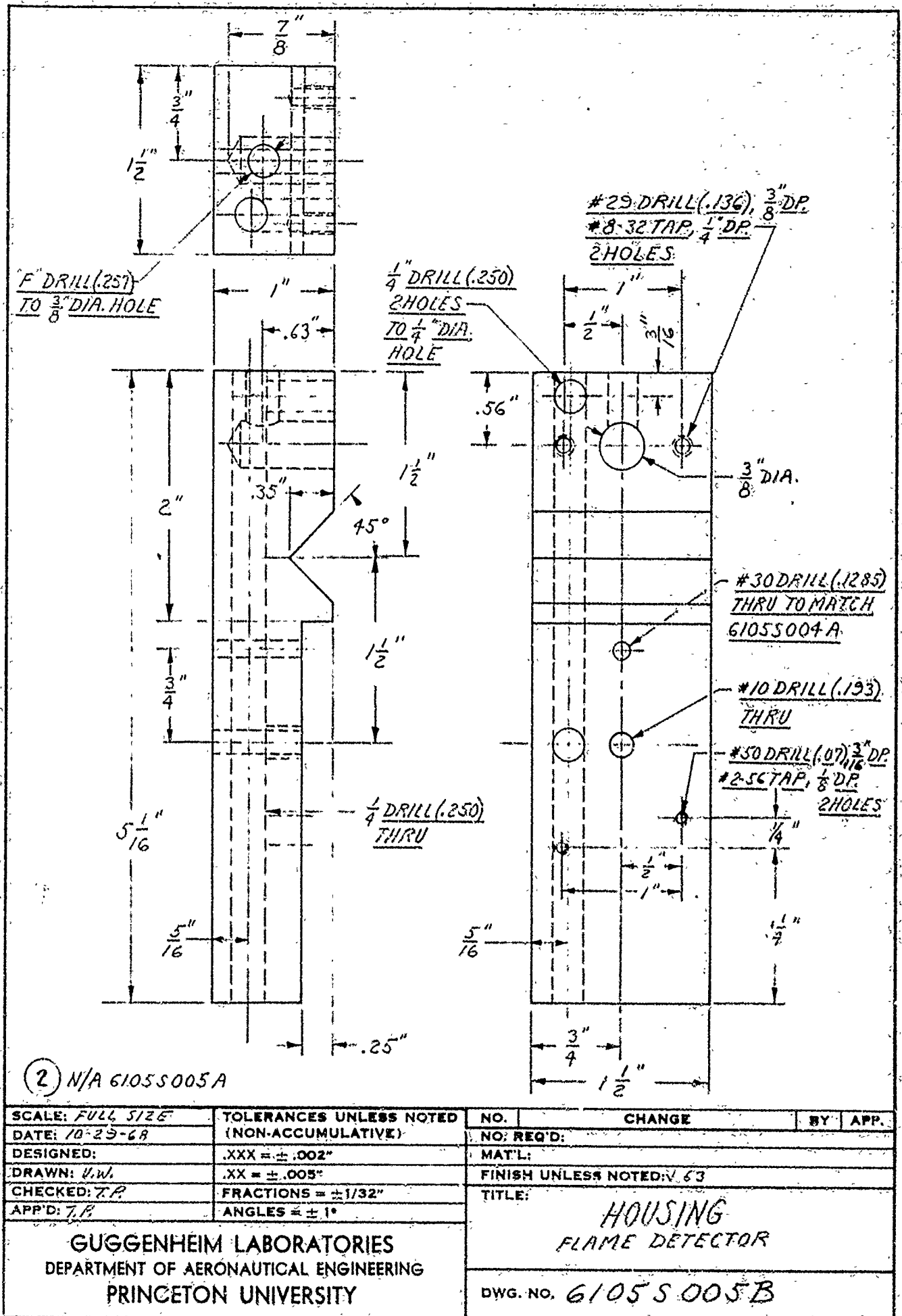
BILL OF MATERIALS For Drawing ELECTRICAL ASSY-FRAME DETECTOR 61555 005A

Date Jan 7-68

[illegible]



SCALE: FULL SIZE	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE). XXX = ± .002" XX = ± .005" FRACTIONS = ± 1/32" ANGLES = ± 1°	NO.	CHANGE	BY	APP.
DATE: 11-4-68		NO. REQ'D:			
DESIGNED:		MAT'L:			
DRAWN: U.W.		FINISH UNLESS NOTED: V			
CHECKED: TP		TITLE:			
APP'D: TP		ELECTRICAL ASSY FLAME DETECTOR			
GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY		DWG. NO. 6105S 005A			



SCALE: FULL SIZE	TOLERANCES UNLESS NOTED (NON-ACCUMULATIVE)	NO.	CHANGE	BY	APP.
DATE: 10-25-68		NO. REQ'D:			
DESIGNED:	.XXX = ± .002"	MAT'L:			
DRAWN: V.W.	.XX = ± .005"	FINISH UNLESS NOTED: V. 63			
CHECKED: T.R.	FRACTIONS = ± 1/32"	TITLE:	HOUSING FLAME DETECTOR		
APP'D: T.R.	ANGLES = ± 1°				
GUGGENHEIM LABORATORIES DEPARTMENT OF AERONAUTICAL ENGINEERING PRINCETON UNIVERSITY		DWG. NO.	6105S005B		