NBS TECHNICAL NOTE 655

U.S. DEPARTMENT OF COMMERCE/ National Bureau of Standards

Cryogenic Refrigerators-
an Updated Survey

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Cryogenic Refrigerators - An Updated Survey

T. R. Strobridge

In 1969, we gave efficiency, weight, volume, and cost data for 95 cryogenic refrigerators and liquefiers excluding air separation plants. Recently, the survey was repeated. The original data and those for 49 additional refrigerators and liquefiers are presented spanning refrigeration capacities from 0.2 to 10^6 W and temperatures from 1.85 to 90 K. Generally, there is no change in the trends exhibited by the older data except that the high temperature, low capacity new units seem to be larger, heavier and slightly less efficient than in prior years. Presumably, these effects are due to efforts to increase useful life and reliability. Costs remain the same as predicted before even though no dollar value adjustments were made.

Key words: Cost; cryogenic refrigerators; efficiency; volume; weight.

Late in 1968, we started collecting data on the efficiency, weight, volume, and cost of cryogenic refrigerators and liquefiers excluding air separation plants. The data on 95 units from the U. S. and Europe were presented in early 1969 [1]. There has been sufficient continuing interest shown so that the survey has been updated. Information on 49 other refrigerators and liquefiers is presented here along with the original data and portions of the original text.

Although there is considerable scatter in the data, significant trends can be identified that yield values useful for estimating purposes. The efficiency data show the amount of input power required by a refrigerator and thus give one part of the operating expense. The mass of a unit may not be of concern to an accelerator designer interested in large units, but it can be important in the applications calling for low cooling capacity aboard spacecraft or airplanes. Space occupied by the refrigerator can be important, especially in the premium areas near accelerators, in experimental halls, in spacecraft and airplanes or on ships. The interest in capital cost is obvious since this type of machinery is not inexpensive. In all of the charts which follow, lines have been drawn through the data which represent the author's judgment of an average and are thus subject to arbitration. The general shape of the curves can be predicted from a knowledge of the characteristics of low temperature refrigerators, but since there is wide variation in the data any quantitative interpretation must be approached with caution.

Through the second law of thermodynamics, the minimum power required to produce a unit of refrigeration under ideal conditions is given by

$$\left.\frac{W_c}{Q}\right)_{Carnot} = \frac{T_o - T}{T}, \qquad (1)$$

where W_c is the net input power required (power for compression minus the power produced by expanders if any), Q is the refrigeration produced, T_o is the temperature of the surroundings, nominally 300 K, and T is the desired refrigeration temperature. As T becomes smaller, the specific power requirement increases rapidly as seen in table 1 which also gives the ideal power requirement for liquefaction. T in table 1 is taken to be the normal boiling temperature of the fluids.

The difference in input power required to cool an object with liquid produced by a liquefier or with a continuously operating refrigerator is evident. More power is required by a liquefier because when the liquid is evaporated at another location, the cold effluent vapor cannot be used in the liquefaction process to help cool the feed gas stream. An ideal helium liquefier would require a power input of 236 W to produce liquid at the rate of 1 liter per hour. The heat of vaporization of helium is low and 1 W will evaporate 1.38 liters per hour. Therefore, 326 W would be required to power a liquefier whose liquid product was used to absorb a 1 W heat load at 4.2 K. An ideal refrigerator would require 70.4 W input power to produce 1 W of refrigeration at the same temperature level. This difference in power requirement does not mean that a refrigerator should be chosen over a liquefier for all cooling applications; there are conceivable circumstances in which a liquefier would be the better choice.

Table 1. Reversible power requirements.

Fluid	T (K)	Refrigeration (W/W)	Liquefaction (W hr/liter)	Evaporating Liquid Refrigeration* (W/W)
Helium	4.2	70.4	236	326
Hydrogen	20.4	13.7	278	31.7
Neon	27.1	10.1	447	15.5
Nitrogen	77.4	2.88	173	3.87
Fluorine	85.0	2.53	238	3.26
Argon	87.3	2.44	185	2.95
Oxygen	90.2	2.33	195	2.89
Methane	111.5	1.69	129	2.15

* Obtained by dividing the ideal liquefaction power requirement by the heat of vaporization of the fluid.

When comparing the efficiencies of low temperature refrigerators, it is informative to examine the ratio

$$\text{Percent Carnot} = \frac{\left.\frac{W_c}{Q}\right)_{\text{Carnot}}}{\left.\frac{W_c}{Q}\right)_{\text{Actual}}} \times 100 . \qquad (2)$$

This ratio indicates the extent to which the actual refrigerator deviates from ideal performance. The same ratio is formed for liquefiers using the values from table 1 and the actual power consumption per liter per hour. The capacity of the liquefiers included in the data has been converted to equivalent refrigeration capacity by determining the percent of Carnot performance that they achieve as liquefiers and then calculating the refrigeration output of a refrigerator operating at the same efficiency with the same input power. In some instances equivalent refrigeration capacity was given by the manufacturers and was used directly. In all instances, the input power was taken as the installed drive power, not the power measured at the input to the drive motor.

In figure 1, the percent of Carnot given by eq (2) is plotted as a function of refrigeration capacity in watts. The largest of the new units in the 1.8 to 9 K temperature range is a proposed liquefier. Actually, the liquefier is now operating at reduced capacity (the equivalent of 3420 W) but is designed for the greater capacity at higher flow rates. The original curve is unchanged as the new data show no significant different trend.

Historically, the contention has been that higher temperature refrigerators (or liquefiers) are more efficient. The data for refrigeration temperatures between 10 and 30 K (and 30 to 90 K) refute that notion

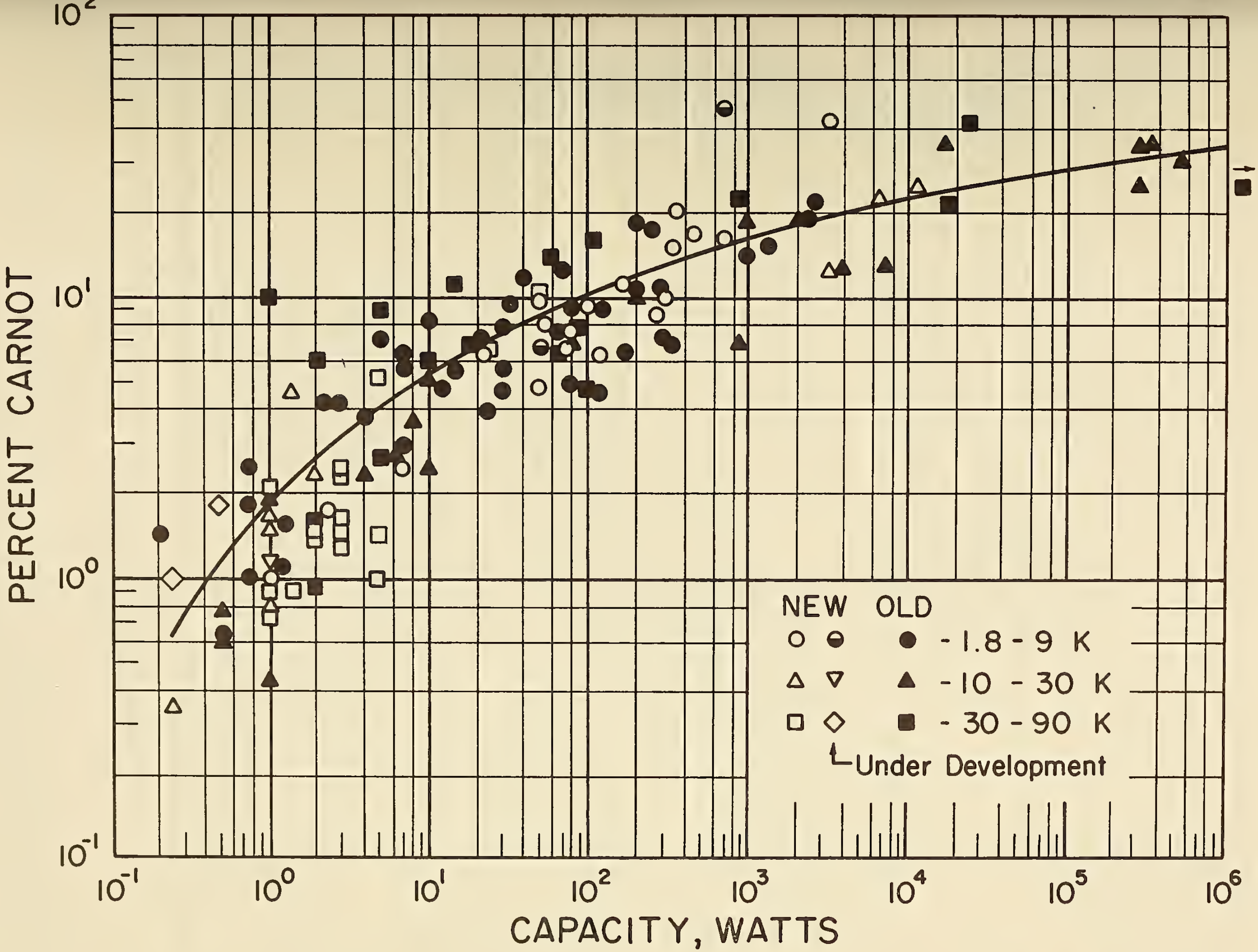

Figure 1. Efficiency of low temperature refrigerators and liquefiers as a function of refrigeration capacity.

at least when presented on this common basis. To be sure, less input power is required to produce the same number of watts of cooling at higher temperatures, but the losses relative to ideal are proportionally the same. For many of the refrigerators of less than 10 kW capacity, liquid nitrogen precooling consumption rates are available, but the equivalent power that would be consumed if the precooling were provided by a closed cycle refrigerator on site has not been included in the efficiency computation. Therefore, the efficiencies of a number of the units would be slightly lower than shown if this factor were included. The largest of the units shown are high capacity hydrogen liquefiers. Here nitrogen temperature precooling is commonly provided by closed cycle nitrogen refrigerators and the input power requirements are known and have been included. This means that the values are more nearly true and are not slightly biased as are some of those at lower capacities.

Performance data for higher temperature plants, in the 30 - 90 K range, are not as numerous but the trend is obvious. In the 10 to 1000 W range, indeed efficiencies are higher, but the estimate given by a supplier of large facilities (shown at the right as off scale) is comparable to lower temperature plants. At lower capacities, the deviation in performance is an entire decade. It must be noted that these are units of very low input power and it is not surprising to find such variation. In spite of the scatter in the data, it is clear that very small low temperature refrigerators are subject to proportionally higher losses than the larger units.

Many of the low capacity refrigerators have been intended for military or space flight missions. Emphasis was necessarily placed on light, small sized machines. Many of the refrigerators in the original survey (1.8 - 9 K) are shown smaller and lighter than the average at that time, figures 2 and 3. This trend has continued. Data recently collected for the 30 to 90 K temperature range, however, show that

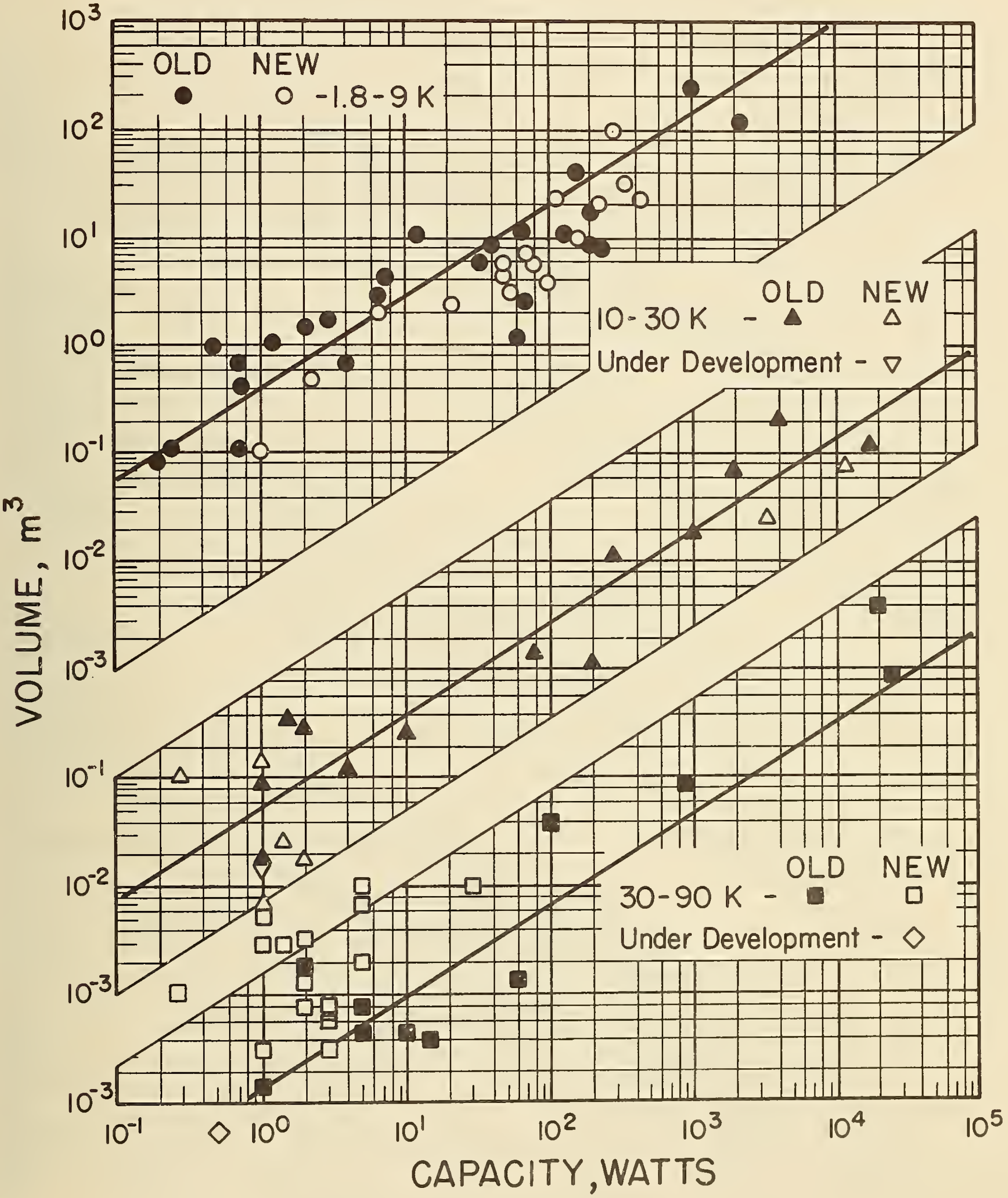

Figure 2. Volume of low temperature refrigerators and liquefiers as a function of refrigeration capacity.

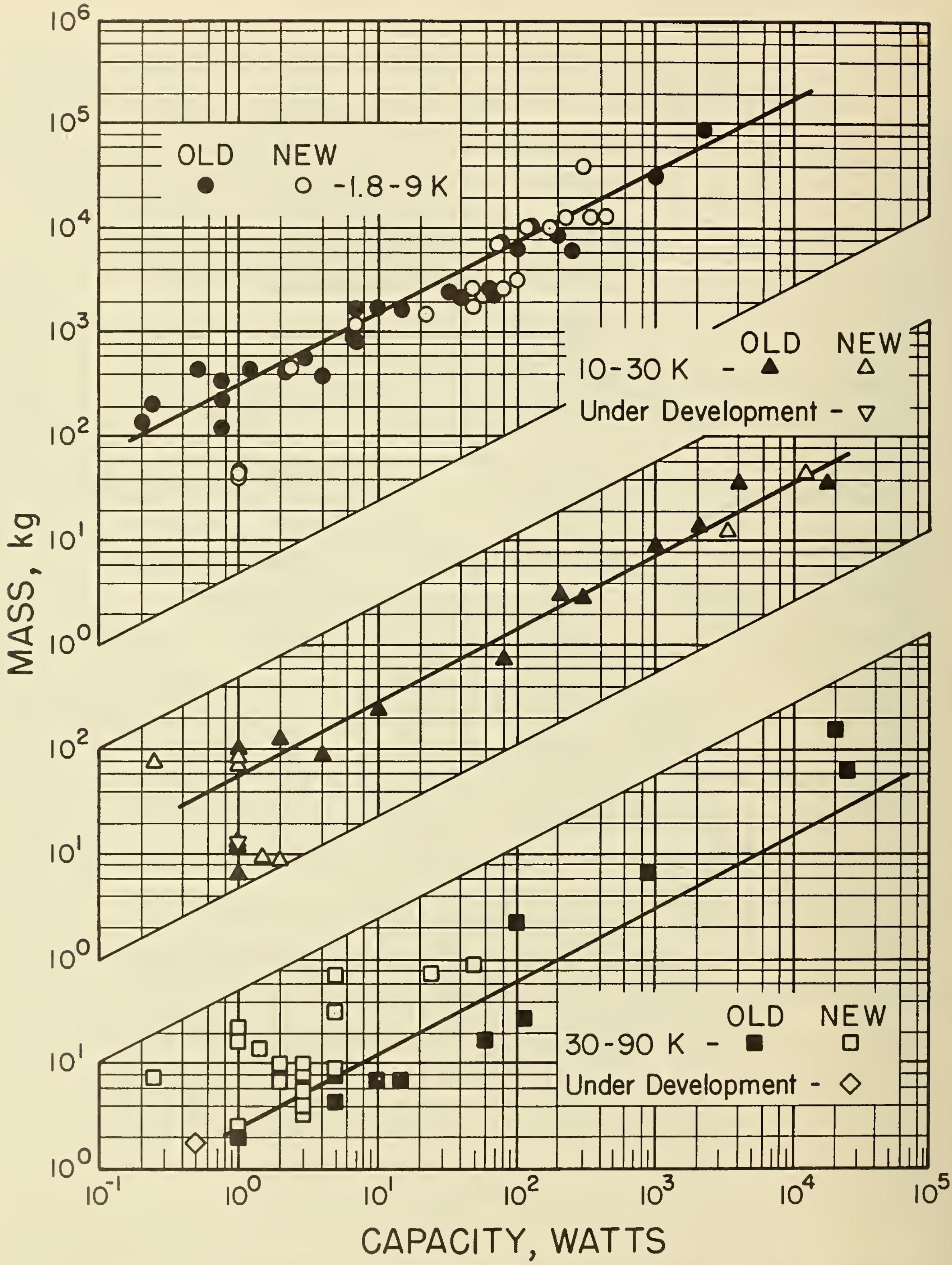

Figure 3. Mass of low temperature refrigerators and liquefiers as a function of refrigeration capacity.

many of the new low capacity units are heavier and larger than the older refrigerators. Many of these new machines use thermodynamic cycles that have not been common in the past. It may be that the demonstrated weight and volume increases are caused by lack of refinement with the new cycles; or it may be that larger heavier structures have been necessary to reach required machine lifetime levels and/or lower costs.

Some time ago the line shown in figure 4 was established for 4 K refrigerators with only a few points. The curve adequately represents subsequent additions of data. Notice that the abscissa is now input power, not refrigeration capacity. The input power at any refrigeration capacity can be determined from the efficiency data. The cost of many classes of machinery is proportional to the 0.7 power of the installed input power. Hydrogen temperature units and even higher temperature refrigerators and liquefiers follow the trend quite well. These data indicate that to a first approximation for refrigerators and liquefiers operating in the range 1.8 to 90 K,

$$C = 6000\ P^{0.7}, \qquad (3)$$

where C is the cost in dollars and P is the installed input power in kilowatts. Adjustments have not been made for the change in value of the dollar since the data are so scattered.

The several million dollar units in the upper right are typical of large hydrogen liquefiers; here the costs are hard to define because in some instances, the equipment for producing hydrogen feed gas is included in the cost figures. Again, it is emphasized that the charts are intended for estimating purposes only.

Existing low temperature refrigerators cover a wide range of capacity and temperatures and the performance (input power) can be fairly well predicted. It does not appear that any significant increase

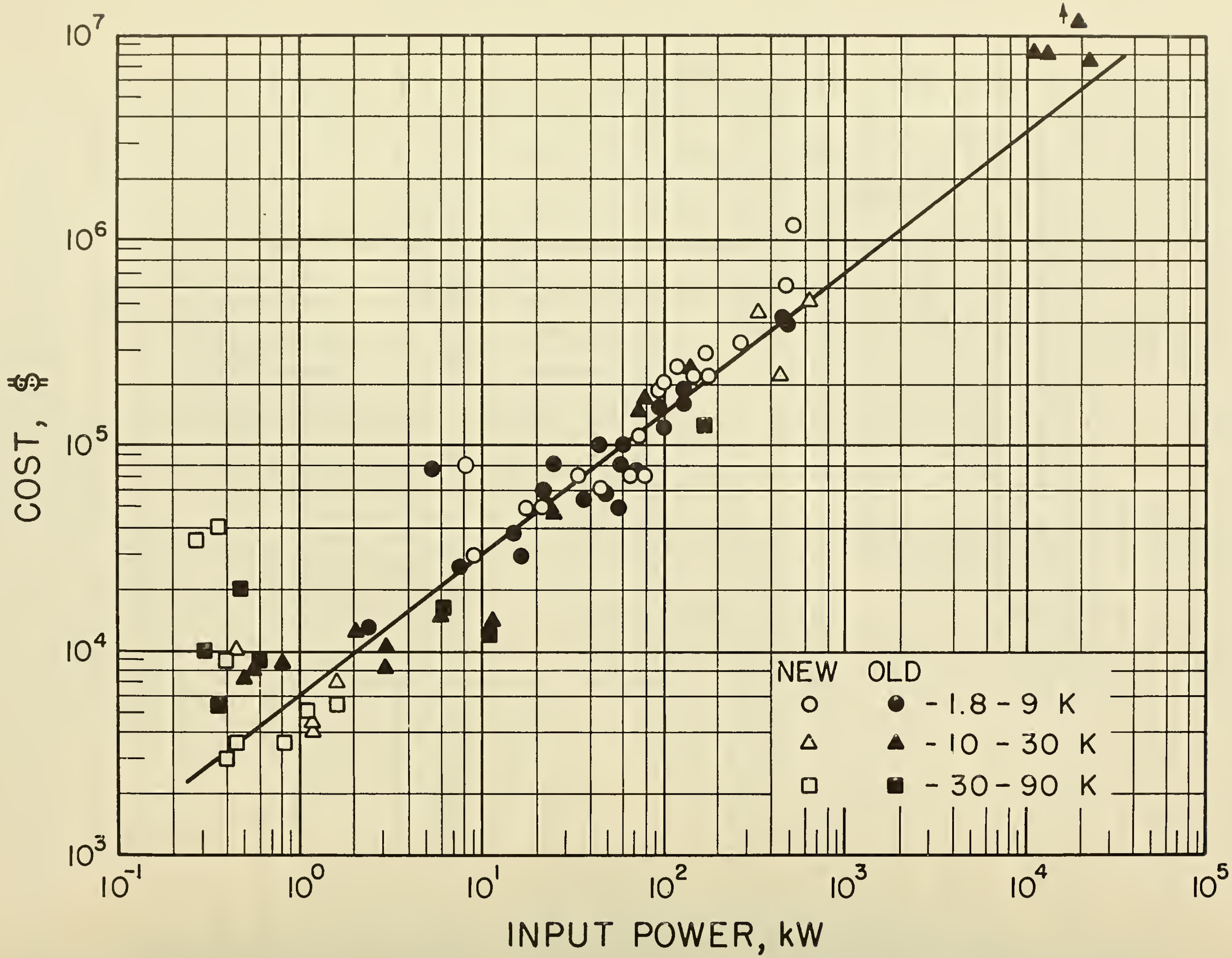

Figure 4. Cost of low temperature refrigerators and liquefiers as a function of installed input power.

in efficiency has been achieved for the entire class of devices in the past few years although in certain instances good performance has been realized. The more efficient facilities are in the large sizes and use complex thermodynamic cycles. Perhaps the same performance potential exists in smaller units, but costs might be prohibitive and the savings in electrical power would not justify the greater capital outlay. The trends are identifiable in the mass and volume characteristics and there is the potential for reducing both, perhaps with an increase in price. Capital cost should be predictable for standard types of refrigerators at least. Experience shows that special requirements are expensive but the field is quite competitive as indicated by the twenty-one European prices which are included.

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In 1969, we gave efficiency, weight, volume, and cost data for 95 cryogenic refrigerators and liquefiers excluding air separation plants. Recently, the survey was repeated. The original data and those for 49 additional refrigerators and liquefiers are presented spanning refrigeration capacities from 0.2 to 10^6 W and temperatures from 1.85 to 90 K. Generally, there is no change in the trends exhibited by the older data except that the high temperature, low capacity new units seem to be larger, heavier and slightly less efficient than in prior years. Presumably, these effects are due to efforts to increase useful life and reliability. Costs remain the same as predicted before even though no dollar value adjustments were made.

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