

Optimizing Strain Gage Excitation Levels

Introduction

A common request in strain gage work is to obtain the recommended value of bridge excitation voltage for a particular size and type of gage. A simple, definitive answer to this question is not possible, unfortunately, because factors other than gage type are involved. The problem is particularly difficult when the maximum excitation level is desired.

This Tech Note is intended to outline the most significant considerations that apply, and to suggest specific approaches to optimizing excitation levels for various strain gage applications.

It is important to realize that strain gages are seldom damaged by excitation voltages considerably in excess of proper values. The usual result is performance degradation, rather than gage failure; and the problem therefore becomes one of meeting the total requirements of each particular installation.

Thermal Considerations

The voltage applied to a strain gage bridge creates a power loss in each arm, all of which must be dissipated in the form of heat. Only a negligible fraction of the power input is available in the output circuit. This causes the sensing grid of every strain gage to operate at a higher temperature than the substrate to which it is bonded. With exceptions, which are discussed later, it can be considered that the heat generated within a strain gage must be transferred by conduction to the mounting surface. The heat flow through the specimen causes a temperature rise in the substrate, which is a function of its heat-sink capacity and the gage power level.

Consequently, both sensing grid and substrate operate at temperatures higher than ambient. When the temperature rise is excessive, gage performance will be affected as follows:

1. A loss of self-temperature-compensation (S-T-C) occurs when the grid temperature is considerably above the specimen temperature. All manufacturers' data on S-T-C are necessarily obtained at low excitation levels.
2. Hysteresis and creep effects are magnified, since these are dependent on backing and glueline temperatures.

A gage backing normally rated at +250°F [+120°C] in transducer service might have to be derated by 20° to 50°F [10° to 30°C] under high-excitation conditions.

3. Zero (no-load) stability is strongly affected by excessive excitation. This is particularly true in strain gages with high thermal output characteristics, and when inherent half-bridge or full-bridge compensation is relied upon to meet a low zero-shift vs. temperature specification. The zero-shift occurs because of variation in heat-sink conditions between gages in the bridge circuit.

Another point should be emphasized. Any tendency for localized areas of the grid to operate at higher temperatures than the rest of the grid will restrict the allowable excitation levels. Creep and instability are particularly susceptible to these "hot-spot" effects, which are usually due to voids or bubbles in the glueline or discontinuities in the substrate. Imperfections in the gage itself can cause hot spots to develop, and only gages of the highest quality should be considered for high-excitation applications.

When other factors are constant, the power-dissipation capability of a strain gage varies approximately with the area of the grid (active gage length x active grid width). The amount or type of waterproofing compound or encapsulant is relatively unimportant. Open-face gages mounted on metal show only 10 to 15% less power-handling capacity than fully encapsulated gages with the same grid area. Note, however, that proper waterproofing materials must always be applied to open-face gages to prevent loss of performance through grid corrosion.

It is sometimes stated that gage adhesives of high thermal conductivity can considerably improve the power-handling capability of strain gage installations. Generally, this is not correct. These adhesives incorporate high-conductivity fillers such as aluminum oxide and metal powders. This produces an adhesive of high viscosity, resulting in excessively thick gluelines and a longer thermal path from gage to substrate. Any net gain in thermal conductivity is more than offset by the performance degradation due to thicker gluelines. It is much better, for high gage excitation as well as normal gage applications, to use high-functionality adhesives that permit thin, void-free gluelines. On smooth mounting surfaces, ideal glueline thicknesses range from 0.0001 to 0.0003 in [0.0025 to 0.0075 mm].

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Factors Affecting Optimum Excitation

Following are factors of primary importance in determining the optimum excitation level for any strain gage application:

1. *Strain gage grid area* (active gage length x active grid width).
2. *Gage resistance*. High resistances permit higher voltages for a given power level.
3. *Heat-sink properties of the mounting surface*. Heavy sections of high-thermal-conductivity metals, such as copper or aluminum, are excellent heat sinks. Thin sections of low-thermal-conductivity metals, such as stainless steel or titanium, are poor heat sinks. Also, the shape of the gaged part may create thermal stresses in portions of the structure due to gage self-heating. Long warm-up times and apparent gage instability can result. The situation often arises in low-force transducers, where thin sections and intricate machining are fairly common.

Strain measurement on plastic requires special consideration. Most plastics act as thermal insulators rather than heat sinks. Extremely low values of excitation are required to avoid serious self-heating effects. The modulus of elasticity of the common plastics drops rapidly as temperature rises, increasing viscoelastic effects. This can significantly affect the material properties in the area under the strain gage. Plastics that are heavily loaded with inorganic fillers in powder or fibrous form present a lesser problem, because such fillers reduce expansion coefficients, increase the elastic modulus, and improve thermal conductivity.

4. *Environmental operating temperature range of the gage installation*. Creep in the gage backing and adhesive will occur at lower ambient temperatures when grid and substrate temperatures are raised by self-heating effects. Thermal output due to temperature will also be altered when grid and substrate temperatures are significantly different.
5. *Required operational specifications*. Gages for normal stress analysis can be excited at a higher level than under transducer conditions, where the utmost in stability, accuracy, and repeatability are needed.

A significant distinction exists between gages used in dynamic strain measurement and those used in static measurement applications. All the various performance losses due to gage self-heating affect static characteristics of the gage much more seriously than the dynamic response. Therefore, it is practical to “drive” the dynamic installations much harder, and thus take advantage of the higher signal-to-noise ratio that results.

6. *Installation and wiring technique*. If the gage is damaged during installation, if solder tabs are partially unbonded due to soldering heat, or if any discontinuities are formed in the glue line, high levels of excitation will create serious problems. Proper technique is essential in obtaining consistent performance in all strain gage work, but particularly under high-excitation conditions.

In addition to the preceding, secondary factors can affect maximum permissible excitation levels. Poor grid design, such as improper line-to-space ratio, will reduce the heat transfer effectiveness. The type of gage matrix, in terms of resin and filler, determines the thermal conductivity of the backing. The backing is usually more important than the adhesive selected because the adhesive layer is thinner than the backing in proper installations.

Stacked Rosette Gages

These represent a special case, because the thermal path length is much greater from the upper grid to the substrate, and because the temperature rise of the lower grids adds directly to those above. For a three-element stacked rosette in which the three grids are completely superimposed, the top grid will have six times the temperature rise of a similar single gage, if all grids receive the same input power. To keep the temperature rise of the top grid equal to that of a similar single gage, the three rosette sections should each receive 1/6 of the power applied to the single gage. This corresponds to a reduction factor of 2.5 for bridge excitation voltage, since power varies as the square of the applied voltage. For two-element stacked rosettes, the comparable derating factor is 3 for power, and 1.7 for bridge voltage.

This discussion is based on rosettes of square grid geometry, where each grid covers essentially all of the grid(s) in the assembly. When substantial areas of the grids are not superimposed, the derating factors mentioned above will be somewhat conservative.

Cryogenic Gage Applications

Many strain gage measurements are made under direct submersion in liquefied gases such as nitrogen, hydrogen, and helium. Since these liquids are electrically nonconductive, open-face gages have been used occasionally without a protective or waterproofing coating. An interesting effect has been reported under these conditions. If excitation voltages are not kept sufficiently low, grid self-heating will cause gas bubbles to form on the gridlines, and thus partially insulate the grid from the cold liquid. Larger bubbles are then created by increased grid temperatures, and bubbles periodically break loose and rise toward the surface. The relative motion of these insulating bubbles with respect to the gridlines produces local temperature changes, which appear in the output signal as noise. Grid alloys that display very high values of thermal output at cryogenic

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temperatures (most constantan alloys, for example) are particularly susceptible to this effect. The remedy is to utilize very low excitation levels, and/or to use protective coatings over the grid to prevent direct liquid contact. Such coatings must necessarily retain sufficient flexibility at cryogenic temperatures to prevent cracking of the protective layer.

Experimental Determination of Maximum Gage Excitation

To be certain that the excitation level chosen for a given strain gage application is not excessive, it is necessary to run performance tests at the maximum environmental temperature. In many cases, however, this rather complicated procedure can be greatly simplified by gradually increasing the bridge excitation under zero-load conditions until a definite zero instability is observed. The excitation should then be reduced until the zero reading becomes stable again, without a significant offset from the low-excitation zero reading. For most applications in experimental stress analysis, this value of bridge voltage is the highest that can be used safely without significant performance degradation. Conducting this test at the maximum operating temperature instead of room temperature will increase the likelihood that the maximum safe bridge voltage has been established.

The rigid operating requirements for precision transducers make the above procedure useful primarily as a first approximation; and further verification is usually required. The performance tests most sensitive to excessive excitation voltage are: (1) zero-shift vs. temperature and (2) stability under load at the maximum operating temperature.

Excitation Levels for Resistance Temperature Sensors

It has become increasingly common to measure specimen temperatures in strain gage work by the use of bondable nickel-grid temperature sensors such as the ETG-50 and WTG-50. These sensors are fabricated in the same manner as strain gages, and consequently experience environmental temperature changes in the same way. By eliminating many of the measurement errors often encountered with thermocouples, temperature sensors are ideal for correcting strain gage data under rapidly changing temperature conditions.

Like strain gages, temperature sensors are adversely affected by excessive excitation levels. Variation in heat-sink conditions and accuracy requirements make universally applicable excitation recommendations impossible, but a simple test procedure is available. The excitation level should be increased until the readout device indicates an excessive grid temperature rise; it should then be reduced as necessary. Since the readout in this case shows temperature measurement error directly, the determination is straightforward.

Since temperature sensors are most often used with linearization networks of the LST type, it is not normally necessary to check for errors due to excitation level. These networks greatly attenuate the input bridge voltage, and the sensors are therefore operated at very low power levels.

Typical Strain Gage Excitation Values

The data curves on pages 15-17 represent general recommendations or starting points for determining optimum excitation levels. These curves are plots of bridge excitation voltage vs. grid area (active gage length x grid width) for constant power-density levels in watts/in² [or kilowatts/m²]. A large number of standard Micro-Measurements single-element gage patterns are listed at the various grid areas they represent. Separate plots are provided for gage resistances of 120, 350, and 1000 ohms. For other grid areas and/or other gage resistances, calculations can be made according to the following formulas for recommended power-density levels:

$$\text{Power Dissipated in Grid (watts)} = \frac{E_B^2}{4R_G} = P_G$$

$$\text{Power Density in Grid (watts/in}^2 \text{ or kW/m}^2\text{)} = \frac{P_G}{A_G} = P'_G$$

where: R_G = Gage resistance in ohms
 A_G = Grid area (active gage length x grid width)
 E_B = Bridge excitation in volts

Note that bridge voltage (E_B) is based on an equal-arm bridge arrangement, where the voltage across the active arm is one-half the bridge voltage.

When grid area (A_G), gage resistance (R_G), and grid power density (P'_G) are known:

$$E_B = 2\sqrt{R_G \times P'_G \times A_G}$$

Grid Power-Density Curves

Selecting the most appropriate power-density lines on the following charts depends, primarily, on two considerations: degree of measurement accuracy required, and substrate heat-sink capacity. A series of general recommendations follows, but should be verified by the procedures previously described for critical applications.

Typical Power-Density Levels in Watts/in² [kW/m²]

It is of interest that some commercial strain measurement/instrumentation utilizes constant excitation voltage of 3 to 5 volts. The power densities created in gages of various sizes and resistances by these bridge voltages can be taken directly from the charts and compared with Table 1. For very

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small gages, it is evident that commercial instruments may require voltage reduction for proper results. A simple circuit modification, which can be utilized when the instrument voltage is not adjustable, involves the insertion of “dead” resistance in the form on high-precision resistors of VPG type in series with the active and dummy gages in the bridge circuit. Power density is then reduced by (multiplied by) the factor $[R_G / (R_D + R_G)]^2$, where R_D is the inactive series resistance in ohms, and R_G is the active gage resistance in ohms. Note that the adjacent bridge arm must be increased by the same R_D to maintain bridge balance under these conditions. The sensitivity of the bridge will be decreased by this procedure, and the readings must be multiplied by the ratio $(R_D + R_G) / R_G$ to correct for this desensitization. Alternately, a shunt calibration resistor can be connected directly across the dummy gage, and the instrument gage factor setting adjusted to display the proper calibration level.

Examples of Chart Use

Case 1: What excitation level can safely be applied to an EA-09-125AD-120 strain gage, mounted on a 1/2 x 1/16 x 6 in [12.5 x 1.5 x 150 mm] stainless-steel bar, for a static stress analysis test with moderate accuracy (3 to 5%)?

From Table 1, determine the typical power-density level, 1 to 2 W/in² [1.6 to 3.1 kW/m²], corresponding to fair heat-sink condition in stainless steel. Refer to Chart 1:

- Enter on the horizontal axis at the arrowhead for the 125AD gage 0.0156 in² [10.06 mm²].
- Mark the intersection of the vertical line with the 1 and 2 W/in² [1.6 and 3.1 kW/m²] sloped lines.
- Read horizontally to the left ordinate for Bridge Excitation of 2.7 and 3.8 volts, respectively. A strain indicator with a maximum bridge excitation of 3.8 volts can be used.

Case 2: Can an instrument with a fixed 4.5V excitation be used? If not, what correction of data points must be made?

To determine the power density in a 125AD gage at a given excitation level, refer to Chart 1:

- Enter the left ordinate at 4.5 volts until intersecting the abscissa value equivalent to the 125AD gage. The power density is 2.7 W/in² [4.2 kW/m²], which is in excess of the maximum power determined in Case 1. If low accuracy (i.e., 5 to 10% data) is acceptable, the higher P'_G can be used. If greater accuracy must be maintained, several alternatives are available: (1) select a higher resistance gage, (2) select a gage with a larger area, or (3) reduce the bridge voltage with an inactive series resistor, R_D .

The inactive resistor (R_D) required to reduce the power density to the desired 2 W/in² (3.1 kW/m²), with a given EB, can be determined from the following relationship:

$$\left(\frac{E_B^2}{4R_G A_G} \right) \left(\frac{R_G}{R_G + R_D} \right)^2 = P'_G(\text{desired})$$

For a desired P'_G of 2 W/in² (3.1 kW/m²)

$$R_D = \frac{E_B}{2} \sqrt{\frac{R_G}{A_G P'_G}} - R_G = 19.5 \text{ ohms}$$

Select the nearest precision resistor value greater than 19.5 ohms for R_D .

For actual strain values, accounting for the inserted inactive resistor, all indicated strain readings must be multiplied by:

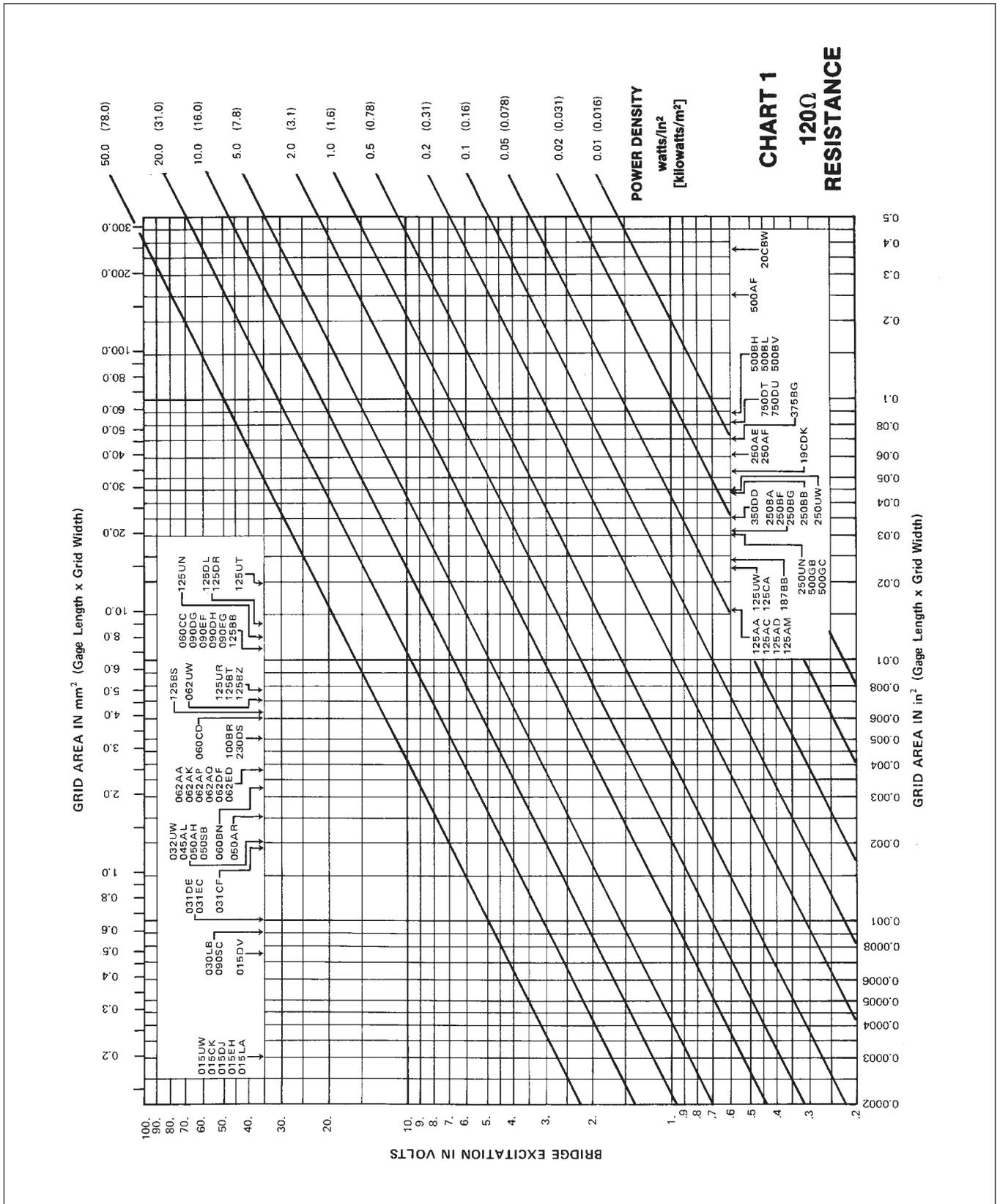
$$\frac{R_D + R_G}{R_G} = \frac{19.5 + 120}{120} = 1.16$$

Table 1 – Heat-Sink Conditions
watts/in² [kilowatts/m²]

Accuracy Requirements		EXCELLENT Heavy Aluminum or Copper Specimen	GOOD Thick Steel	FAIR Thin Stainless Steel or Titanium	POOR Filled Plastic such as Fiberglass/Epoxy	VERY POOR Unfilled Plastic such as Acrylic or Polystyrene
STATIC	High	2-5 [3.1-7.8]	1-2 [1.6-3.1]	0.5-1 [0.78-1.6]	0.1-0.2 [0.16-0.31]	0.01-0.02 [0.016-0.031]
	Moderate	5-10 [7.8-16]	2-5 [3.1-7.8]	1-2 [1.6-3.1]	0.2-0.5 [0.31-0.78]	0.02-0.05 [0.031-0.078]
	Low	10-20 [16-31]	5-10 [7.8-16]	2-5 [3.1-7.8]	0.5-1 [0.78-1.6]	0.05-0.1 [0.078-0.16]
DYNAMIC	High	5-10 [7.8-16]	5-10 [7.8-16]	2-5 [3.1-7.8]	0.5-1 [0.78-1.6]	0.01-0.05 [0.016-0.078]
	Moderate	10-20 [16-31]	10-20 [16-31]	5-10 [7.8-16]	1-2 [1.6-3.1]	0.05-0.2 [0.078-0.31]
	Low	20-50 [31-78]	20-50 [31-78]	10-20 [16-31]	2-5 [3.1-7.8]	0.2-0.5 [0.31-0.78]

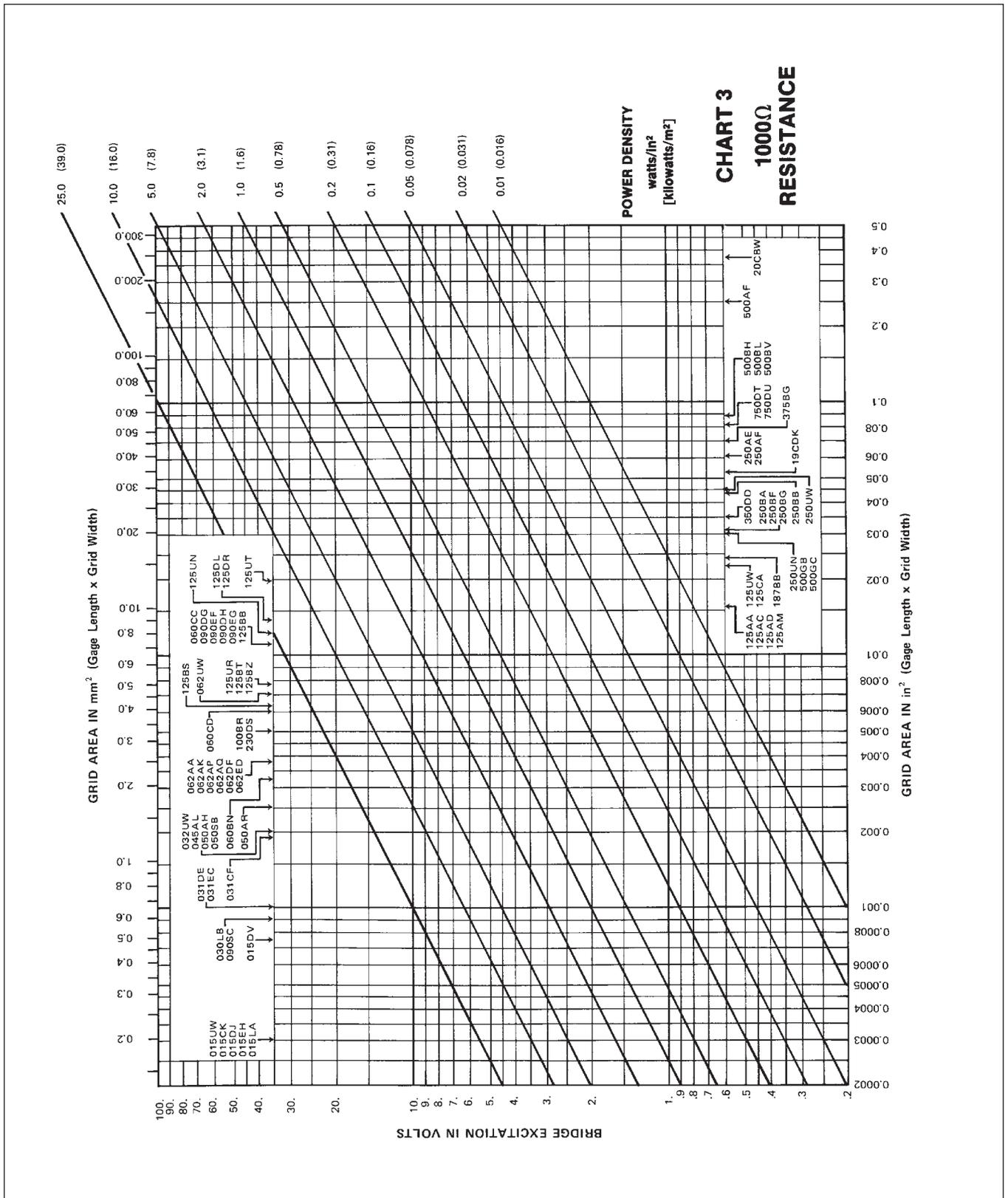
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