NATIONAL BUREAU OF STANDARDS REPORT

4288

EFFECT OF CHANGES OF ENGINE SPEED ON THE CAPACITY OF THE 1/2-TON THERMO KING REFRIGERATING UNIT, MODEL K-10

by

Minoru Fujii
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to

Mechanical Engineering Division
Headquarters, Quartermaster Research & Development Command
Natick, Mass.

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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NBS PROJECT **NBS REPORT**

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Abstract

A study was made of the effect of speed change on the net refrigerating capacity of a plug-type refrigerating unit, Model K-10, manufactured by the U. S. Thermo Control Company of Minneapolis, Minn. The stock unit, of nominal 1/2-ton capacity, is belt-driven by a gasoline engine fixing the speed ratios between engine and compressor and between engine and the condenser and evaporator fans at about 1.34 and 1.59, respectively. The results showed that there was an optimum speed for the unit near to the design speed of 2400 rpm. A maximum net refrigerating capacity was obtained for engine speeds in the range from 2400 rpm to 2700 rpm for all refrigerator temperatures below 35°F. There was no significant change in capacity in this speed range. The maximum capacity values were about 17000 Btu/hr for a refrigerator temperature of 35°F, 9300 Btu/hr for a refrigerator temperature of 10°F, and 7400 Btu/hr for a refrigerator temperature of 2°F in an ambient temperature of 110°F. It was observed that the net refrigerating capacity increased almost linearly with refrigerator temperature. The gasoline consumption rate increased with engine speed, and was higher for any given speed at a refrigerator temperature of 10°F than for either higher or lower refrigerator temperatures. During approximately 500 hours of operation some adjustment of belt tension and servicing of the distributor points on the gasoline engine was required, but there were no component failures, no breaks in the refrigerant lines, and no failures in the gasoline engine.

1. INTRODUCTION

At the request of the Office of The Quartermaster General, tests were made of a 1/2-ton gasoline-engine driven refrigerating unit, Model K-10, of the plug type manufactured by the

U. S. Thermo Control Company of Minneapolis, Minnesota. It was tested in a 600 cubic foot, portable, walk-in refrigerator of the type usually equipped with this type refrigerating unit in the field. The refrigerator was employed as a calorimeter for the purpose of these tests.

The purposes of this investigation can be divided into two main parts as follows:

A. Measurement of the net refrigerating capacity of the unit at design compressor speed for an ambient temperature of 110°F and at refrigerator temperatures of 35°F, 10°F and the lowest temperature attainable without internal load in the refrigerator.

B. Investigation of the effect of changing the compressor speed on net refrigerating capacity of the unit when the speed ratios between the compressor, and the evaporator and condenser fans remained fixed at the design value.

The results observed with respect to the above two objectives are reported in Parts A and B of the section on Test Results, respectively.

2. DESCRIPTION OF TEST SPECIMEN

The specimen refrigerating unit was identified as follows:

(NBS Test Specimen 100-53)
U.S. Thermo Control Co., Minneapolis, Minn.
Model K-10
Serial Number GQ109QS

The unit was of the plug type and used Freon 12 as the refrigerant. The compressor was identified as Thermo-King, Model 2R, Serial Number 2093. The refrigerating unit was driven by a gasoline engine manufactured by D. W. Onan & Sons, Inc., of Minneapolis, Minnesota with the following nameplate data:

Model CK-MS
Specification 190J
Serial Number 101-444545
Maximum Horsepower 10.1 at 3,000 R.P.M.

Three photographs of the specimen refrigerating unit are attached as Figures 1 - 3 inclusive. Figure 1 and Figure 2 show the exterior views of the front (condenser section) and rear (evaporator section) respectively. Figure 3 is a side view showing the relative locations of the engine, compressor, condenser and evaporator section with the top perforated panels removed and side doors opened.

The condenser fan was of the propeller type made of cast aluminum. It has 12 blades, 6 1/4"long, and the diameter was 20 inches. Ambient air was drawn through the condenser, forced around the engine and compressor and discharged from the top and sides of the condensing unit section.

The evaporator fan was also of the propeller type made of cast aluminum. It had 12 blades, 5" long, and the diameter was 20 inches. The air was drawn from the top and sides of the evaporator section and forced through the evaporator. The air leaving the evaporator was discharged into the refrigerator through a duct of about one third the cross-section area of the face of the evaporator. The top and side panels of the discharge duct projected straight out from the edges of the evaporator whereas the bottom panel projected upward, thereby reducing the cross-sectional area to approximately one-third of the evaporator face as shown in Fig. 2 and 3. A defrosting damper pivoted on a horizontal axis was located in the discharge opening.

The condenser and evaporator fans were mounted on opposite ends of a common shaft. The pulleys of the engine, compressor and fans were connected in that order in a clockwise direction, as viewed from the condenser end of the unit, by two Gates Vulco Ropes. These ropes, or belts, connected the pulleys in such a way that the direction of rotation of the fan pulley was opposite to that of the engine and compressor pulleys. The outside diameters of the engine, compressor, and fan pulleys were 6 1/4", 8" and 9 1/2", respectively.

The physical dimensions of the refrigerating unit were as follows:

(1) Gross weight, without batteries, lb., 703
(Gross weight indicated on nameplate 720 lbs)

(2)	Width	Height	Depth
Overall dimension, inches without batteries, including door handles and lifting hooks	44	33 1/2	57 1/2

	Width	Height	Depth
(3) Condensing unit section inches	44	33 1/2	24 1/2
(4) Evaporator section, in. including plug section but not the discharge duct	36 3/16	27 1/4	20 1/8

(5) Compressor
- a) Model - 2R
- b) Serial Number - 2093
- c) Type - 2 cylinder vertical
- d) Bore, inches - 2 1/4
- e) Stroke, inches - 1 3/4
- f) Speed, rpm, design - 1875
- f) Displacement, cu.in. - 13.91

(6) Condenser:

a)	Width, in. overall	31 3/4
b)	Height, in. overall	27 1/2
c)	Depth, in. overall	4 1/2
d)	Fin size, in.	27 1/2 x 3
e)	Fin spacing	8 per inch
f)	Tube size, in.	1/2 O.D.
g)	Number of tubes	66
h)	Series or parallel	22 tubes in series per circuit, 3 circuits in parallel
i)	Primary surface area, sq. ft.	20.5
j)	Secondary surface area, sq.ft.	218.3
k)	Total surface area, sq. ft.	238.8
l)	Ratio primary to total surface, %	8.6
m)	Tube material	Copper
n)	Fin material	Aluminum

(7) Engine

a)	Model number	CK-MS
b)	Specification	190J
c)	Serial number	101-444545
d)	Type	4 cycle, 2 cylinder opposed horizontal, air-cooled

(7)	Engine (Cont'd)	
	e) Material	Aluminum
	f) Speed, design, rpm	2400
	g) Rated maximum brake horsepower at 3000 rpm	10.1
	h) Lubrication	Force feed
	i) Fuel system	Pump feed to carburetor
	j) Ignition system	Special 12-volt motor-generator built into flywheel of engine provided automatic starting, battery charging and ignition.
	k) Cooling system	Fan on armature of engine generator forced air over engine block and finned cylinder heads as guided by engine shrouding.
	l) Governor	Pierce Governor Company GC 1408 9 1
(8)	Evaporator	
	a) Width, in. finned	31 1/8
	b) Height, in. finned	22 5/8
	c) Depth, in. finned	6
	d) Fin size, in.	6x22 1/2
	e) Fin spacing	5 per inch
	f) Tube size, in.	1/2 O.D.
	g) Number of tubes	108
	h) Series or parellel	18 tubes in series per circuit, 6 circuits in parallel
	i) Primary surface area, sq. ft.	36.6
	j) Secondary surface area, sq. ft.	245.0
	k) Total surface area, sq. ft.	281.6
	l) Ratio primary to total surface, %	13.0
	m) Tube material	Copper
	n) Fin "	Aluminum

3. TEST PROCEDURE

The specimen refrigerating unit was installed in a 600 cu. ft. portable walk-in refrigerator for the capacity tests. The refrigerator was located in a test room where the ambient

temperature could be controlled. Refrigerator temperature was maintained at the desired level by an electronic rheostat controlling the input to electric heaters which were used for the internal load. The heat output of these heaters was measured by means of watthour meters in the supply circuits. Temperatures were measured by means of calibrated thermocouples using an electronic, constant-balance type potentiometer.

The engine speeds were varied by adjusting the governor. The engine, compressor and fans were connected with a pair of Gates Vulco Ropes throughout the tests. Therefore, the compressor and fan speeds were proportional to the engine speed as determined by the constant pulley ratio.

After steady state test conditions were reached, they were maintained for a period of at least five hours while observations of pressures, temperatures, speeds, voltage, current and wattage were made at 30-minute intervals.

4. TEST RESULTS

Part A

In preparation for the capacity determinations, a test was made to determine the heat transmission factor of the 600 cubic foot, portable, walk-in refrigerator used as a calorimeter. During this test the refrigerator temperature averaged 30.1°F and the ambient temperature averaged 129.9°F for five hours during steady state conditions. The heat transmission factor was computed to be 65.03 Btu/hr per °F temperature difference between inside and outside.

The net refrigerating capacity of the Model K-10 Thermo King unit at design engine and compressor speeds of 2400 RPM and 1870 RPM respectively were: 7,370 Btu/hr, 9,230 Btu/hr and 16,620 Btu/hr at refrigerator temperature of 1.8°F, 10.9°F and 35.4°F respectively. The net refrigerating capacity varied approximately in linear relation to the refrigerator temperature at these engine and compressor speeds. This is shown graphically by one of the curves in Fig. 4. The net refrigerating capacity increased 290 Btu/hr per degree rise in refrigerator temperature, on the average.

Part B

Results of the capacity tests for a range of engine speed from 1800 rpm to 3000 rpm at an ambient temperature of

110°F and refrigerator temperatures of 35°F, 10°F, and lowest attainable without internal load are summarized in Table 1 and shown graphically in Fig. 5.

The engine speed bore an average ratio of 1.34 to 1 relative to the compressor speed and 1.59 to 1 relative to the fan speed during these tests. The pulley ratios (outside diameters) were 1.28 and 1.52 respectively indicating that very little belt slippage was occurring during most of the tests. There was a tendency toward more belt slippage at an engine speed of 3000 rpm than at lower speeds as indicated by tests 5 and 15 in Table 1. In particular in test 15 the observed ratio of engine to compressor speed was 1.51 as compared to an average of 1.33 for the remainder of the tests.

Figure 5 shows that the net refrigerating capacity reached a maximum value in the range of engine speed between 2400 rpm and 2700 rpm and that it was less for speeds below 2400 rpm and above 2700 rpm. This is characteristic of a unit for which the fan speeds increase proportionally to the engine speed by virtue of a fixed pulley ratio. It would be expected that the total refrigerating capacity of the compressor would increase proportionally with engine speed if the volumetric efficiency remained constant. However, the power to drive the evaporator fan would increase as the cube of the engine speed. Thus at some engine speed the increment of increased compressor capacity caused by an increase in engine speed would be exactly offset by the incremental increase in evaporator fan power. This would be the point of maximum net refrigerating capacity. At higher speeds the rapid increase in evaporator fan power would cause a decrease in net refrigerating capacity.

Assuming that the volumetric efficiency of the compressor remained constant for the speed range under consideration and that the evaporator fan power increased as the cube of the fan speed, the characteristic curve for the net refrigerating capacity can be expressed by an equation of the form:

$$R = AS - BS^3 \quad \text{where}$$

R is the net refrigerating capacity in Btu/hr
S is the engine speed in rpm
A and B are constants which can be evaluated using observed values of R and S for two test conditions.

Figure 5 shows that the net refrigerating capacity reached a maximum value of about 17,000 Btu/hr at an engine speed of about 2600 rpm for a refrigerator temperature of 35°F. The corresponding maximum net refrigerating capacities for refrigerator temperatures of 10°F and 2°F were about 9300 Btu/hr and 7400 Btu/hr respectively. Figure 5 shows that the net refrigerating capacity was affected less by speed change at the lower refrigerator temperatures than for a refrigerator temperature of 35°F. The refrigerating unit was unable to cool the refrigerator to 0°F in an ambient temperature of 110°F at any engine speed because of the large heat leakage of the 600 cubic foot refrigerator.

The net refrigerating capacity observed in Test 1 is believed to be too low. The low suction pressure and low temperatures observed on the evaporator indicate excessive frost on the evaporator. If the volumetric efficiency in Test 1 were as high as for Tests 2 and 3 the net refrigerating effect would have been about 12000 Btu/hr for Test 1. This is a safe assumption since volumetric efficiency usually increases rather than decreases as the compressor speed is decreased. The curve for a refrigerator temperature of 35°F in Figure 5 is drawn for an estimated capacity of 12000 Btu/hr for Test 1, although the observed capacity is also plotted for this test.

Figure 4 shows that the net refrigerating capacity of the unit varied approximately in linear relation to the refrigerator temperature at any given engine speed in the range from 1800 rpm to 3000 rpm. This figure also shows the capacity to be approximately equal at engines speeds of 2400 rpm and 2700 rpm and to be slightly lower at an engine speed of 3000 rpm. In figure 4 the curve for a speed of 1800 rpm is drawn through a computed capacity value of about 12000 Btu/hr rather than the observed value of 7770 Btu/hr corresponding to a refrigerator temperature of 35°F because the data for Test 1 reveal that the evaporator probably had excessive frost on it when this test was made.

Table 1 shows that the temperature difference between inlet and outlet air for the condenser remained reasonably steady as the engine speed was increased. This indicates that the total heat rejection of the condenser increased proportionally with engine speed since the air delivery of a fan increases proportionally with speed. On the other hand, the temperature difference between inlet and outlet air for the evaporator decreased somewhat as the engine speed was

increased indicating that the heat transfer to the evaporator increased less than proportionally as the engine speed was increased.

There was a gradual decrease in suction pressure as the engine speed was increased for a given value of refrigerator temperature. This also indicates that the total heat transfer to the evaporator was increasing as the engine speed was increased even though the net refrigerating capacity may not have increased. Table 1 also shows that the compression ratio increased slowly as the speed was increased primarily because the suction pressure decreased.

Figure 6 shows how the gasoline consumption rate was affected by engine speed and refrigerator temperature. At any given refrigerator temperature the fuel consumption rate increased with the speed although not along a straight line. Fuel consumption rate could be affected by belt tension, carburetor adjustment, and perhaps other factors that would prevent obtaining a smooth curve for this relationship. It will be noted in Figure 6 that the highest fuel consumption rate was observed consistently for a refrigerator temperature of 10°F and the lowest rate was observed with the lowest attainable refrigerator temperature.

The superheat of the refrigerant gas at the bulb of the thermostatic expansion value as compared to saturated evaporator temperatures near the coil inlet ranged from seven to 14 degrees F for all tests except tests 1 and 2, for which the superheat was 0.5 and 4.4 degrees F, respectively. Neglecting these two exceptions, the average superheat was 12.8 degrees F for a 35°F refrigerator temperature, 10.9 degrees F for a 10°F refrigerator temperature, and 9.8 degrees F for the lowest temperature attainable in the refrigerator.

Experience with the maintenance of the Model K-10 unit during the tests indicated that the distributor points and condenser were too inaccessible considering the amount of servicing required. It was also observed that the Pierce governor was sluggish and did not provide very precise speed control for the unit with changes in load. Hunting of the engine speed was also observed during some of the tests.

In the course of testing this unit, it was operated approximately 500 hours. During this period there were no component failures, no breaks in the refrigerant lines, and no failures in the gasoline engine. Adjustment of belt tension and servicing of the distributor points was required at intervals.

5. DISCUSSION AND CONCLUSIONS

The capacity tests of the Thermo King refrigerating unit showed that the maximum net refrigerating capacity was obtained for engine speeds in the range from 2400 rpm to 2700 rpm for all refrigerator temperatures below 35°F when the condenser and evaporator fans and the compressor were belt-driven with fixed pulley ratios. There was no significant change in capacity in this speed range, which included the design engine speed of 2400 rpm. These tests were not planned to establish whether or not the speed ratio between compressor and fans was the optimum for this unit.

The warehouse used to test this unit was of such size that the specimen refrigerating unit was not able to cool it to 0°F. At a 0°F refrigerator temperature the net refrigerating capacity of the unit would be about 6500 Btu/hr for an engine speed of 2400 rpm as determined by extrapolation of the appropriate curve in Figure 4.

Test	12	13	14	15
Net I	7370	7360	7210	7150
	2305	2416	2694	2999
Engi	1753	1864	2050	1981
Comp	1502	1569	1700	1909
Evap				
Rati Com	1.31	1.30	1.31	1.51 b)
Rati Eva	1.53	1.54	1.58	1.57
	3.5	4.5	5.5	6.6
Gaso	1.8	1.6	2.6	3.7
Aver	110.6	110.4	109.2	110.2
Aver	171	171	173	172
Disc	3.9	3.4	3.1	3.5
Suct	9.98	10.26	10.54	10.26
Comp	78.2	76.4	78.0	78.2
Suct				
Temp Con	112.7	113.7	114.9	114.6
Temp Con	120.3	120.4	121.9	122.7
Air Acr	7.6	6.7	7.0	8.1
Temp Eva	5.0	4.1	5.3	6.4
Temp Eva	0.1	-0.2	1.1	2.5
Air Acr	4.9	4.3	4.2	3.9

apacity in Test 1 indicates that the evaporator needed

compressor indicates belt slippage.

TABLE 1

EFFECT OF ENGINE SPEED AND REFRIGERATOR TEMPERATURE
ON UNIT CAPACITY AT CONSTANT AMBIENT TEMPERATURE

THERMO KING, MODEL K-10 UNIT

Test Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Net Refrigerating Capacity	BTU/HR	7,770 a)	13,890	16,620	16,790	15,590	8,190	8800	9230	9270	9250	6990	7370	7360	7210	7150
Engine Speed	R.P.M.	1837	2168	2393	2719	3005	1777	2086	2351	2708	2991	1788	2305	2416	2694	2999
Compressor Speed	R.P.M.	1378	1648	1789	2068	2145	1360	1580	1724	2068	2261	1356	1753	1864	2050	1981
Evaporator Fan Speed	R.P.M.	1178	1446	1491	1715	1765	1121	1315	1391	1708	1815	1154	1502	1569	1700	1909
Ratio of Engine Speed to Compressor Speed		1.33	1.32	1.34	1.31	1.40	1.31	1.32	1.36	1.31	1.32	1.32	1.31	1.30	1.31	1.51 b)
Ratio of Engine Speed to Evaporator Fan Speed		1.56	1.50	1.60	1.59	1.70	1.59	1.59	1.69	1.59	1.65	1.55	1.53	1.54	1.58	1.57
Gasoline Consumption	lb/hr	3.2	3.9	5.4	6.5	6.8	3.3	4.7	6.4	6.8	7.5	3.0	3.5	4.5	5.5	6.6
Average Refrigerator Temp.	°F	35.1	34.8	35.4	34.0	34.3	10.7	10.5	11.0	10.7	10.8	6.0	1.8	1.6	2.6	3.7
Average Ambient Temperature	°F	109.7	109.8	111.3	109.9	109.3	110.7	110.7	111.5	110.8	110.5	109.1	110.6	110.4	109.2	110.2
Discharge Pressure	Psig	173	189	191	183	187	181	177	184	176	174	174	171	171	173	172
Suction Pressure	Psig	7.2 a)	15.2	15.8	13.3	13.0	8.1	7.1	6.9	5.5	4.6	6.3	3.9	3.4	3.1	3.5
Compression Ratio		8.57	6.81	6.74	7.06	7.28	8.58	8.79	9.20	9.44	9.78	8.99	9.98	10.26	10.54	10.26
Suction Gas Temperature	°F	82.2	81.3	82.4	81.0	81.4	81.0	79.1	80.0	81.9	80.2	79.1	78.2	76.4	78.0	78.2
Temperature of Air Entering Condenser	°F	114.0	113.9	113.4	111.0	113.3	116.9	115.4	116.9	114.4	113.2	114.0	112.7	113.7	114.9	114.6
Temperature of Air Leaving Condenser	°F	121.9	124.6	123.4	121.2	123.6	125.2	123.3	124.9	124.0	123.4	121.4	120.3	120.4	121.9	122.7
Air Temperature Difference Across Condenser	°F	7.9	10.7	10.0	10.2	10.3	8.3	7.9	8.0	9.6	10.2	7.4	7.6	6.7	7.0	8.1
Temperature of Air Entering Evaporator	°F	37.0	37.2	37.2	35.3	35.7	12.5	13.2	13.4	12.8	13.1	9.0	5.0	4.1	5.3	6.4
Temperature of Air Leaving Evaporator	°F	30.4	28.8	28.7	27.6	28.7	6.6	7.3	8.1	8.0	8.4	3.4	0.1	-0.2	1.1	2.5
Air Temperature Difference Across Evaporator	°F	6.6	8.4	8.5	7.7	7.0	5.9	5.9	5.3	4.8	4.7	5.6	4.9	4.3	4.2	3.9

a) The low suction pressure and low capacity in Test 1 indicates that the evaporator needed defrosting.

b) The high speed ratio of engine to compressor indicates belt slippage.


THERMO KING
U. S. THERMO CONTROL CO.
MINNEAPOLIS, MINNESOTA
NBS

Fig. 1

Fig. 2

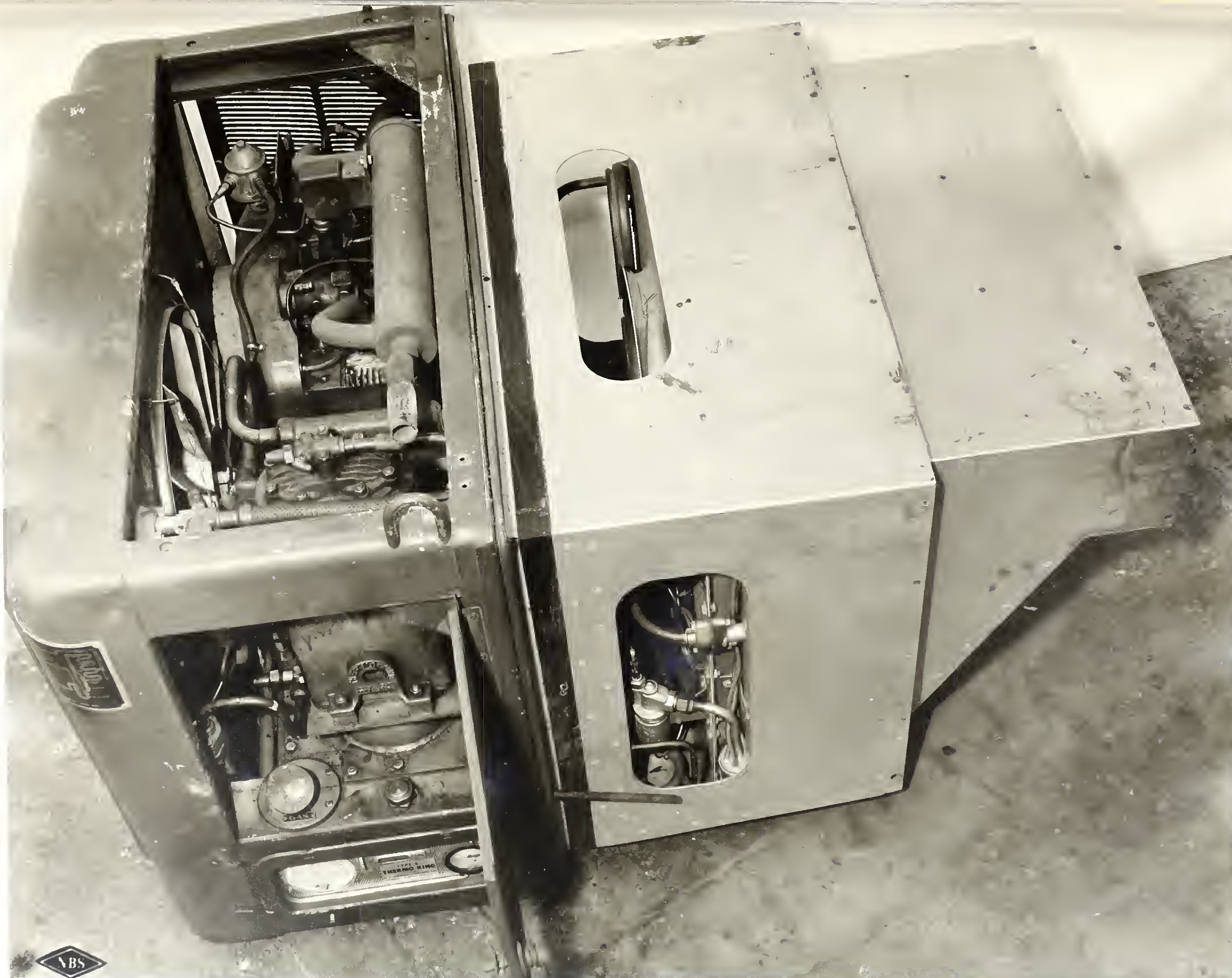


Fig. 3

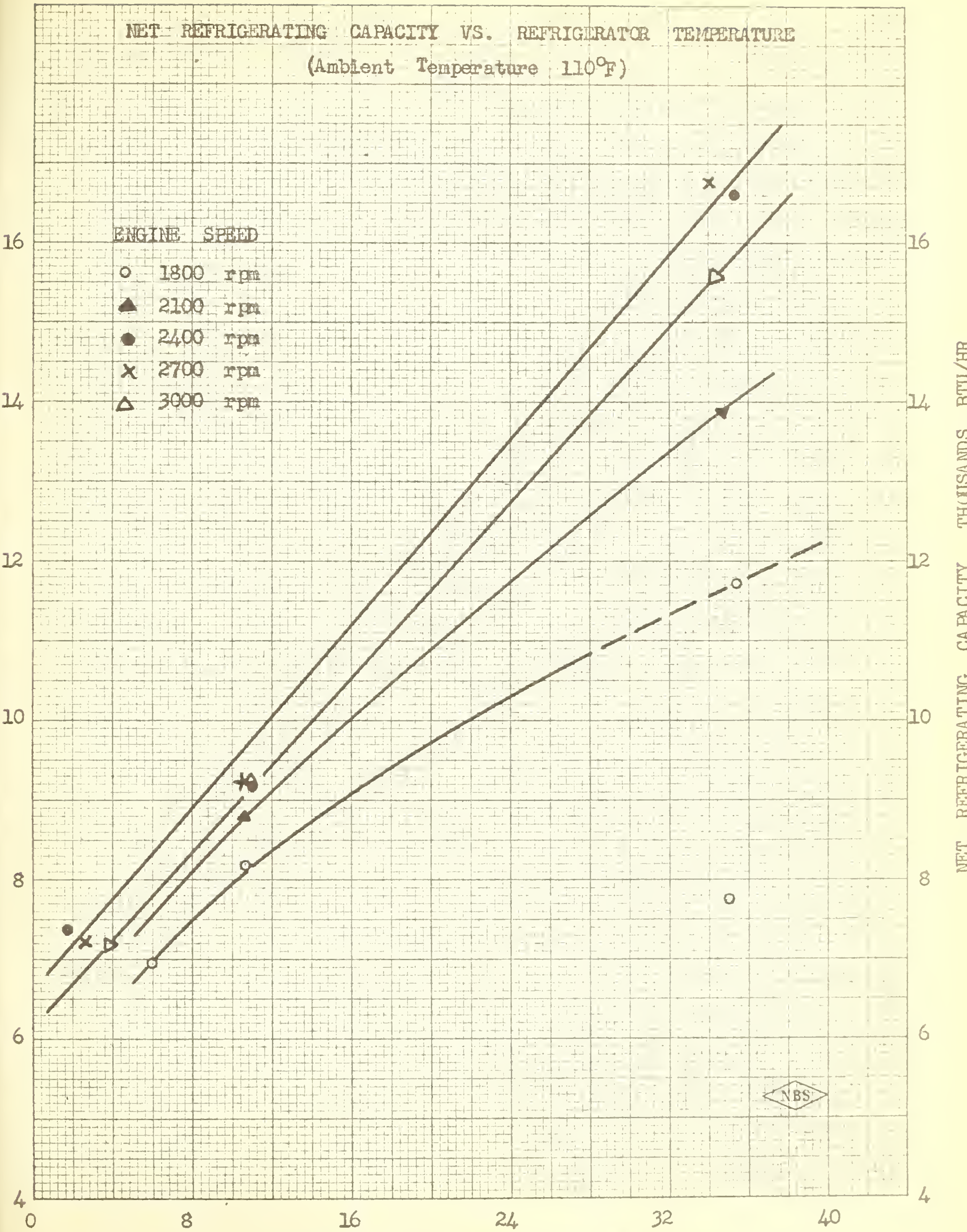
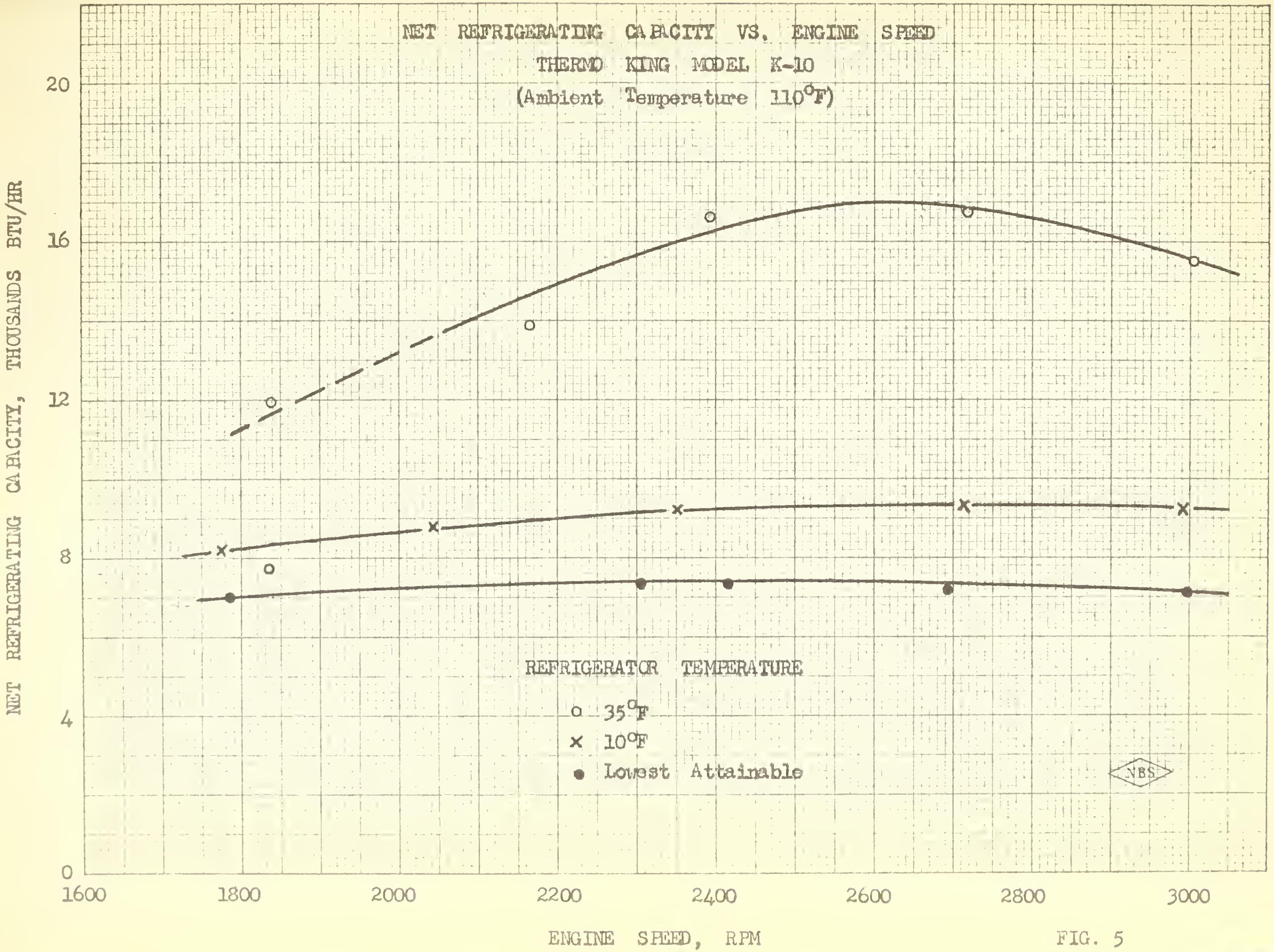
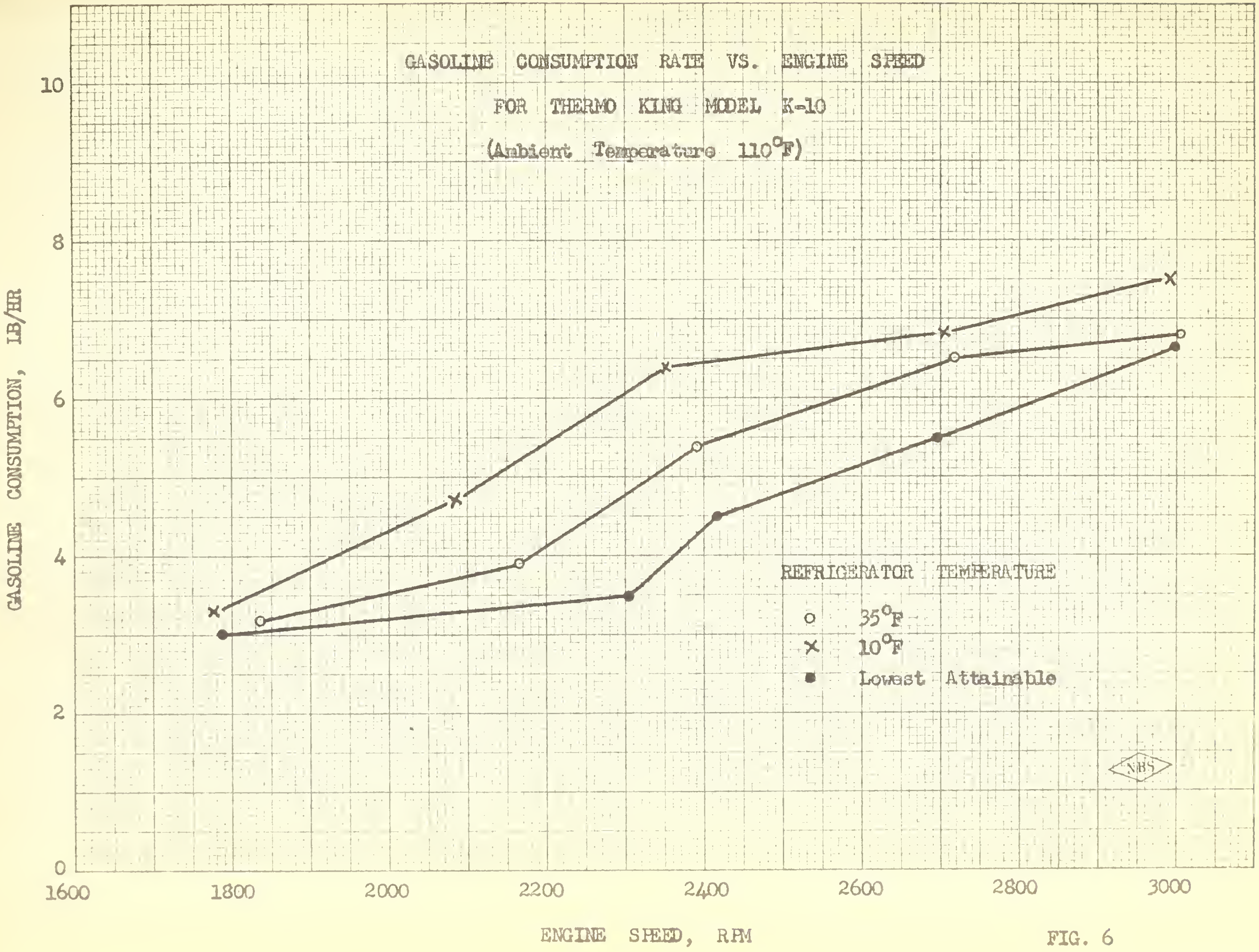

NET REFRIGERATING CAPACITY VS. REFRIGERATOR TEMPERATURE
(Ambient Temperature 110°F)
ENGINE SPEED
1800 rpm
2100 rpm
2400 rpm
2700 rpm
3000 rpm
4
6
8
10
12
14
16
0
8
16
24
32
40
NET REFRIGERATING CAPACITY, THOUSANDS BTU/HR
REFRIGERATOR TEMPERATURE, °F
NBS

FIG. 4



NET REFRIGERATING CAPACITY VS. ENGINE SPEED
THERMO KING MODEL K-10
(Ambient Temperature 110°F)
NET REFRIGERATING CAPACITY, THOUSANDS BTU/HR
0
4
8
12
16
20
1600
1800
2000
2200
2400
2600
2800
3000
ENGINE SPEED, RPM
REFRIGERATOR TEMPERATURE
35°F
10°F
Lowest Attainable
NBS

FIG. 5



GASOLINE CONSUMPTION RATE VS. ENGINE SPEED
FOR THERMO KING MODEL K-10
(Ambient Temperature 110°F)
REFRIGERATOR TEMPERATURE
35°F
10°F
Lowest Attainable
GASOLINE CONSUMPTION, LB/HR
ENGINE SPEED, RPM
0
2
4
6
8
10
1600
1800
2000
2200
2400
2600
2800
3000
NBS

FIG. 6

THE NATIONAL BUREAU OF STANDARDS

Functions and Activities

The functions of the National Bureau of Standards are set forth in the Act of Congress, March 3, 1901, as amended by Congress in Public Law 619, 1950. These include the development and maintenance of the national standards of measurement and the provision of means and methods for making measurements consistent with these standards; the determination of physical constants and properties of materials; the development of methods and instruments for testing materials, devices, and structures; advisory services to Government Agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; and the development of standard practices, codes, and specifications. The work includes basic and applied research, development, engineering, instrumentation, testing, evaluation, calibration services, and various consultation and information services. A major portion of the Bureau's work is performed for other Government Agencies, particularly the Department of Defense and the Atomic Energy Commission. The scope of activities is suggested by the listing of divisions and sections on the inside of the front cover.

Reports and Publications

The results of the Bureau's work take the form of either actual equipment and devices or published papers and reports. Reports are issued to the sponsoring agency of a particular project or program. Published papers appear either in the Bureau's own series of publications or in the journals of professional and scientific societies. The Bureau itself publishes three monthly periodicals, available from the Government Printing Office: The Journal of Research, which presents complete papers reporting technical investigations; the Technical News Bulletin, which presents summary and preliminary reports on work in progress; and Basic Radio Propagation Predictions, which provides data for determining the best frequencies to use for radio communications throughout the world. There are also five series of nonperiodical publications: The Applied Mathematics Series, Circulars, Handbooks, Building Materials and Structures Reports, and Miscellaneous Publications.

Information on the Bureau's publications can be found in NBS Circular 460, Publications of the National Bureau of Standards ($1.25) and its Supplement ($0.75), available from the Superintendent of Documents, Government Printing Office. Inquiries regarding the Bureau's reports and publications should be addressed to the Office of Scientific Publications, National Bureau of Standards, Washington 25, D. C.

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