ENERGY CONSERVATION

ORNL/TM-10809

ENERGY DIVISION

# Performance Testing of a Commercially Produced Cryogenic Refrigerator

E. G. Keshock*
R. W. Murphy

*Mechanical and Aerospace Engineering Department
The University of Tennessee
Knoxville, Tennessee 37916



Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.

for the
U. S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE-AC05-84OR21400
OFFICE OF BUILDINGS
AND COMMUNITY SYSTEMS

ORNL/TM-10809

Energy Division

# PERFORMANCE TESTING OF A COMMERCIALLY PRODUCED CRYOGENIC REFRIGERATOR

E. G. Keshock*
R. W. Murphy

---

*Mechanical and Aerospace Engineering Department
The University of Tennessee
Knoxville, Tennessee 37916

Date Published - September 1990

Prepared for the
Office of Buildings and Community Systems
U.S. DEPARTMENT OF ENERGY

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
Operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

## TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

## ACKNOWLEDGMENTS

The authors wish to express gratitude to Dr. Stephen F. Malaker, President of Cryodynamics, Inc., for providing the cryocooler unit that was tested as described herein. The degree of cooperation and support was, in fact, far more extensive than that of providing the unit to be tested. In addition to shipping the unit to The University of Tennessee laboratories, Cryodynamics provided technical support personnel to assist in installing and preparing the unit for the laboratory tests.

Special thanks are due to Mr. Henry P. Cramer (Cryodynamics) for assisting in installing and operating the experimental unit. Likewise the assistance of Mr. Tom Phillips (The University of Tennessee) in numerous aspects of the preparation and conduct of the testing program is acknowledged.

Finally, the initiatives and support of Dr. F. C. Chen (ORNL) contributed substantially to the successful conduct of these tests.

## ABSTRACT

A commercially available cryogenic refrigeration unit, model M-20, (3-phase, 60-Hz, 230-V) manufactured by Cryodynamics, Inc., was subjected to laboratory testing to measure some of its performance characteristics. Comparisons were made with those performance characteristics given in manufacturer literature for the M-20 unit (3-phase, 400-Hz, 208-V). At 77 K, the measured cooling capacity of the 60-Hz/230-V unit was very nearly the same (<2% difference) as the specified capacity (110 W) of the 400-Hz/208-V unit. At temperature levels higher than 77 K, measured cooling capacities exceeded the manufacturer product data sheet values. Coefficients of performance (COP) based on the experimental measurements ranged from about 0.37 at 250 K to 0.03 at 70 K. Comparison of measured to ideal (Carnot cycle) COPs yielded values ranging from about 8 to 18%, with a broad maximum occurring between approximately 100 and 150 K. Finally, the measured cool-down time from room temperature to 77 K was about 10 minutes compared with a specification sheet value of 7.4 minutes. This difference may be attributed to lower thermal mass (without heater block) and higher operating frequency conditions associated with the specification.

## INTRODUCTION

For several years Cryodynamics, Inc., has produced a line of compact closed-cycle cryogenic refrigeration units that are employed in numerous military, aerospace, and industrial applications. The units use helium as the working fluid in a modified Stirling cycle system. Refrigeration units have been produced that provide cooling at a temperature level as low as 25 K. A more recent application employs a unit that provides 25,000 Btu/h of cooling at $0^{o}F$ for trailer-truck payload refrigeration. One of the very attractive features of such refrigeration units is their use of helium as a working medium rather than chlorofluorocarbon refrigerants, since any leakage of helium into the atmosphere is without the deleterious environmental consequences of chlorofluorocarbon refrigerant fluids.

Because of the potential for the worldwide use of non-polluting refrigeration systems, tests were conducted at the Mechanical and Aerospace Engineering Department of The University of Tennessee on a refrigeration unit (Cryodynamics, Inc., Model M-20) to establish its performance capabilities. The performance tests conducted are described herein, with quantitative results tabulated and presented in graphical form.

## EXPERIMENTAL SETUP

The Cryodynamics M-20 refrigeration unit was installed on a portable bench top. The M-20 unit, with auxiliary apparatus and instrumentation, is illustrated in Fig. 1. Shown in the figure are (1) the M-20 unit, (2) a vacuum pump, (3) a wattmeter (for measuring input power), (4) a variable transformer (for controlling the heating load to the cooling head of the cryocooler), (5) an ohmmeter (for measuring the temperature of the cooling head via a calibrated resistance thermometer), and (6) a fan (for heat rejection to ambient air).

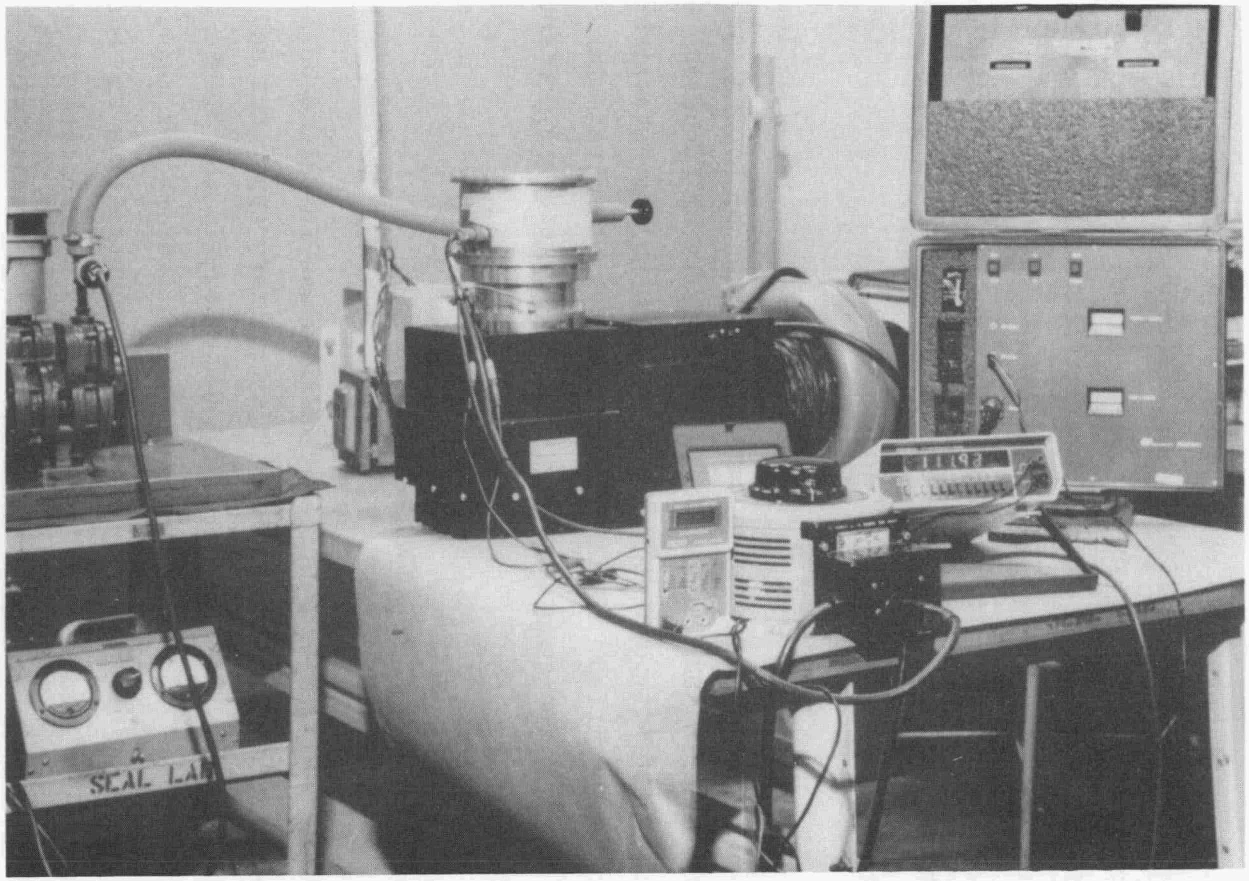



Fig. 1. Photograph of experimental apparatus.

Relative to the design details of the M-20 unit, a description consisting of the product data sheet supplied by Cryodynamics is presented in Appendix I. Engineering details of the Stirling cycle piston-regenerator system itself are considered proprietary. However, a schematic representation of the internals of a compact Stirling cycle unit is shown in Appendix I.

For the tests reported here, the cooling head of the M-20 unit was equipped with a top-mounted heater block and a surrounding vacuum jacket. As shown in Fig. 2, four electric cartridge heaters were installed in the upper section of the copper heater block to provide the heat load required for performance measurements. To reduce thermal contact resistance, Dow-Corning 340 grease was applied to the mating surfaces. A platinum resistance thermometer was fastened to the lower section of the block by means of a small bolted metallic tab. The heater block assembly was bolted to the upper cooling head surface. The vacuum jacket provided an airtight enclosure around the cooling head, which, when evacuated by the vacuum pump arrangement illustrated in Fig. 1, minimized convection heat leaks from the surroundings to the cooling head.

The M-20 unit operated on 3-phase, 60-Hz, 230-V AC power measured with a wattmeter having a least count of 0.01 kW. Power input to the cartridge heaters was controlled by a variable transformer and measured by means of a voltmeter (least count of 0.1 V) and an ammeter (least count of 0.01 A). The resistance of the thermometer element was measured with a digital multimeter (least count of 0.01 $\Omega$). The element itself was calibrated such that a precision of about 0.02 K was possible. (The complete temperature-resistance relationship for the element is presented in Appendix II.) Ambient air temperature was monitored with a mercury-in-glass thermometer located near the air inlet to the refrigeration unit.

A detailed listing and description of test equipment is presented in Appendix II.

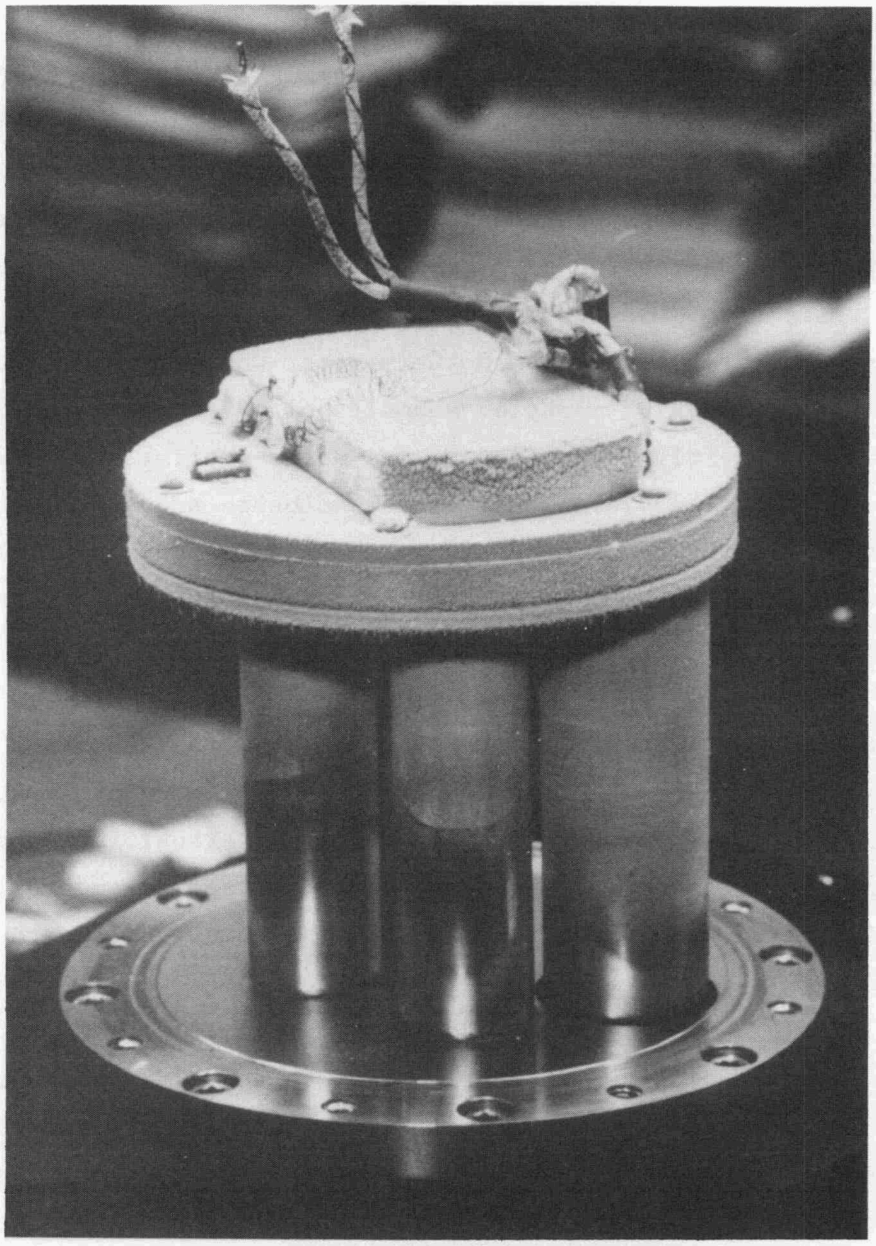


Fig. 2. Photograph of cartridge heaters and resistance thermometer element affixed to M-20 cooling head shortly after removal of vacuum jacket.

## PROCEDURE

Tests were conducted on two consecutive days. Each day, tests were initiated after the vacuum jacket had been pumped down to 15 $\mu$m Hg. After the M-20 unit had been activated, temperature measurements of the cooling head were made 1 minute apart to establish the cool-down time required to reach the desired initial operating temperature level. Measurements were made of the cooling head temperature, power to the cartridge heaters (volts and amps), power to the M-20 unit (which includes power to the cooling fan), ambient air temperature, and vacuum-jacket pressure.

On the first day of the testing, the initial operating temperature level was approximately 77 K. Thereafter, the operating temperature was consistently increased up to a maximum of 250 K and returned to the 77 K level. Selected operating temperature levels were attained by adjusting the energy input level to the cartridge heaters (i.e., by applying increasingly larger heating loads to the cooling head and obtaining higher operating temperature levels).

On the second day, cool down to 70 K was first performed. Thereafter, the operating temperature levels were varied in a "ratchet-like" fashion, rather than in a continuously increasing manner. That is, temperature levels in sequence were 70, 77, 120, 100, 175, and 150 K.

Prior to the tests, measurements were made of power input to the cooling fan, which removes both the energy input to the M-20 unit and ultimately the load under which the cryocooler operates (removes from the cartridge heaters) at a given temperature level. The power level to the fan was found to be about 200 W. Thus, the measured total power to the M-20 system includes about 200 W of fan power.

## RESULTS

The measured results of the two-day testing program are tabulated in Table 1. Additionally, from the measured values of the cooling load and input power to the M-20 (subtracting 200 W that was used to drive the heat rejection fan), the coefficient of performance (COP) has been calculated at numerous operating temperature levels.

The ideal COP (Carnot refrigerator COP) has been calculated based on the temperature extremes of cooling head temperature and ambient air temperature (Table 2). Also in Table 2, the actual COP for the M-20 is compared with the Carnot COP in terms of the ratio, $COP/COP_{ideal}$.

In Fig. 3, the measured cooling capacities for both testing days (as reflected by the maintenance of a steady cooling head temperature when subjected to a steady heating input) are shown superimposed. Although the cooling capacity data were gathered in two different sequences (steadily increasing operating temperature levels vs "ratcheted" levels), good agreement appears to exist between the two sets of data. This agreement increased confidence in the experimental measurements made, in the techniques employed, and in the operational stability of the M-20 unit.

Figure 4 repeats a portion of the cooling capacity data shown in Fig. 3 (i.e., data only from the first day) and also presents the COP values calculated from the measured cooling capacity and power input data. It is of interest to observe that above 77 K the measured cooling capacities are somewhat higher than the manufacturer product data sheet values for the 400-Hz/208 V unit (dashed line). Those values are available only over a limited temperature range and have been obtained from the literature (Appendix I).

Table 1. Performance data and calculated COP values for M-20 unit tested

| Time | Cooling head temperature |  | Heater power (cooling load) |  |  | Power to M-20 & fan | Ambient air temperature | Vacuum | COP |
|---|---|---|---|---|---|---|---|---|---|
|  | (Ω) | (K) | (V) | (A) | (W) | (kW) | (°F) | (μm-Hg) |  |
| (first day) (on) 1:08 | 110.70 | 300.0 | 0 | 0 | 0 |  | 82 | 15 |  |
| 1:09:20 | 99.00 | 270.0 | 0 | 0 | 0 |  |  |  |  |
| 1:10 | 91.44 | 252 | 0 | 0 | 0 |  |  |  |  |
| 1:11 | 80.33 | 224 | 0 | 0 | 0 | 1.25 |  | 15 |  |
| 1:12 | 69.60 | 198 | 0 | 0 | 0 |  |  |  |  |
| 1:13 | 60.14 | 175 | 0 | 0 | 0 |  |  |  |  |
| 1:14 | 51.13 | 153 | 0 | 0 | 0 | 1.58 |  |  |  |
| 1:15 | 42.35 | 132 | 0 | 0 | 0 | 1.74 |  |  |  |
| 1:16 | 34.33 | 113 | 0 | 0 | 0 | 1.91 |  |  |  |
| 1:17 | 26.87 | 96 | 0 | 0 | 0 | 2.08 |  |  |  |
| 1:18 | 20.48 | 81 | 0 | 0 | 0 | 2.25 |  |  |  |
| 1:18:20 | 18.74 | 77 | 0 | 0 | 0 |  |  |  |  |
| 1:24 | 18.59 | 76.65 | 48.7 | 2.21 | 108 | 2.34 | 82 | 15 |  |
| 1:26 | 18.65 | 76.85 | 48.7 | 2.21 | 108 | 2.40 | 82 | 13 | 0.0491 |
| 1:32 | 21.95 | 83.86 | 57.5 | 2.62 | 151 | 2.38 | 83 | 13 |  |
| 1:36 | 27.71 | 97.64 | 64.2 | 2.92 | 187 | 2.24 | 83 | 13 |  |
| 1:39 | 28.89 | 100.44 | 62.2 | 2.83 | 176 | 2.23 | 83 | 13 |  |

Table 1 (continued)

| Time | Cooling head temperature | | Heater power (cooling load) | | | Power to M-20 & fan | Ambient air temperature | Vacuum | COP |
|---|---|---|---|---|---|---|---|---|---|
| | (Ω) | (K) | (V) | (A) | (W) | (kW) | (°F) | (μm-Hg) | |
| 1:41 | 28.85 | 100.30 | 61.8 | 2.81 | 174 | 2.23 | 83 | 13 | 0.0857 |
| 1:47 | 35.94 | 116.84 | 71.0 | 3.22 | 229 | 2.06 | 83 | 13 | |
| 1:50 | 37.19 | 119.77 | 69.5 | 3.15 | 220 | 2.03 | 83 | 13 | |
| 1:54 | 37.36 | 120.17 | 68.3 | 3.10 | 212 | 2.04 | 83 | 13 | 0.115 |
| 2:08 | 49.00 | 147.76 | 78.7 | 3.57 | 281 | 1.79 | 84 | 13 | |
| 2:12 | 49.92 | 149.98 | 77.5 | 3.51 | 272 | 1.77 | 85 | 13 | 0.173 |
| 2:27 | 60.26 | 174.86 | 83.0 | 3.76 | 312 | 1.60 | 85 | 13 | 0.223 |
| 2:38 | 69.40 | 197.12 | 90.2 | 4.07 | 367 | 1.47 | 85 | 13 | |
| 2:44 | 70.52 | 199.85 | 87.8 | 3.96 | 348 | 1.45 | 85 | 13 | 0.278 |
| 3:00 | 80.75 | 225.02 | 91.5 | 4.12 | 377 | 1.38 | 85 | 13 | 0.319 |
| 3:15 | 91.00 | 250.47 | 94.8 | 4.26 | 404 | 1.30 | 85 | 20 | |
| 3:18 | 90.81 | 250.00 | 95.1 | 4.27 | 406 | 1.30 | 85 | 20 | 0.369 |
| 3:29:20 | 18.74 | 77.0 | 0 | 0 | 0 | 2.55 | 85 | 12 | |
| 3:34 | 15.79 | 70.14 | 41.1 | 1.87 | 76.9 | 2.65 | 85 | 11 | 0.0314 |
| (second day) 10:41 | 112.00 | 303.6 | 0 | 0 | 0 | | 82 | 15 | |
| 10:42 | 97.71 | 267.3 | 0 | 0 | 0 | | | | |
| 10:43 | 86.31 | 238.8 | 0 | 0 | 0 | | | | |

Table 1 (continued)

| Time | Cooling head temperature | | Heater power (cooling load) | | | Power to M-20 & fan | Ambient air temperature | Vacuum | COP |
|---|---|---|---|---|---|---|---|---|---|
| | (Ω) | (K) | (V) | (A) | (W) | (kW) | (°F) | (μm-Hg) | |
| 10:44 | 75.04 | 211.0 | 0 | 0 | 0 | | | | |
| 10:45 | 63 | 181.5 | 0 | 0 | 0 | | | | |
| 10:46 | 55 | 162.2 | 0 | 0 | 0 | | | | |
| 10:47 | 46 | 140.6 | 0 | 0 | 0 | | | | |
| 10:48 | 38.36 | 122.5 | 0 | 0 | 0 | | | | |
| 10:49 | 30.81 | 104.9 | 0 | 0 | 0 | | | | |
| 10:50 | 24.00 | 89.1 | 0 | 0 | 0 | | | | |
| 10:51 | 18.74 | 77.0 | 0 | 0 | 0 | | | | |
| 10:55 | | ~70 | 41.2 | 1.87 | 77.0 | 2.53 | 84 | 13 | |
| 10:58 | 15.74 | 70.0 | 43.2 | 1.97 | 85.1 | 2.58 | 84 | 13 | 0.0358 |
| 11:08 | 18.70 | 76.9 | 46.2 | 2.10 | 97.0 | 2.63 | 86 | 13 | 0.0399 |
| 11:29 | 37.30 | 120.0 | 67.4 | 3.06 | 206 | 2.06 | 86 | 13 | 0.111 |
| 11:50 | 28.78 | 100.1 | 58.9 | 2.68 | 158 | 2.29 | 86 | 15 | 0.0755 |
| 12:00 | 60.32 | 175.0 | 84.1 | 3.78 | 318 | 1.63 | 87 | 15 | 0.222 |
| 12:10 | 49.87 | 149.9 | 77.6 | 3.52 | 273 | 1.77 | 87 | 15 | 0.174 |

Table 2. Data tabulation for COP computation and comparison with Carnot cycle COP

| Time | Temperature (K) | Cooling load (W) | Power to M-20 (W) | COP | $COP_{ideal}$ | $COP/COP_{ideal}$ |
|---|---|---|---|---|---|---|
| 1:26 (first day) | 76.9 | 108 | 2200 | 0.0491 | 0.345 | 0.142 |
| 1:41 | 100.3 | 174 | 2030 | 0.0857 | 0.502 | 0.171 |
| 1:54 | 119.1 | 212 | 1840 | 0.115 | 0.658 | 0.175 |
| 2:12 | 150.0 | 272 | 1570 | 0.173 | 1.00 | 0.173 |
| 2:27 | 174.9 | 312 | 1400 | 0.223 | 1.40 | 0.159 |
| 2:44 | 199.9 | 348 | 1250 | 0.278 | 2.00 | 0.139 |
| 3:00 | 225.0 | 377 | 1180 | 0.319 | 3.00 | 0.106 |
| 3:18 | 250.0 | 406 | 1100 | 0.369 | 5.00 | 0.0738 |
| 3:34 | 70.1 | 76.9 | 2450 | 0.0314 | 0.305 | 0.102 |
| 10:58 (second day) | 70.0 | 85.1 | 2380 | 0.0358 | 0.300 | 0.119 |
| 11:08 | 76.9 | 97.0 | 2430 | 0.0399 | 0.339 | 0.118 |
| 11:29 | 120.0 | 206 | 1860 | 0.111 | 0.654 | 0.170 |
| 11:50 | 100.1 | 158 | 2090 | 0.0755 | 0.492 | 0.153 |
| 12:00 | 175.0 | 318 | 1430 | 0.222 | 1.36 | 0.163 |
| 12:10 | 149.9 | 273 | 1570 | 0.174 | 0.975 | 0.178 |

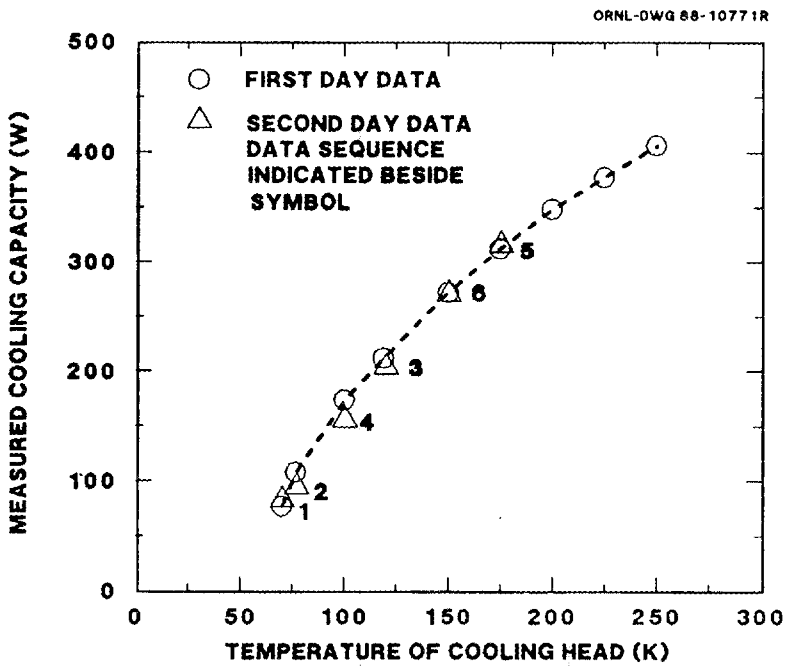



Fig. 3. Performance of M-20 unit measured on two consecutive testing days.

ORNL-DWG 88-10773 R

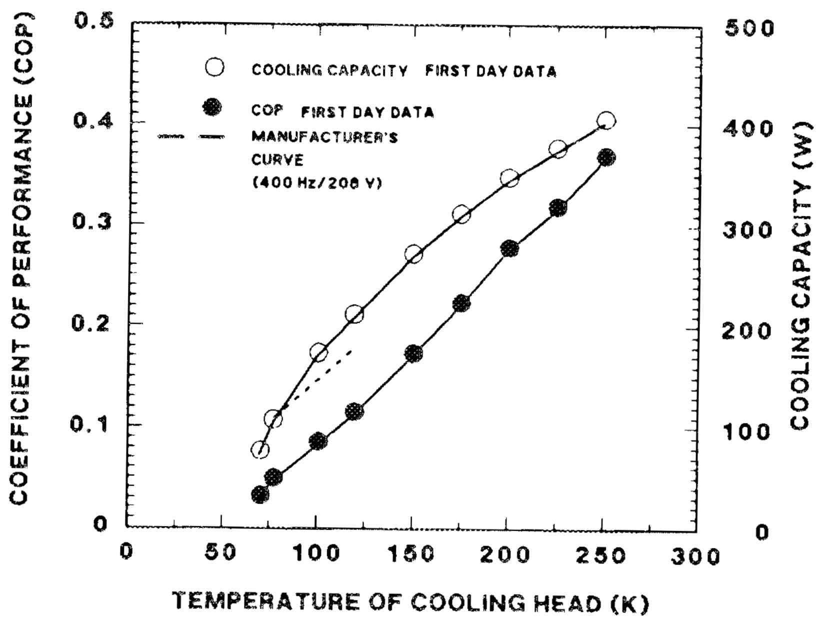



Fig. 4. Performance characteristics of M-20 unit in terms of cooling capacity and COP (first day data only).

Figure 5 compares the actual COP (calculated from measured values) with the COP of an ideal Carnot refrigeration system. As ideal conditions are approached, the ratio of the values approaches unity. The maximum value obtained here is nearly 0.18. A broad maximum appears evident over the temperature range from about 100 to 150 K. This maximum appears to reflect an operation that is optimal over that range, though the unit was apparently intended to provide cooling at a 77-K level. The display of data in this manner may be helpful in identifying the potential for design improvements required in different operating temperature ranges. Ultimately, such improvements would result in such refrigerating units approaching the Carnot cycle COP more closely.[1]

In Fig. 6, the cool-down time to 77 K on both test days is seen to be about 10 minutes as compared to the 7.4-minute value appearing in the specifications of Appendix I. According to the manufacturer, two primary factors account for this difference. First, during the manufacturer cool-down tests, no heater block was installed on the cold head. The substantial additional thermal mass of the copper block and cartridge heaters installed for the tests reported here would be expected to increase the apparent cool-down time. Second, the manufacturer tests were conducted with a 400-Hz/208-V unit rather than the 60-Hz/230-V unit used here. The higher frequency unit might be expected to provide more rapid cool downs.

## SUMMARY

From these tests of the performance characteristics of the Cryodynamics M-20 refrigerator, the following observations may be made:

---

[1]The manufacturer claims the ability to change the width and height of the performance curve as well as the position of the curve peak by suitable design parameter modifications.

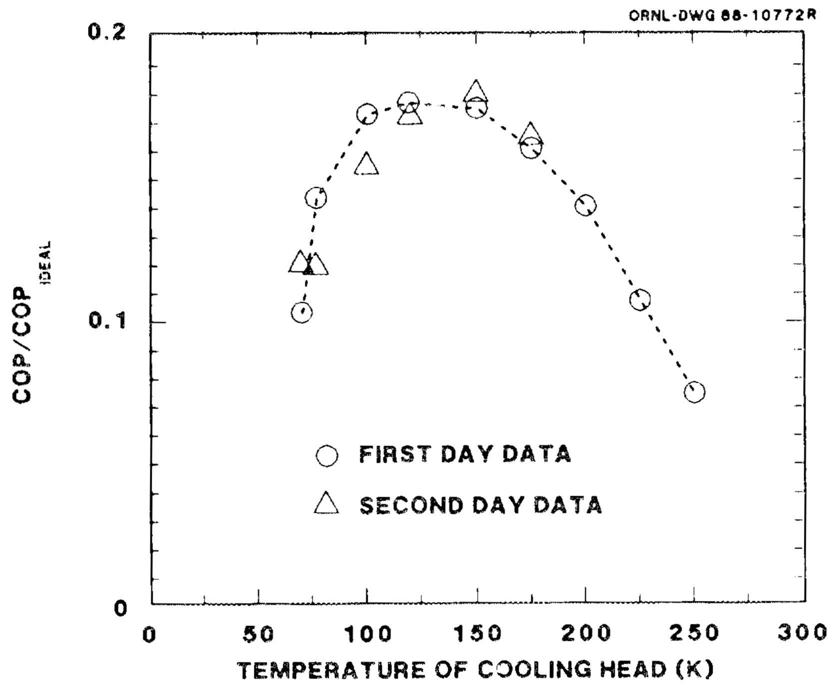



Fig. 5. Comparison of actual performance of M-20 unit with that of Carnot cycle system.

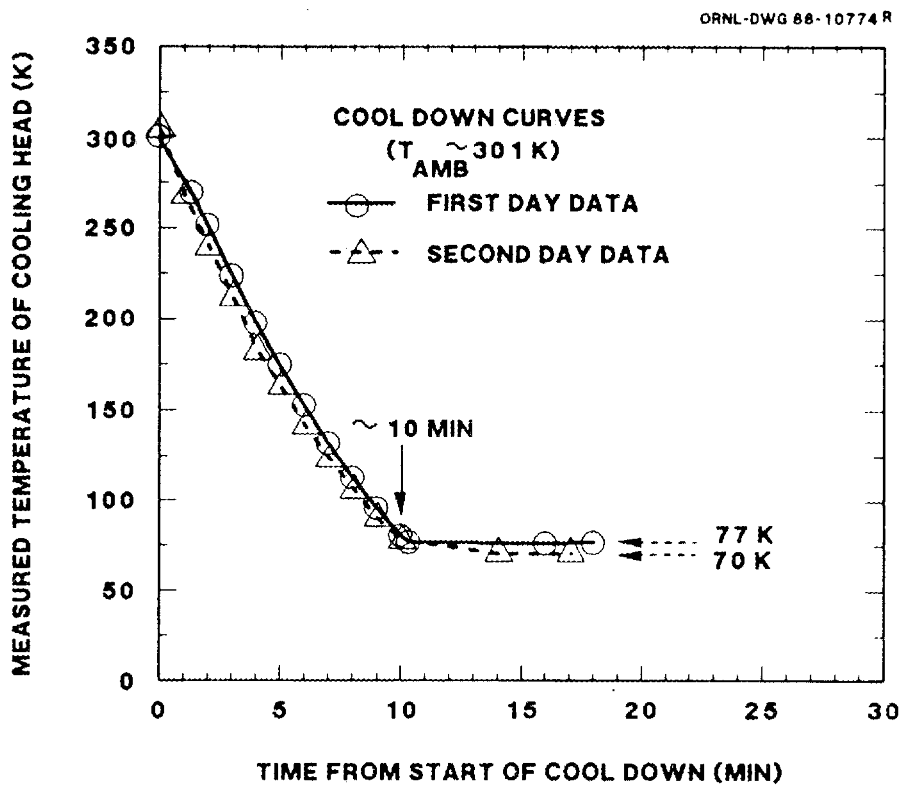



Fig. 6. Cool-down characteristics of the M-20 unit.

1. Measured cooling capacities of the unit appear to exceed the manufacturer product data sheet values at temperatures above 77 K.

2. At 77 K the measured cooling capacity is less than 2% lower than the manufacturer's quoted value. This result indicates reasonable agreement, considering experimental uncertainties -- especially those associated with different power frequency/voltage operating conditions for the two units compared.

3. The reproducibility of the measured cooling capacity results on two separate days of testing and in different loading sequences appears to lend confidence to the measurement system itself and to indicate stable operational characteristics in the M-20 system.

4. The maximum performance level of the M-20 unit occurred in the range of 100 to 150 K, as reflected by comparison of the actual COP of the unit with the COP of a Carnot cycle refrigerator. The maximum performance was nearly 18% of a comparable Carnot cycle system.

5. The existence of a maximum in the $COP/COP_{ideal}$ curve as a function of cooling head temperature indicates an optimal performance region and suggests the potential for design improvements when operating any such device at temperatures other than those specified.

6. The measured cool-down time to 77 K (10 minutes) is greater than that given (7.4 minutes) on the specification sheet. The manufacturer indicates that this difference was due primarily to the added thermal mass of the heater block assembly and the lower frequency characteristic associated with the equipment used in the tests of this study.

## CONCLUDING REMARKS

The performance measurements of the M-20 unit obtained in the tests described herein are in essential agreement with manufacturer-supplied information.

Additional insight into the performance of the M-20 unit is gained by comparison with that of a Carnot device over its operating temperature range. Not only is its optimal operating condition clearly evident when viewed from such a perspective, but the potential for improving its performance is also evident. Such a perspective makes it clear that the design of such Stirling units for operation in another temperature range (e.g., as in domestic refrigerators) may require "tuning" to achieve optimal performance. If, for example, the performance of a Stirling refrigerator unit operating between 250 K (source) and 300 K (sink) could be improved from the 7.4% of Carnot reported here for the M-20 at those temperatures to the 17.8% of Carnot measured between 150 K and 300 K, the corresponding COP would rise from 0.37 to 0.89. If, as indicated by the manufacturer, further improvements might lead to achieving 25% of Carnot, the related COP would reach 1.25.

# APPENDIX I

## MANUFACTURER'S DESCRIPTION OF MODEL M-20 STIRLING CYCLE REFRIGERATOR

| | |
|---|---|
| Manufacturer: | Cryodynamics, Inc.<br>191 Mill Lane<br>Mountainside, NJ 07092 |
| Model: | M-20 |
| Serial No.: | 1381 |
| Volts: | 230 |
| Current: | 60-Hz, 3-phase |
| Coolant: | Air |

# CRYODYNAMICS, INC.

## MODEL M20

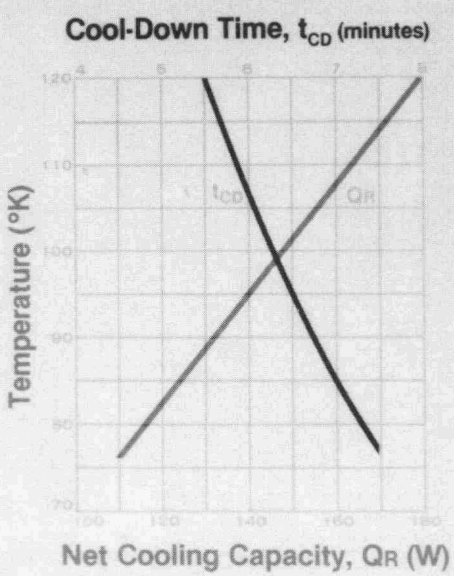
CRYOGENIC REFRIGERATOR

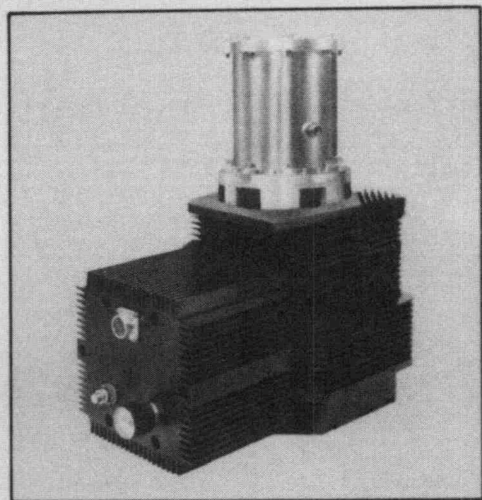
PRODUCT DATA NO. 120

## Description

The Cryodynamics standard product line of miniature closed cycle cryogenic refrigerators are the most versatile, efficient, and reliable available for application to military, aerospace, and industrial high performance requirements.

The Model M20 requires less than 2000 watts input power to produce 110 watts net useable cooling at 77°K in 7.4 minutes with a minimum reliability of 1,000 hours continuous or ON/OFF operation. An integrated modified Stirling cycle 4 piston cryogenic engine, it uses helium as a working gas and operates at low pressure. Unique seal and mechanical design preclude requirements for lubrication, replenishment, or purging. Precise dynamic mechanical balancing results in very low vibration and acoustic noise. A specially designed high efficiency motor delivers the exact speed and torque required to optimize the input power to net useable cooling ratio. The temperature, capacity, cool-down time, and input power are variable; providing functional tailoring to a specific application operating condition. Its physical design flexibility facilitates ready adaptation to configuration requirements.



## Features

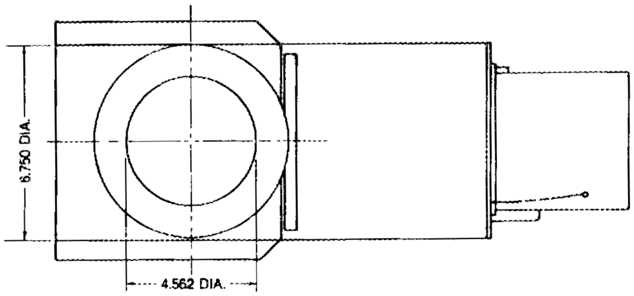
- High Efficiency
- Fast Cool-Down
- Reliable Maintenance Free Operation
- 60 Hz/400 Hz Air or Water Cooled
- MIL and NASA Spec. Compliance
- Hermetically sealed
- Custom Modification Adaptable

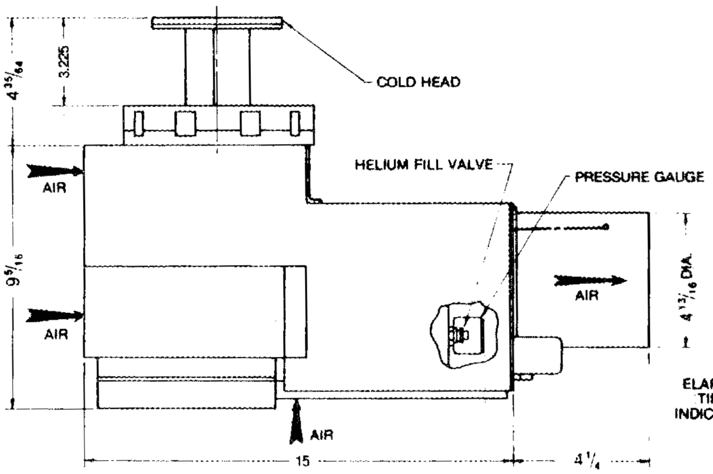
## Applications

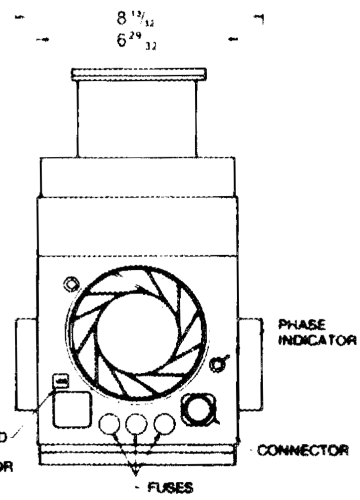
- IR Sensors and Lasers
- Range Instrumentation
- Low Noise Amplifiers and Antennae
- Process and Quality Control
- High Vacuum Cryo-Pumps
- Gas Liquefaction and Reliquefaction
- Vacuum Apparatus Cold Surfaces
- Electron Microscope Specimens

# Specifications M20

| | |
|---|---|
| Working Gas | Helium |
| Refrigerative Power (Net Useable) | 110 W at 77°K |
| Cool-down Time | 7.4 min. to 77°K |
| Input Power incl. Fan | 1990 W at 77°K |
| Coolant | Air |
| Weight incl. Fan | 65 lbs. |
| Power Required | 400~3ø 208V |




## NOTES:

A. Helium fill valve and power electrical mating connectors, performance data, and operating manual supplied.

B. Cold Head protective cover supplied in lieu of illustrated Vacuum Jacket. Standard shroud - 15 pounds.

C. Fan selection may alter dimensions.

D. Cryodynamics, Inc., whose policy is one of continuous product improvement, reserves the right to discontinue models or change specifications at anytime without incurring obligation.

## CUSTOM MODIFICATION—BY QUOTATION

*For information on additional standard models or CUSTOM MODIFICATION to your requirements, contact Cryodynamics.*

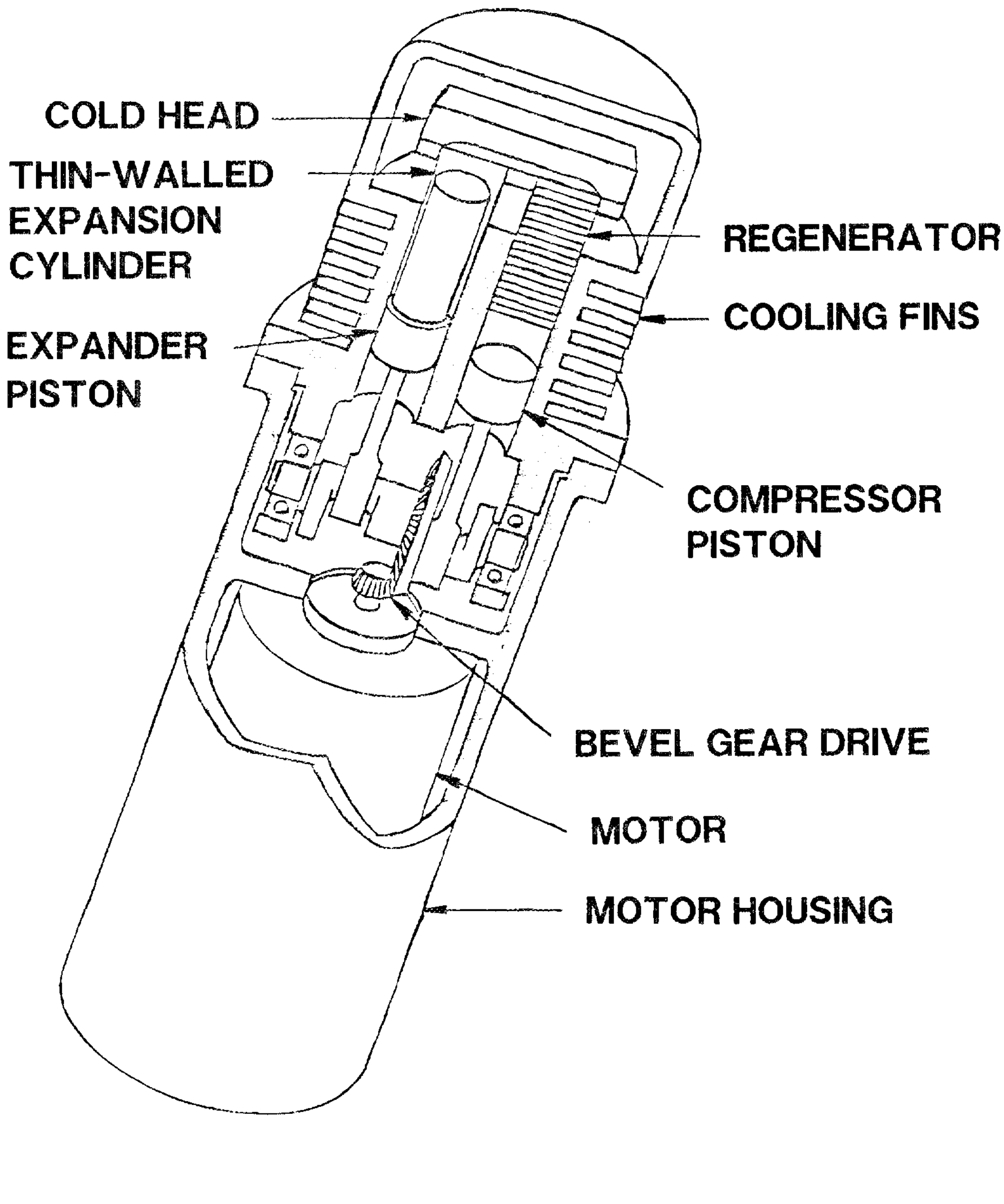
## OPTIONAL ACCESSORIES:

Temperature transducers
  Platinum resistor & mount (calibrated)
End view window vacuum jacket
Controls

**cryodynamics, inc.**

191 Mill Lane,
Mountainside, N.J. 07092
(201) 654-7700 • TWX 710-991-9553

cryodynamics, inc.
1101 Bristol Road, Mountainside, N.J. 07092
(201) 654-7700 • TWX 710-991-9553 • FAX (201) 654-4981



# APPENDIX II

## INSTRUMENTATION AND EQUIPMENT

Heater Unit Power Input

Current:
Micronta Digital Multimeter
Range: Auto-Range
Least Count - 0.01 Amps

Voltage: Speco Model FD-80
Digital Multitester
Range: 0-500 Volts
Least Count - 0.1 Volts

Powerstat Variac
Type - 3PN136B
Input V - 120 Volts
Freq. - 50/60
Single Phase
Output voltage: 0-140 Volts
Amps: 22
KVA: 3.1

RTD Resistance Measurement

Keithley 177 Microvolt DMM
UT No. - 368137
Range: 0-999.99 Ohms
Least Count: 0.01 Ohms

Fan Exit Air Temp.

Omega Thermocouple Thermometer (Type E) 450 AET
Range: -215.0 F to 398.0 F
Least Count - 0.1°F

Cryo-Unit Power Input Measurement

TIF Instruments, Inc.
Watt Meter KW 220-3
used with Copper Coils (Multiply Digital Readout by 0.1)
Range: 0-999.9 kW (0-99.99 with multiplying factor)
Least Count: 0.1 kW (0.01 with multiplying factor)

Vacuum Pump and Measurement

Master a-c Motor
Serial No.: SF7352, Style: 133731
Type: RA, Frame: 5835, HP: 1/3
Volts: 115/230
RPM - 1725

NRC Equipment Corporation
Vacuum Gauge Control Type 701
UT No. 142425
Range: 0-1000 Microns
Least Count: 5 Microns
@ 0.62 A.C. Amps

Transformer to Boost From 208-230 V

Heavi-Duty Electric Co., Type HS (Quantity - 2)
Catalog No. - H519F500 A
Primary Volts - 120/240
Secondary Volts - 12/24
60 Hz, 1-Phase, 0.5 KVA

**Platinum Resistance, K/°F/°C**

| Temp., K | Res., Ω | Temp., °F | Temp., °C |
|---|---|---|---|
| 300 | 110.71 | 80.6 | 27 |
| 299 | 110.32 | 78.8 | 26 |
| 298 | 109.92 | 77.0 | 25 |
| 297 | 109.53 | 75.2 | 24 |
| 296 | 109.13 | 73.4 | 23 |
| 295 | 108.74 | 71.6 | 22 |
| 294 | 108.34 | 69.8 | 21 |
| 293 | 107.94 | 68.0 | 20 |
| 292 | 107.55 | 66.2 | 19 |
| 291 | 107.15 | 64.4 | 18 |
| 290 | 106.76 | 62.6 | 17 |
| 289 | 106.36 | 60.8 | 16 |
| 288 | 105.96 | 59.0 | 15 |
| 287 | 105.57 | 57.2 | 14 |
| 286 | 105.17 | 55.4 | 13 |
| 285 | 104.77 | 53.6 | 12 |
| 284 | 104.37 | 51.8 | 11 |
| 283 | 103.98 | 50.0 | 10 |
| 282 | 103.58 | 48.2 | 9 |
| 281 | 103.18 | 46.4 | 8 |
| 280 | 102.79 | 44.6 | 7 |
| 279 | 102.39 | 42.8 | 6 |
| 278 | 101.99 | 41.0 | 5 |
| 277 | 101.59 | 39.2 | 4 |
| 276 | 101.19 | 37.4 | 3 |
| 275 | 100.80 | 35.6 | 2 |
| 274 | 100.40 | 33.8 | 1 |
| 273 | 100.00 | 32.0 | 0 |
| 272 | 99.60 | 30.2 | -1 |
| 271 | 99.20 | 28.4 | -2 |
| 270 | 98.80 | 26.6 | -3 |
| 269 | 98.41 | 24.8 | -4 |
| 268 | 98.01 | 23.0 | -5 |
| 267 | 97.61 | 21.2 | -6 |
| 266 | 97.21 | 19.4 | -7 |
| 265 | 96.81 | 17.6 | -8 |
| 264 | 96.41 | 15.8 | -9 |
| 263 | 96.01 | 14.0 | -10 |
| 262 | 95.61 | 12.2 | -11 |
| 261 | 95.21 | 10.4 | -12 |
| 260 | 94.81 | 8.6 | -13 |
| 259 | 94.41 | 6.8 | -14 |
| 258 | 94.01 | 5.0 | -15 |
| 257 | 93.61 | 3.2 | -16 |
| 256 | 93.21 | 1.4 | -17 |
| 255 | 92.81 | -0.4 | -18 |
| 254 | 92.41 | -2.2 | -19 |

Platinum Resistance, K/°F/°C

| Temp., K | Res., Ω | Temp., °F | Temp., °C |
|---|---|---|---|
| 253 | 92.01 | -4.0 | -20 |
| 252 | 91.61 | -5.8 | -21 |
| 251 | 91.21 | -7.6 | -22 |
| 250 | 90.81 | -9.4 | -23 |
| 249 | 90.40 | -11.2 | -24 |
| 248 | 90.00 | -13.0 | -25 |
| 247 | 89.60 | -14.8 | -26 |
| 246 | 89.20 | -16.6 | -27 |
| 245 | 88.80 | -18.4 | -28 |
| 244 | 88.40 | -20.2 | -29 |
| 243 | 87.99 | -22.0 | -30 |
| 242 | 87.59 | -23.8 | -31 |
| 241 | 87.19 | -25.6 | -32 |
| 240 | 86.79 | -27.4 | -33 |
| 239 | 86.39 | -29.2 | -34 |
| 238 | 85.98 | -31.0 | -35 |
| 237 | 85.58 | -32.8 | -36 |
| 236 | 85.18 | -34.6 | -37 |
| 235 | 84.77 | -36.4 | -38 |
| 234 | 84.37 | -38.2 | -39 |
| 233 | 83.97 | -40.0 | -40 |
| 232 | 83.56 | -41.8 | -41 |
| 231 | 83.16 | -43.6 | -42 |
| 230 | 82.76 | -45.4 | -43 |
| 229 | 82.35 | -47.2 | -44 |
| 228 | 81.95 | -49.0 | -45 |
| 227 | 81.55 | -50.8 | -46 |
| 226 | 81.14 | -52.6 | -47 |
| 225 | 80.74 | -54.4 | -48 |
| 224 | 80.33 | -56.2 | -49 |
| 223 | 79.93 | -58.0 | -50 |
| 222 | 79.52 | -59.8 | -51 |
| 221 | 79.12 | -61.6 | -52 |
| 220 | 78.71 | -63.4 | -53 |
| 219 | 78.31 | -65.2 | -54 |
| 218 | 77.90 | -67.0 | -55 |
| 217 | 77.50 | -68.8 | -56 |
| 216 | 77.09 | -70.6 | -57 |
| 215 | 76.68 | -72.4 | -58 |
| 214 | 76.28 | -74.2 | -59 |
| 213 | 75.87 | -76.0 | -60 |
| 212 | 75.47 | -77.8 | -61 |
| 211 | 75.06 | -79.6 | -62 |
| 210 | 74.65 | -81.4 | -63 |
| 209 | 74.25 | -83.2 | -64 |
| 208 | 73.84 | -85.0 | -65 |

**Platinum Resistance, K/°F/°C**

| Temp., K | Res., Ω | Temp., °F | Temp., °C |
|---|---|---|---|
| 207 | 73.43 | -86.8 | -66 |
| 206 | 73.02 | -88.6 | -67 |
| 205 | 72.62 | -90.4 | -68 |
| 204 | 72.21 | -92.2 | -69 |
| 203 | 71.80 | -94.0 | -70 |
| 202 | 71.39 | -95.8 | -71 |
| 201 | 70.99 | -97.6 | -72 |
| 200 | 70.58 | -99.4 | -73 |
| 199 | 70.17 | -101.2 | -74 |
| 198 | 69.76 | -103.0 | -75 |
| 197 | 69.35 | -104.8 | -76 |
| 196 | 68.94 | -106.6 | -77 |
| 195 | 68.53 | -108.4 | -78 |
| 194 | 68.13 | -110.2 | -79 |
| 193 | 67.72 | -112.0 | -80 |
| 192 | 67.31 | -113.8 | -81 |
| 191 | 66.90 | -115.6 | -82 |
| 190 | 66.49 | -117.4 | -83 |
| 189 | 66.08 | -119.2 | -84 |
| 188 | 65.67 | -121.0 | -85 |
| 187 | 65.26 | -122.8 | -86 |
| 186 | 64.85 | -124.6 | -87 |
| 185 | 64.43 | -126.4 | -88 |
| 184 | 64.02 | -128.2 | -89 |
| 183 | 63.61 | -130.0 | -90 |
| 182 | 63.20 | -131.2 | -91 |
| 181 | 62.79 | -133.6 | -92 |
| 180 | 62.38 | -135.4 | -93 |
| 179 | 61.97 | -137.2 | -94 |
| 178 | 61.55 | -139.0 | -95 |
| 177 | 61.14 | -140.8 | -96 |
| 176 | 60.73 | -142.6 | -97 |
| 175 | 60.32 | -144.4 | -98 |
| 174 | 59.90 | -146.2 | -99 |
| 173 | 59.49 | -148.0 | -100 |
| 172 | 59.08 | -149.8 | -101 |
| 171 | 58.66 | -151.6 | -102 |
| 170 | 58.25 | -153.4 | -103 |
| 169 | 57.84 | -155.2 | -104 |
| 168 | 57.42 | -157.0 | -105 |
| 167 | 57.01 | -158.8 | -106 |
| 166 | 56.59 | -160.6 | -107 |
| 165 | 56.18 | -162.4 | -108 |
| 164 | 55.76 | -164.2 | -109 |
| 163 | 55.35 | -166.0 | -110 |

Platinum Resistance, K/°F/°C

| Temp., K | Res., Ω | Temp., °F | Temp., °C |
|---|---|---|---|
| 162 | 54.93 | -167.8 | -111 |
| 161 | 54.52 | -169.6 | -112 |
| 160 | 54.10 | -171.4 | -113 |
| 159 | 53.69 | -173.2 | -114 |
| 158 | 53.27 | -175.0 | -115 |
| 157 | 52.86 | -176.8 | -116 |
| 156 | 52.44 | -178.6 | -117 |
| 155 | 52.02 | -180.4 | -118 |
| 154 | 51.61 | -182.2 | -119 |
| 153 | 51.19 | -184.0 | -120 |
| 152 | 50.77 | -185.8 | -121 |
| 151 | 50.35 | -187.6 | -122 |
| 150 | 49.93 | -189.4 | -123 |
| 149 | 49.52 | -191.2 | -124 |
| 148 | 49.10 | -193.0 | -125 |
| 147 | 48.68 | -194.8 | -126 |
| 146 | 48.26 | -196.6 | -127 |
| 145 | 47.84 | -198.4 | -128 |
| 144 | 47.42 | -200.2 | -129 |
| 143 | 47.00 | -202.0 | -130 |
| 142 | 46.58 | -203.8 | -131 |
| 141 | 46.16 | -205.6 | -132 |
| 140 | 45.74 | -207.4 | -133 |
| 139 | 45.32 | -209.2 | -134 |
| 138 | 44.90 | -211.0 | -135 |
| 137 | 44.48 | -212.8 | -136 |
| 136 | 44.06 | -214.6 | -137 |
| 135 | 43.64 | -216.4 | -138 |
| 134 | 43.22 | -218.2 | -139 |
| 133 | 42.80 | -220.0 | -140 |
| 132 | 42.37 | -221.8 | -141 |
| 131 | 41.95 | -223.6 | -142 |
| 130 | 41.53 | -225.4 | -143 |
| 129 | 41.10 | -227.2 | -144 |
| 128 | 40.68 | -229.0 | -145 |
| 127 | 40.26 | -230.8 | -146 |
| 126 | 39.83 | -232.6 | -147 |
| 125 | 39.41 | -234.4 | -148 |
| 124 | 38.99 | -236.2 | -149 |
| 123 | 38.56 | -238.0 | -150 |
| 122 | 38.14 | -239.8 | -151 |
| 121 | 37.71 | -241.6 | -152 |
| 120 | 37.29 | -243.4 | -153 |
| 119 | 36.86 | -245.2 | -154 |

**Platinum Resistance, K/$^{o}$F/$^{o}$C**

| Temp., K | Res., Ω | Temp., $^{o}$F | Temp., $^{o}$C |
|---|---|---|---|
| 118 | 36.43 | -247.0 | -155 |
| 117 | 36.01 | -248.8 | -156 |
| 116 | 35.58 | -250.6 | -157 |
| 115 | 35.15 | -252.4 | -158 |
| 114 | 34.73 | -254.2 | -159 |
| 113 | 34.30 | -256.0 | -160 |
| 112 | 33.87 | -257.8 | -161 |
| 111 | 33.44 | -259.6 | -162 |
| 110 | 33.02 | -261.4 | -163 |
| 109 | 32.59 | -263.2 | -164 |
| 108 | 32.16 | -265.0 | -165 |
| 107 | 31.73 | -266.8 | -166 |
| 106 | 31.30 | -268.6 | -167 |
| 105 | 30.87 | -270.4 | -168 |
| 104 | 30.44 | -272.2 | -169 |
| 103 | 30.01 | -274.0 | -170 |
| 102 | 29.58 | -275.8 | -171 |
| 101 | 29.15 | -277.6 | -172 |
| 100 | 28.72 | -279.4 | -173 |
| 99 | 28.29 | -281.2 | -174 |
| 98 | 27.85 | -283.0 | -175 |
| 97 | 27.42 | -284.8 | -176 |
| 96 | 26.99 | -286.6 | -177 |
| 95 | 26.56 | -288.4 | -178 |
| 94 | 26.12 | -290.2 | -179 |
| 93 | 25.69 | -292.0 | -180 |
| 92 | 25.25 | -293.8 | -181 |
| 91 | 24.82 | -295.6 | -182 |
| 90 | 24.39 | -297.4 | -183 |
| 89 | 23.95 | -299.2 | -184 |
| 88 | 23.52 | -301.0 | -185 |
| 87 | 23.08 | -302.8 | -186 |
| 86 | 22.65 | -304.6 | -187 |
| 85 | 22.21 | -306.4 | -188 |
| 84 | 21.78 | -308.2 | -189 |
| 83 | 21.34 | -310.0 | -190 |
| 82 | 20.91 | -311.8 | -191 |
| 81 | 20.47 | -313.6 | -192 |
| 80 | 20.04 | -315.4 | -193 |
| 79 | 19.60 | -317.2 | -194 |
| 78 | 19.17 | -319.0 | -195 |
| 77 | 18.74 | -320.8 | -196 |
| 76 | 18.31 | -322.6 | -197 |
| 75 | 17.88 | -324.4 | -198 |
| 74 | 17.45 | -326.2 | -199 |
| 73 | 17.02 | -328.0 | -200 |

**Platinum Resistance, K/°F/°C**

| Temp., K | Res., Ω | Temp., °F | Temp., °C |
|---|---|---|---|
| 72 | 16.59 | -329.8 | -201 |
| 71 | 16.16 | -331.6 | -202 |
| 70 | 15.73 | -333.4 | -203 |
| 69 | 15.31 | -335.2 | -204 |
| 68 | 14.88 | -337.0 | -205 |
| 67 | 14.46 | -338.8 | -206 |
| 66 | 14.03 | -340.6 | -207 |
| 65 | 13.61 | -342.4 | -208 |
| 64 | 13.19 | -344.2 | -209 |
| 63 | 12.77 | -346.0 | -210 |
| 62 | 12.36 | -347.8 | -211 |
| 61 | 11.95 | -349.6 | -212 |
| 60 | 11.54 | -351.4 | -213 |
| 59 | 11.13 | -353.2 | -214 |
| 58 | 10.72 | -355.0 | -215 |
| 57 | 10.32 | -356.8 | -216 |
| 56 | 9.92 | -358.6 | -217 |
| 55 | 9.53 | -360.4 | -218 |
| 54 | 9.14 | -362.2 | -219 |
| 53 | 8.75 | -364.0 | -220 |
| 52 | 8.37 | -365.8 | -221 |
| 51 | 7.99 | -367.6 | -222 |
| 50 | 7.62 | -369.4 | -223 |
| 49 | 7.25 | -371.2 | -224 |
| 48 | 6.89 | -373.0 | -225 |
| 47 | 6.53 | -374.8 | -226 |
| 46 | 6.18 | -376.6 | -227 |
| 45 | 5.84 | -378.4 | -228 |
| 44 | 5.50 | -380.2 | -229 |
| 43 | 5.17 | -382.0 | -230 |
| 42 | 4.85 | -383.8 | -231 |
| 41 | 4.54 | -385.6 | -232 |
| 40 | 4.24 | -387.4 | -233 |
| 39 | 3.94 | -389.2 | -234 |
| 38 | 3.66 | -391.0 | -235 |
| 37 | 3.38 | -392.8 | -236 |
| 36 | 3.12 | -394.6 | -237 |
| 35 | 2.87 | -396.4 | -238 |
| 34 | 2.62 | -398.2 | -239 |
| 33 | 2.39 | -400.0 | -240 |
| 32 | 2.17 | -401.8 | -241 |
| 31 | 1.96 | -403.6 | -242 |
| 30 | 1.76 | -405.4 | -243 |
| 29 | 1.58 | -407.2 | -244 |
| 28 | 1.41 | -409.0 | -245 |

**Platinum Resistance, K/°F/°C**

| Temp., K | Res., Ω | Temp., °F | Temp., °C |
|---|---|---|---|
| 27 | 1.25 | -410.8 | -246 |
| 26 | 1.10 | -412.6 | -247 |
| 25 | 0.96 | -414.4 | -248 |
| 24 | 0.84 | -416.2 | -249 |
| 23 | 0.73 | -418.0 | -250 |
| 22 | 0.63 | -419.8 | -251 |
| 21 | 0.54 | -421.6 | -252 |
| 20 | 0.46 | -423.4 | -253 |
| 19 | 0.39 | -425.2 | -254 |
| 18 | 0.33 | -427.0 | -255 |
| 17 | 0.28 | -428.8 | -256 |
| 16 | 0.23 | -430.6 | -257 |
| 15 | 0.20 | -432.4 | -258 |
| 14 | 0.17 | -434.2 | -259 |
| 13 | 0.14 | -436.0 | -260 |
| 12 | 0.12 | -437.8 | -261 |

## INTERNAL DISTRIBUTION

1. V. D. Baxter
2. F. C. Chen
3. R. S. Carlsmith
4. G. E. Courville
5. F. A. Creswick
6. P. D. Fairchild
7. V. C. Mei

8-17. R. W. Murphy
18. R. B. Shelton
19. Central Research Library
20. Document Reference Section
21-23. Laboratory Records
24. Laboratory Records--Record Copy

## EXTERNAL DISTRIBUTION

25. B. G. Buchanan, Professor of Computer Science, Department of Computer Science, Room 318, Alumni Hall, University of Pittsburgh, Pittsburgh, PA 15260
26. H. P. Cramer, Cryodynamics, Inc., 1101 Bristol Road, Mountainside, NJ 07092
27. R. J. Fiskum, Energy Conversion Equipment Branch, CE-132, 5H-048/FORS, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington, DC 20585

28-32. E. G. Keshock, Department of Mechanical and Aerospace Engineering, The University of Tennessee, 414 Dougherty Hall, Knoxville, TN 37996-2210

33. I. Magill, Fisher and Paykel, P.O. Box 58-046, East Tamaki, Auckland, NEW ZEALAND

34-43. S. F. Malaker, Cryodynamics, Inc., 1101 Bristol Road, Mountainside, NJ 07092

44. D. E. Morrison, Professor of Sociology, Michigan State University, 201 Berkey Hall, East Lansing, MI 48824-1111
45. R. L. Perrine, Professor, Engineering and Applied Sciences, Civil Engineering Department, Engineering I, Room 2066, University of California, Los Angeles, CA 90024
46. J. D. Ryan, Energy Conversion Equipment Branch, CE-132, 5H-048/FORS, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington, DC 20585
47. T. G. Statt, Energy Conversion Equipment Branch, CE-132, 5H-048/FORS, U.S. Department of Energy, 1000 Independence Avenue, SW, Washington, DC 20585
48. Office of the Assistant Manager for Energy Research and Development, DOE-ORO, P. O. Box 2001, Oak Ridge, TN 37831-8600

49-60. Office of Scientific and Technical Information P.O. Box 62, Oak Ridge, Tn 37831