# COOLING TOWER PERFORMANCE CURVES

## I. *INTRODUCTION*

The purpose of this book is to provide a technically sound method, of sufficient accuracy, to make valid thermal performance studies of water cooling towers. Over twenty years ago a major industrial cooling tower manufacturer made a limited publication of a book "Cooling Tower Performance", generally known as the "Black Book". This was a collection of curves relating the variables which affect water cooling tower performance to a common index. This index provided a characteristic, a "degree of difficulty", for the various combinations of cooling ranges, approaches, wet bulb temperatures, and water-to-air loadings. Although it was a major contribution to the art, the "Black Book" was not generally available, and its accuracy was decreased by simplifying assumptions made to facilitate calculations and the plotting of data, both of which were done by hand.

As a service to the industry, and in consideration of a real need for a dependable generalized method for evaluating cooling towers which is simple to use, the Cooling Technology Institute has published this book, destined to be known in the trade as the "Blue Book".

Many ways of calculating cooling tower performance have been proposed and published in the past, however, the theory which is the basis of this publication is the one generally accepted in the industry as being the most technically correct and accurate.

The use of this theory involves integration procedures that can become cumbersome when it is necessary to determine several factors or points. Therefore, these integrations have been made over limits that encompass all normal operating conditions encountered in cooling tower work, and are presented in this publication in curve form to facilitate handling and rapid calculation.

This book is applicable for use in designing cooling towers, for analysis of test data, and for prediction of performance with changes in operating conditions. It enables the evaluation of the performance of a given cooling tower, within reasonable operating limits, without the necessity of original performance curves. It also allows prediction of performance over a much broader range of operating conditions than the usual performance curves.

Curves of this same nature, using the same performance calculation method, have been published by others. However, in every case the utility of the curves has been reduced appreciably by inaccuracies in calculations and drafting. Maximum accuracy and consistency have been obtained by use of a computer for making calculations and plotting the curves in this book.

The utility of these prior publications has also been limited by insufficiently broad coverage of the operating variables of wet bulb temperature, range, approach, and liquid-to-gas ratio. This publication has broadened the coverage to include all normally encountered conditions of cooling tower operations and has added sufficient curves to minimize the necessity for interpolation.

## II. *COOLING TOWER THEORY*

The basic function of a cooling tower is to cool water by intimately mixing it with air. This cooling is accomplished by a combination of sensible heat transfer between the air and the water and the evaporation of a small portion of the water. This type of transfer is represented by the equation

$$\frac{KaV}{L} = \int_{T_2}^{T_1} \frac{\mathrm{dT}}{h_w - h_a}$$

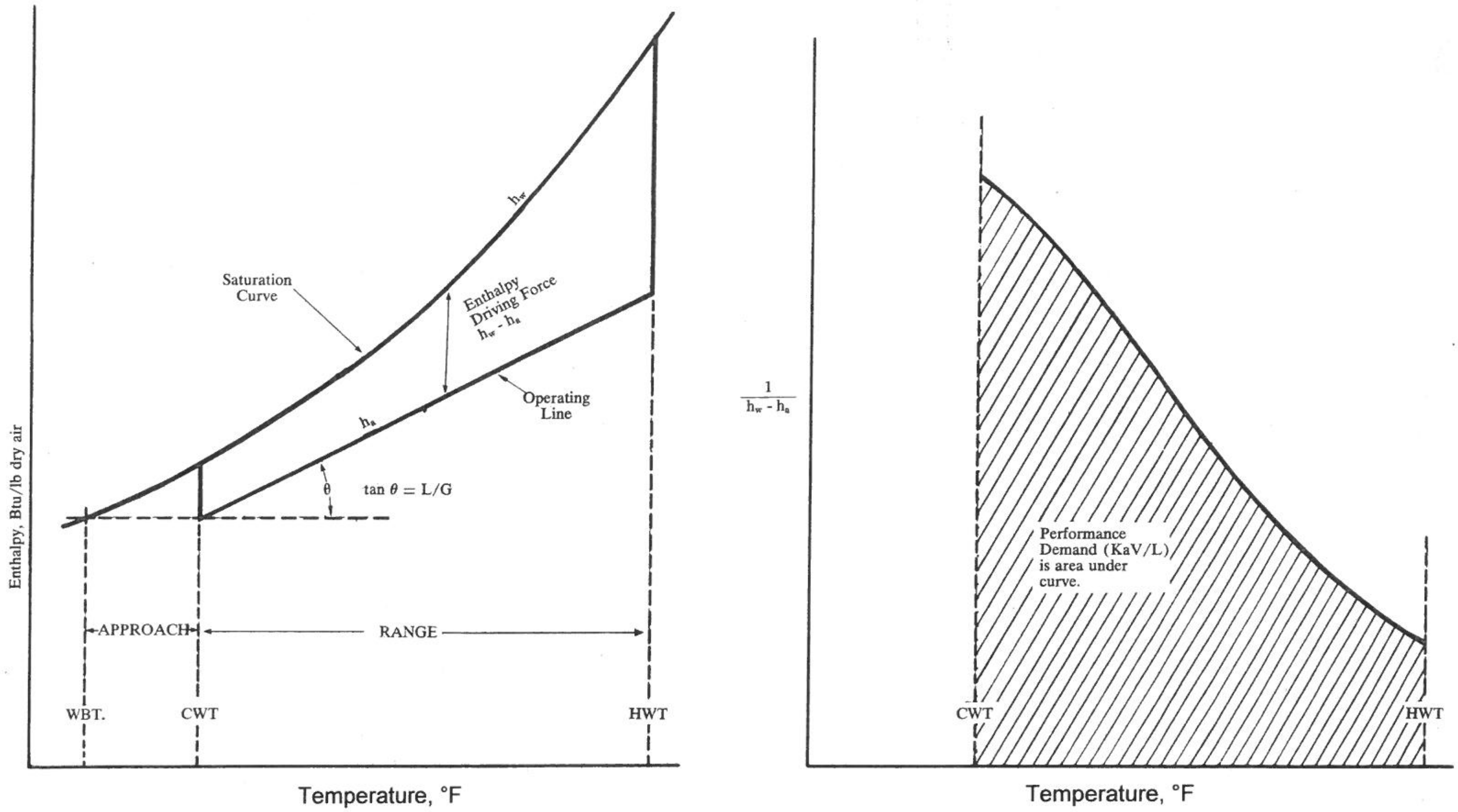
This equation is commonly referred to as the Merkel equation. The derivation can be found in Kern, D. Q., "Process Heat Transfer," McGraw-Hill Book Company, Inc., New York, 1950.

This equation can be represented graphically by the following diagram:

***Figure 1.***

(a) Saturation Curve & Operating Line

(b) Evaluation of $\frac{1}{h_w - h_a}$




This basic heat transfer equation, which is applicable to any direct contact water-air cooling method has been integrated by the "Four-Point Tchebycheff Function Evaluation" by computer over a broad range of variables.

Any additional point that is desired can be calculated by following the instructions in CTI Bulletin ATC-105 and using the CTI Form ATC-127.

Included in this volume is an enthalpy table covering conditions from 0°F. to 200°F. This is helpful if additional points need to be calculated.

It is normal for the performance requirement of a cooling tower to change during its life-time. Heat removal requirements may change drastically, and often the optimum values of cooling range and approach to the wet bulb temperature are appreciably affected by changes in product quality, market value, and price changes of associated equipment and/ or products. Thus, the need for performance calculations normally does not end with the initial design and installation.

***Example No. 1. The determination of tower capability.****

A water cooling tower was purchased to cool 10,000 gpm from 110°F to 90°F with 80°F wet bulb temperature, using a total of 136 fan driver-output horsepower. The following data were obtained from a field test:

| | |
|---|---|
| Water circulation rate, gpm | 8,950 |
| Hot water temperature, °F | 110 |
| Cold water temperature, °F | 84 |
| Cooling range, °F | 26 |
| Wet bulb temperature, °F | 69 |
| Approach, °F | 15 |
| Total Fan Driver-output horsepower | 115 |

The manufacturer has submitted Figure 2 in accordance with paragraph 6 of CTI Bulletin ATC-105.

*Step 1.* The design L/G, from Figure 2, is 1.37. Compute the test L/G, using equation (2), ATC-105:

$$\left(\frac{L}{G}\right)_{test} = \frac{8{,}950}{10{,}000} \text{ x } \left(\frac{136}{115}\right)^{1/3} \text{ x } 1.37 = 1.30$$

Select the curve for 69°F WBT and 26° range (test values). The intersection of the 15° approach curve and the L/G = 1.30 line occurs at the ordinate 1.51, which is the test KaV/L.

*Step 2*. The point determined in Step 1 is plotted on Figure 3. A curve is drawn through this point parallel to the characteristic curve submitted by the manufacturer, intersecting the 10° approach curve at an L/G of 1.45.

*Step 3*. The tower capability from paragraph 9 of ATC-105 is: $Q = \frac{1.45}{1.37} \text{ x } 100 = 105.8\%$

***Example No. 2. The effect of wet bulb temperature.***

Using the test KaV/L versus L/G point for the Example 1 tower, we can now predict cold water temperatures for various operating wet bulb temperatures. If the range, water flow, and air flow remain constant at test values but the WBT drops to 60°F, CWT and HWT are predicted as follows:

Select the curve for 60°F WBT and 26° range. Plot the test point KaV/L = 1.51, L/G = 1.30 (see Figure 4). Read the approach: 19.6°. The CWT is 60° + 19.6° = 79.6°F, and the HWT is 79.6° + 26° = 105.6°F.

***Example No. 3. The effect of cooling range.***

Using the test KaV/L versus L/G point for the Example 1 tower, we may also predict cold water temperatures for various cooling ranges (HWT – CWT). If the WBT, water flow, and air flow remain constant but the range increases to 35°, CWT and HWT are predicted as follows:

Select the curve for 69°F WBT and 35° range. Plot the test point KaV/L = 1.51, L/G = 1.30 (see Figure 5). Read the approach: 17°. The CWT is 69° + 17° = 86°F, and the HWT is 86°F, and the HWT is 86° + 35° = 121°F.

***Example No. 4. The effect of water circulation rate.***

Now suppose the water circulation rate for the Example 1 tower is increased by 10%, keeping the air flow, range, and WBT constant. Using the test characteristic curve (described in Step 2 of Example 1 and shown as the upper line on Figure 3) CWT and HWT are predicted as follows:

New circulation rate – 8,950 x 1.1 = 9,845 gpm

New L/G = 1.30 x 1.1 = 1.43

The new KaV/L is read from Figure 3 at the intersection of the test characteristic curve and the L/G = 1.43 line: KaV/L = 1.43.

**Refer to paragraph IV, "Limitations on Use of Book"*

Select the curve for 69°F WBT and 26° range (test conditions). The intersection of KaV/L = 1.43 and L/G = 1.43 lines occurs at an approach of 16.5° (see Figure 6). The corresponding CWT is 69° + 16.5° = 85.5°F, and the HWT is 85.5° + 26° = 111.5°F.

## III. *BASIS OF CALCULATIONS*

Several assumptions were necessary to calculate the data presented in this book. These assumptions and their effect on overall accuracy are as follows:

1. It is assumed that the effect of the heat of the vaporized liquids on the results is negligible.
2. The equation illustrated above is based upon the counter-current flow of air and water. Vertical towers having upward air flow and downward water fall are predominantly counterflow. Towers with horizontal air flow and downward water fall are predominantly crossflow. Most towers are a combination of counter and crossflow. Although the equation is based on pure counter-current flow, the curves are applicable, within the limits set forth in CTI Bulletin ATC-105, to both crossflow and counterflow towers.

## IV. *LIMITATIONS ON USE OF BOOK*

1. The accuracy decreases as calculations or tests are run at conditions further from design. However, within the limits listed in ATC-105 these deviations will be less than test measurement inaccuracies. Under conditions beyond the limits listed in ATC-105 the deviations may become larger than test inaccuracies. However, the curves and calculations in this book will still have sufficient accuracy to be useful to the tower operator.
2. Actual tower performance may deviate from predicted performance at water loadings considerably different from design, because of uneven water distribution at relatively low or high levels, and possible channeling of air and water. Also, it may be necessary to correct or measure* air flow (G) at water loadings (L) considerably different from design, since water loading affects the resistance to the flow of air.
3. A single known L/G versus Ka V/L point is sufficient for the prediction of performance at various wet bulb temperatures and cooling ranges, if L/G is held constant. If L/G is varied, the tower characteristic curve is used for the predictions. If this curve is not available, it can be constructed by drawing a straight line on logarithmic paper through two (or more) test L/G versus KaV/L points. If only one point is available, the use of – 0.6 as the slope of the characteristic curve for splash type fill is valid within reasonable limits. A slope of – 0.8 can be used for film type fill (see CTI Bulletin ATC-105, paragraph 2.33, for recommended limitations). Lines with slopes of -0.6 are printed on an overlay contained in the pocket in the front of this book. This grid simplifies the use of the book when transferring from one set of conditions to another. For example, a line parallel to the grid lines may be drawn through a known L/G versus KaV/L point, and the graph then used to predict approaches at other ranges, wet bulb temperatures, and values of L/G. Also included is a blank overlay for penciling in tower characteristic curves of other slopes.

## V. *SCOPE OF CURVES*

Included in this book are 821 pages of curves on logarithmic paper, with L/G (water to air ratio) as abscissa, Ka V/L (tower characteristic) as ordinate, and approach as parameter. Each page represents a fixed combination of wet bulb temperature and cooling range.

In the low wet bulb range, sets of approach curves are provided for wet bulb temperatures of 0, 20, 30, 40, and 45°F, and for cooling ranges of 10, 12, 14, 15, 16, 20, 24, 30, 40, 50, 60, 70 and 80°F. In the higher wet bulb range, sets of curves are provided for wet bulb temperatures of 50, 52, 54, 56, 58 and from 60 to 90°F in 1° increments, and for ranges of 4, 6, 8, 10, 12, 14, 15, 16, 18, 20, 22, 24, 26, 28, 30, 35, 40, 50, 60, 80 and 100°F. For all curve sets, approach curves are for 2 to 12°F in 1° increments, 14 to 30°F in 2° increments, and 30 to

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**See CTI Bulletin TPR-122 "Field Tests of Fan Performance on Induced Draft Cooling Towers.*

100°F in 5° increments. No curves are given for conditions where hot water temperatures would exceed 200°F or where cold water temper-atures would be below 34°F.

## VI. *HOW TO USE THIS BOOK*

The following examples are illustrative of the types of performance problems which can be solved using these curves. They also demonstrate the exact method of solving each type of problem.

***Example No. 5. The effect of air delivery.***

Assume air delivery to the Example 1 tower is increased by 10%, with no change in water circulation rate, range and WBT. The CWT and HWT can be predicted as follows;

New L/G = 1.30/1.10 = 1.18
The new KaV/L is read from Figure 3 at the intersection of the test characteristic curve and the L/G = 1.18 line: KaV/L = 1.60.

Select the curve for 69°F WBT and 26° range (test conditions). The intersection of KaV/L – 1.60 and L/G = 1.18 occurs at an approach of 13.5° (see Figure 7). The corresponding CWT is 69° + 13.5° = 82.5°F, and the HWT is 82.5° + 26° = 108.5°G.

## VII. *ILLUSTRATION OF THE CALCULATION OF TOWER CAPABILITY BY MEANS OF ATC-105*

The use of this book of curves is not intended in any way to replace the procedures outline in CTI Bulletin ATC-105 for cooling tower acceptance testing. The book simply provides a convenient, time saving method of evaluating the effects of cooling tower variables. All the performance problems (paragraph VI) solved by use of the curves can also be solved by direct calculations, but at the expense of considerably more time and effort. To illustrate this point, the Example No. 1 problem will be solved without the use of the curves.

***Example No. 1. The determination of tower capability*.***

A water cooling tower was purchased to cool 10,000 gpm from 110°F to 90°F with 80°F wet bulb temperature, using a total of 136 fan driver-output horsepower. The following data was obtained from a field test:

| | |
|---|---|
| Water circulation rate, gpm | 8,950 |
| Hot water temperature, °F | 110 |
| Cold water temperature, °F | 84 |
| Cooling range, °F | 26 |
| Wet bulb temperature, °F | 69 |
| Approach, °F | 15 |
| Total fan driver-output horsepower | 115 |

The manufacturer has submitted Figure 8 in accordance with paragraph 6 of CTI Bulletin ATC-105.

*Step 1.* The design L/G, from Figure 8, is 1.37. Compute the test L/G, using equation (2), ATC-105.

$$\left(\frac{L}{G}\right)_{test} = \frac{8{,}950}{10{,}000} \text{ x } \left(\frac{136}{115}\right)^{1/3} \text{ x } 1.37 = 1.30$$

*Step 2.* The value of the tower characteristic KaV/L is calculated using test values of HWT, CWT, WBT, and L/G, by the procedure described in Part III-A of ATC-105.

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**Refer to Paragraph IV, "Limitations on Use of Book".*

## Calculation of KaV/L

The Tchebycheff method for numerically evaluating the integral

$$\int_a^b y\, dx$$

uses values of y at predetermined values of x within the interval a to b, so selected that the sum of these values of y multiplied by a constant time the interval $(b-a)$ gives the desired value of the integral. In its four-point form the values of y so selected are taken at values of x of 0.102673..., 0.406204..., 0.593796..., and 0.897327... of the interval $(b-a)$. For the determination of KaV/L, rounding off these values to the nearest tenth is entirely adequate. The approximate formula becomes:

$$\int_a^b y\, dx = \frac{(b-a)}{4}\,(y_1 + y_2 + y_3 + y_4) \qquad \text{...4}$$

where

$y_1 = value\ of\ y\ at\ x = a + 0.1\,(b{-}a)$
$y_2 = value\ of\ y\ at\ x = a + 0.4\,(b{-}a)$
$y_3 = value\ of\ y\ at\ x = b - 0.4\,(b{-}a)$
$y_4 = value\ of\ y\ at\ x = b - 0.1\,(b{-}a)$

*For the evaluation of KaV/L,*

$$KaV/L = \int_{T_2}^{T_1} \frac{dT}{h_w - h_a} \cong \frac{T_1 - T_2}{4}\left[\frac{1}{\Delta h_1} + \frac{1}{\Delta h_2} + \frac{1}{\Delta h_3} + \frac{1}{\Delta h_4}\right] \qquad \text{...5}$$

where

$\Delta h_1 = value\ of\ (h_w - h_a)\ at\ T_2 + 0.1\,(T_1 - T_2)$
$\Delta h_2 = value\ of\ (h_w - h_a)\ at\ T_2 + 0.4\,(T_1 - T_2)$
$\Delta h_3 = value\ of\ (h_w - h_a)\ at\ T_2 - 0.4\,(T_1 - T_2)$
$\Delta h_4 = value\ of\ (h_w - h_a)\ at\ T_2 - 0.1\,(T_1 - T_2)$

## Example of KaV/L Calculation

Given T1 = 110°F
T2 = 84°F
WBT= 69°F
L/G = 1.3

From the enthalpy table* at 69°F, $h_1$ = 33.25

$h_2 = h_1 + L/G\,(T_1 - T_2)$
= 33.25 + 1.3 (110 – 84) = 67.05

| T, °F | $h_w$ | $h_a$ | $(h_w - h_a)$ | $\left(\frac{1}{\Delta h}\right)$ |
|---|---|---|---|---|
| $T_2 = 84.0$ | | $h_1 = 33.25$ | | |
| $T_2 + 0.1\,(T_1 - T_2) = 86.6$ | 51.41 | $h_1 + 0.1L/G\,(T_1 - T_2) = 36.63$ | $\Delta h_1 = 14.78$ | .0676 |
| $T_2 + 0.4\,(T_1 - T_2) = 94.4$ | 62.38 | $h_1 + 0.4L/G\,(T_1 - T_2) = 46.77$ | $\Delta h_2 = 15.61$ | .0640 |
| $T_1 - 0.4\,(T_1 - T_2) = 99.6$ | 71.02 | $h_2 - 0.4L/G\,(T_1 - T_2) = 53.53$ | $\Delta h_3 = 17.49$ | .0571 |
| $T_1 + 0.1\,(T_1 - T_2) = 107.6$ | 86.43 | $h_2 - 0.1L/G\,(T_1 - T_2) = 63.67$ | $\Delta h_4 = 22.76$ | .0441 |
| $T_1 = 84.0$ | | $h_2 = 67.05$ | | |

From Equation (5):

$$KaV/L = \frac{(110 - 84)}{4}\,(.0676 + 0640 + .0571 + .0441) = 1.51$$

*Step 3.* The test KaV/L versus L/G point from above Steps 1&2 is plotted on Figure 9. The test characteristic curve for the tower is constructed by drawing a line through this point, parallel to the characteristic curve submitted by the manufacturer (see Figure 8). The new curve intersects the 10o approach curve at an L/G of 1.45.

*Step 4.* The tower capability from paragraph 9 of ATC-105 is: $Q = \frac{1.45}{1.37}\ x\ 100 = 105.8\%$

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**For enthalpy data, see Table 1.*

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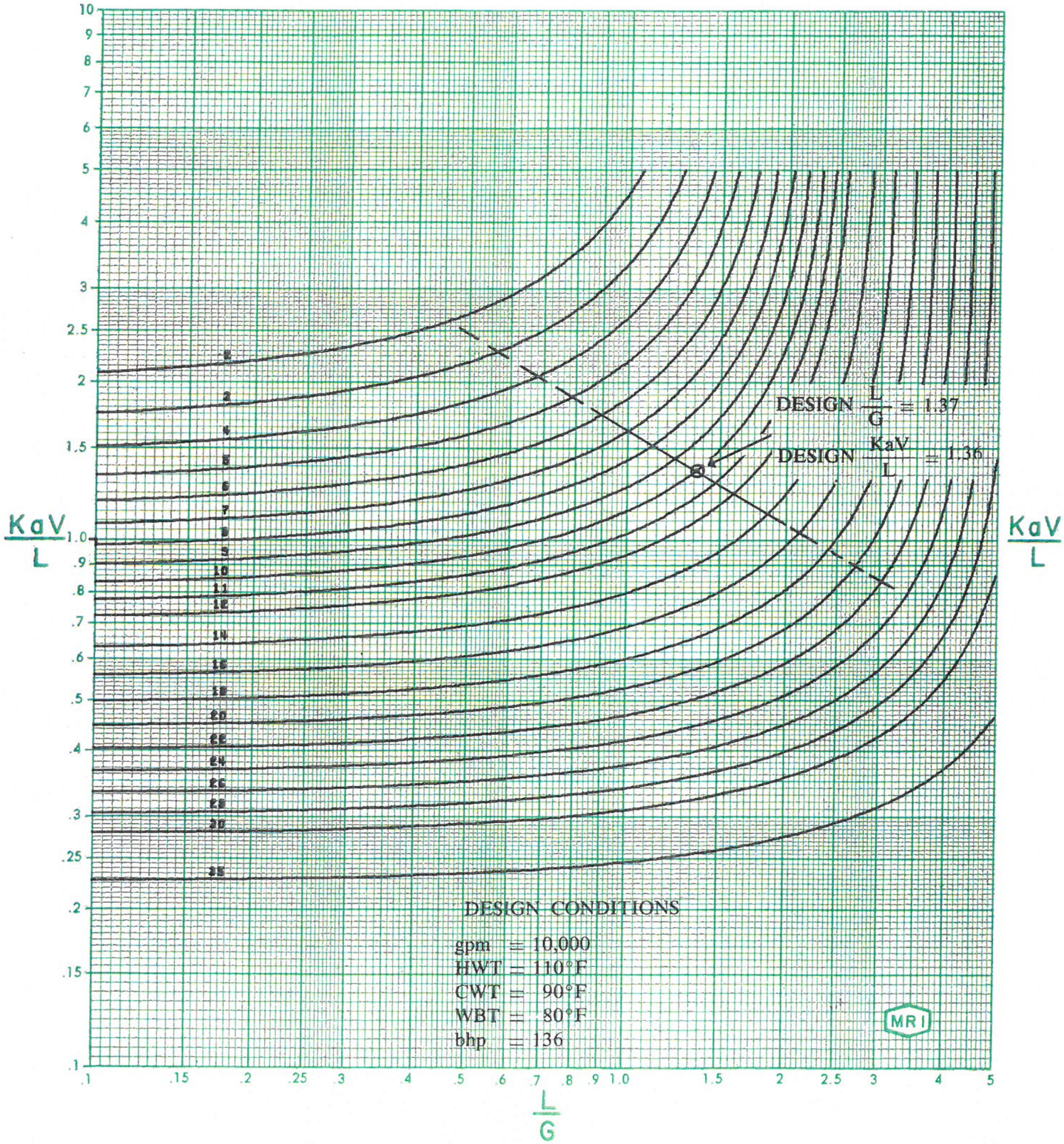
80 WET BULB ($^{o}$F)
20 RANGE ($^{o}$F)

Figure 2



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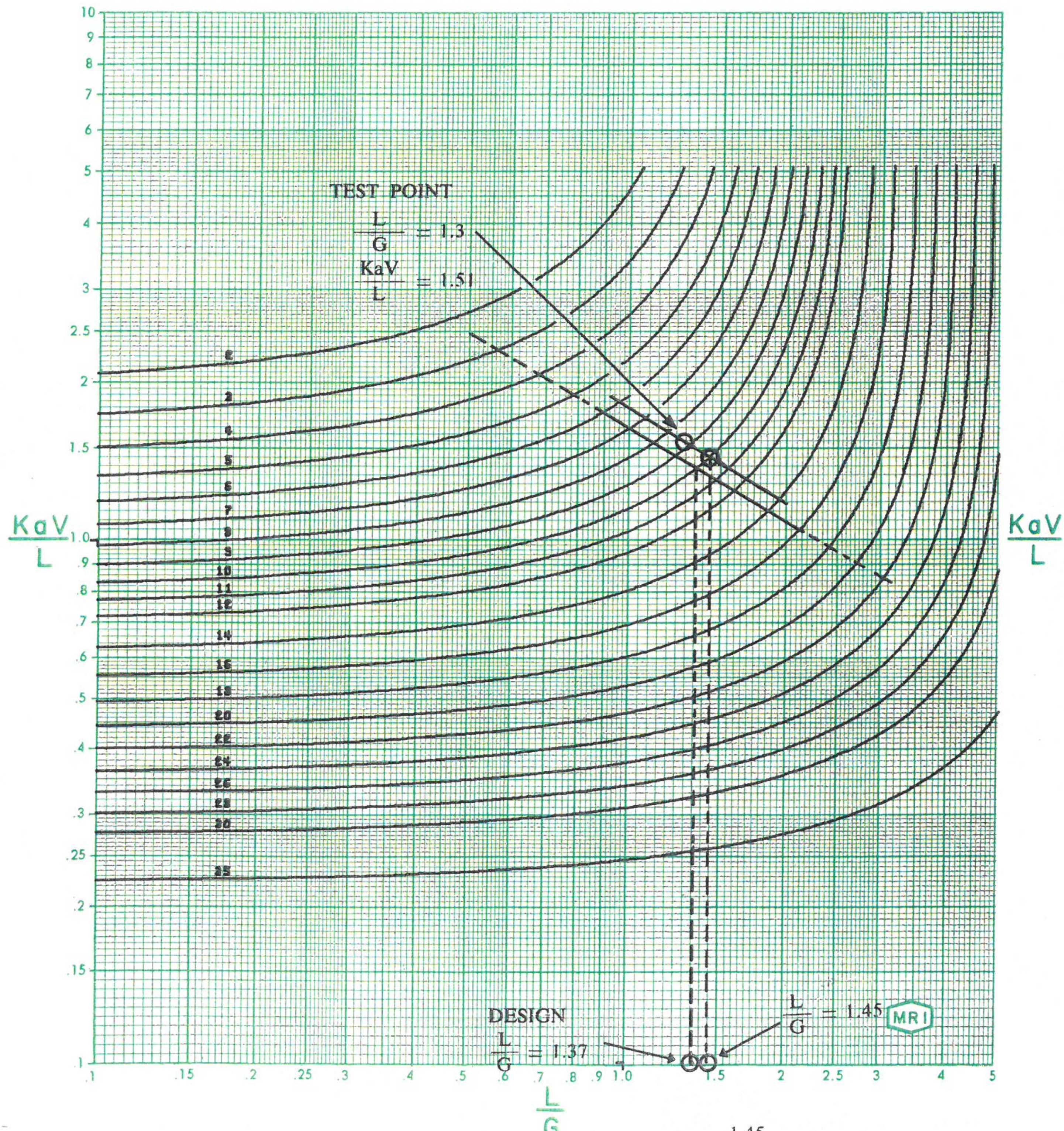
80 WET BULB ($^{O}$F)
20 RANGE ($^{O}$F)

Figure 3




$$\text{PERCENT CAPABILITY} = \frac{1.45}{1.37} \times 100 = 105.8\%$$

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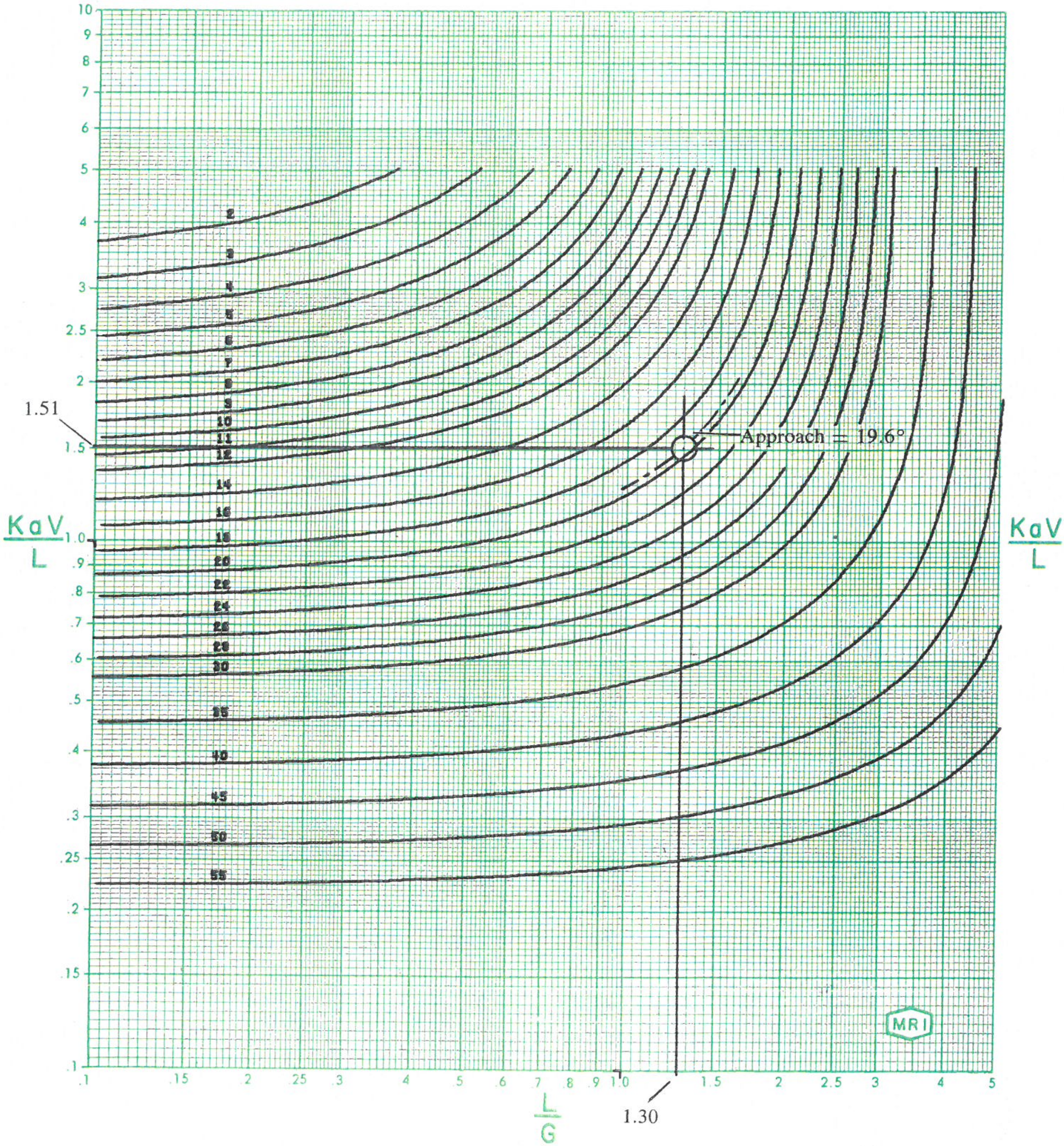
60 WET BULB ($^{O}$F)
26 RANGE ($^{O}$F)

Figure 4



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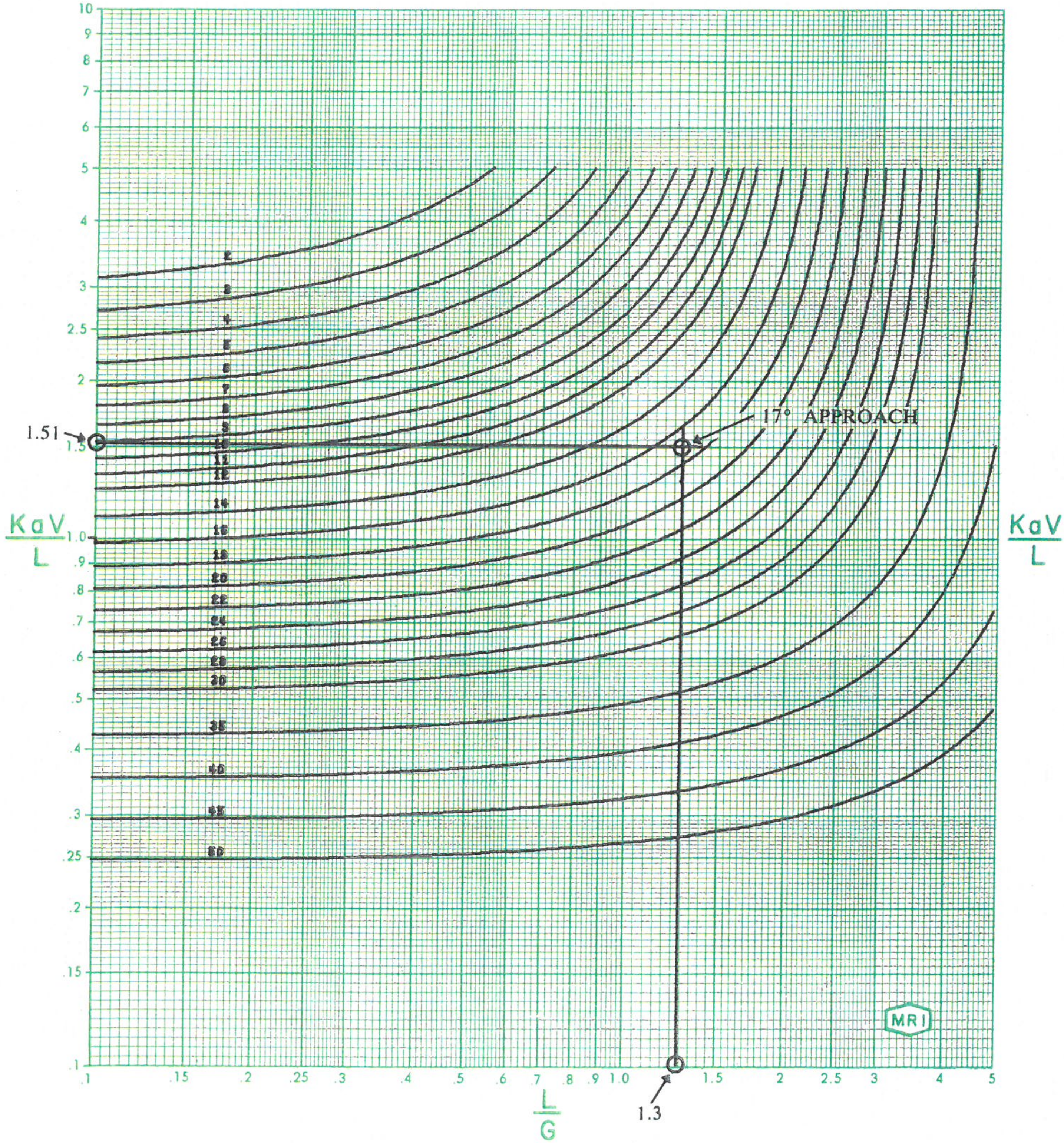
69 WET BULB ($^{O}$F)
35 RANGE ($^{O}$F)

Figure 5



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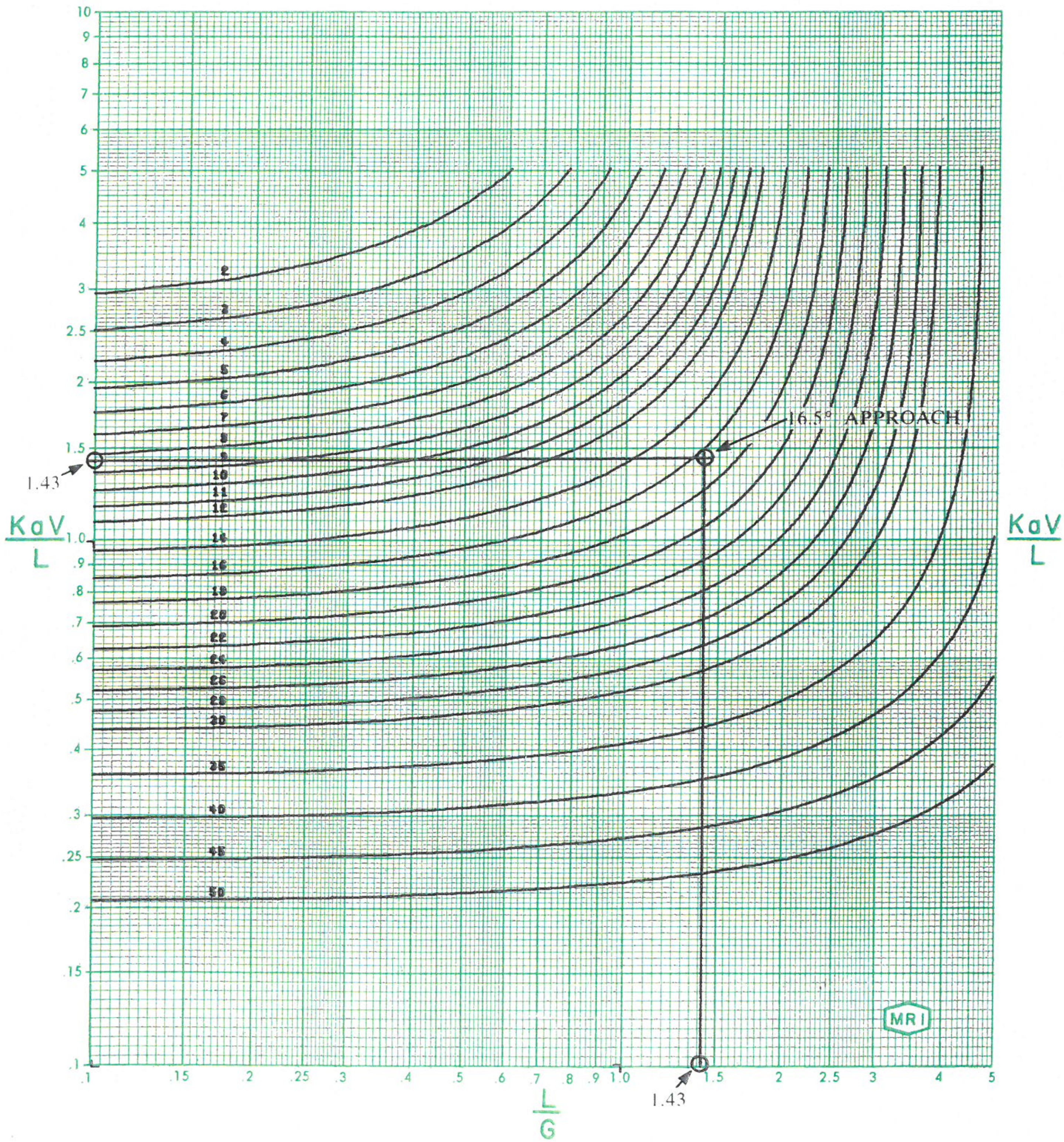
69 WET BULB (°F)
26 RANGE (°F)

Figure 6



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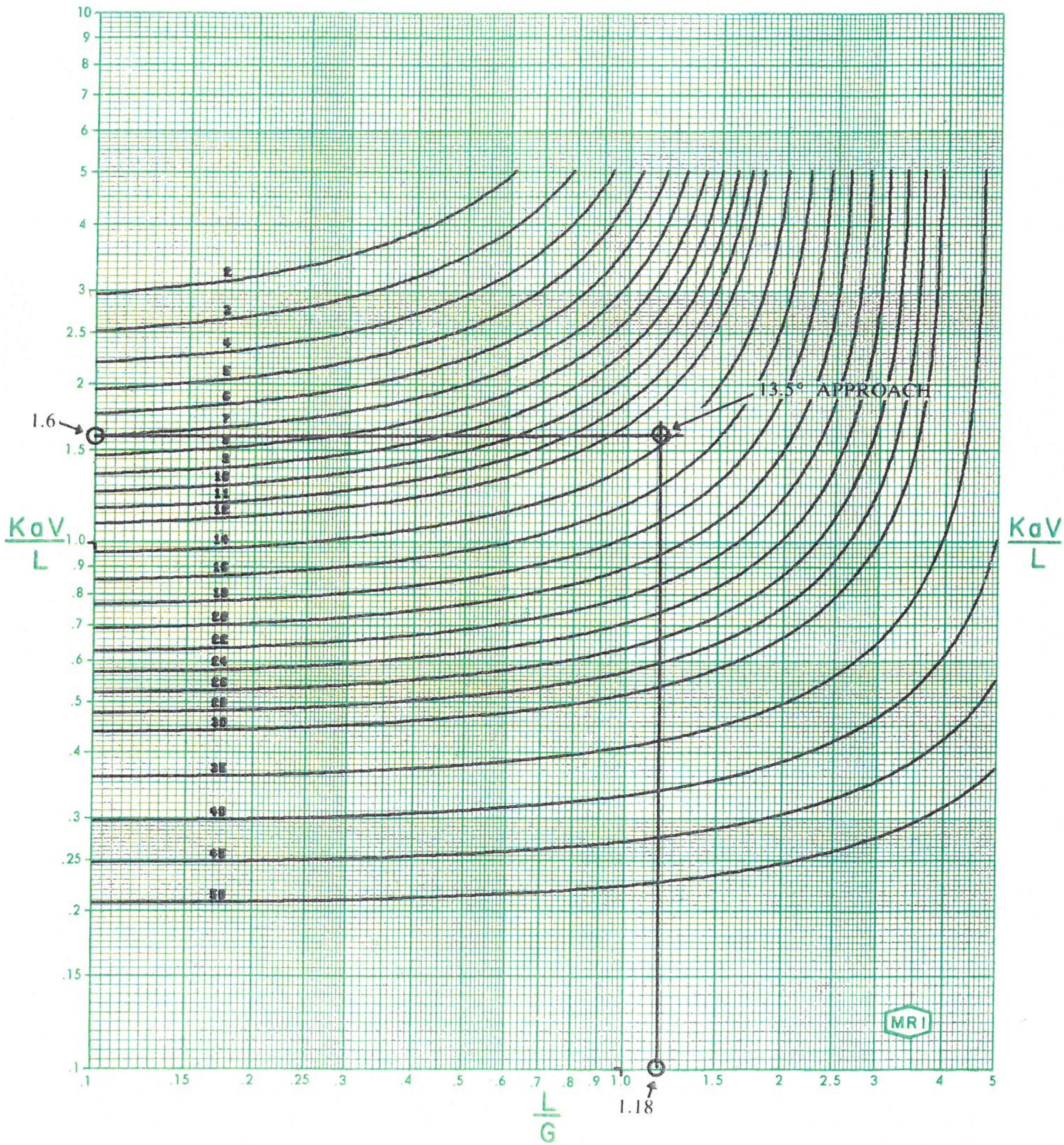
69 WET BULB ($^{O}$F)

26 RANGE ($^{O}$F)

Figure 7



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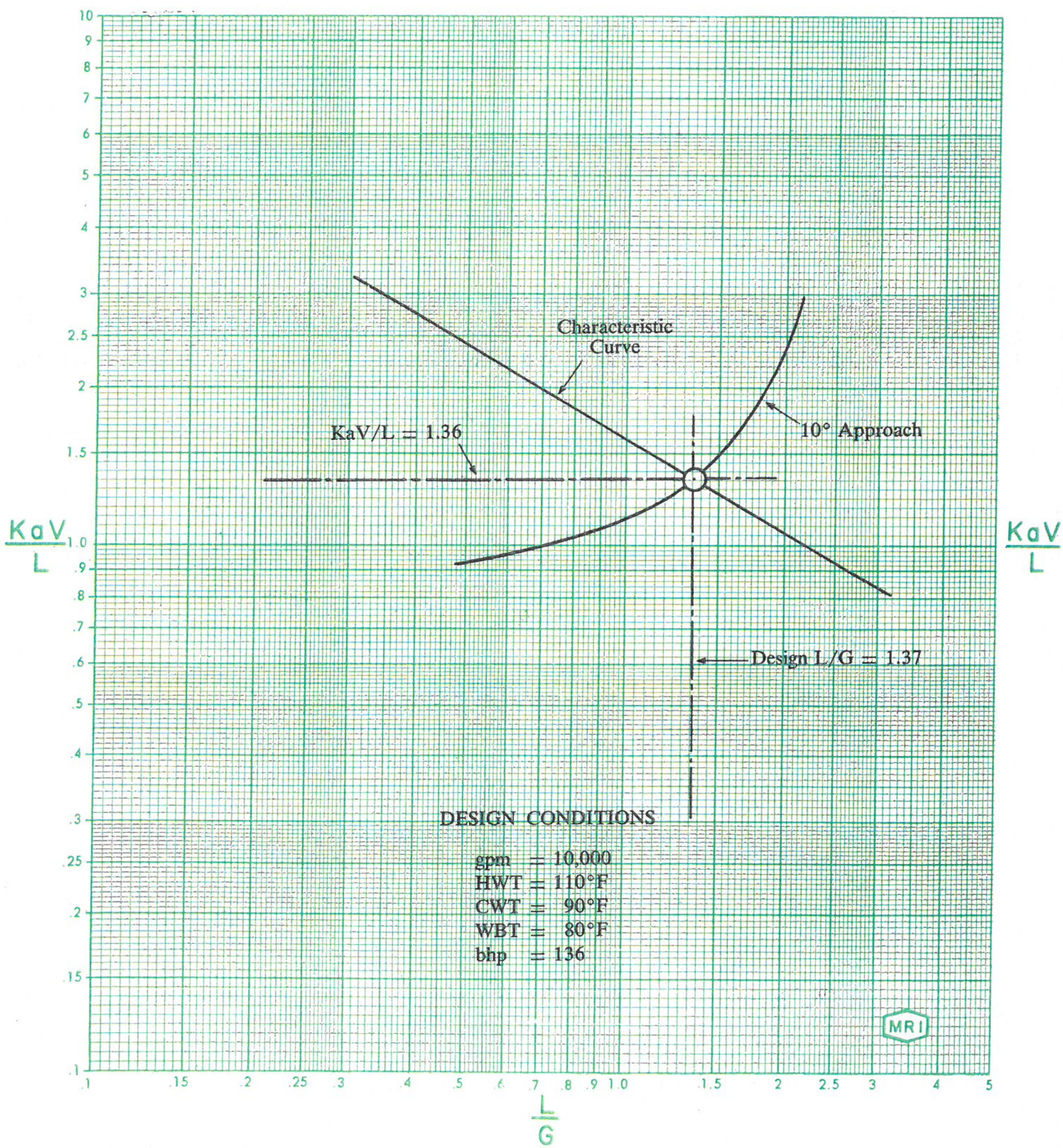
WET BULB ($^{O}$F)
RANGE ($^{O}$F)

Figure 8



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WET BULB ($^{O}$F)
RANGE ($^{O}$F)

Figure 9