Resistors for Power Supply Applications

IRC is the leading specialist resistor manufacturer in the USA, offering one of the most diverse ranges of high current and high voltage resistors. Across the HV range from 1 to 100 kV and 1 amp to 50 amp products are available which provide reliability, accuracy, and precision. For designers requiring a resistor with parameters outside of this range, custom-made solutions for specific applications may be supplied.

From commercial thick-film and precision high voltage devices with ultra high resistance values (100T or 10^{14} Ω) to high current low resistance products, which are supplied to key commercial and military standards. ROHS compliant Pb-free finish and SnPb finish are both available across most product families.

Because of its ability to maintain good stability of resistivity in the presence of high voltage stress, the technology normally used for compact high voltage resistors is thick film.

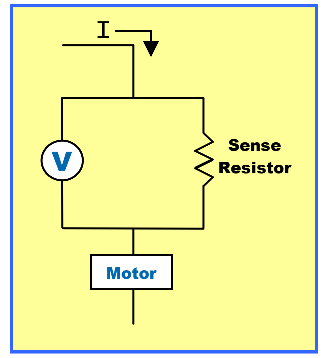
IRC is a leader in power and high voltage thick-film product development since the 1960's and can now offer a full range of component styles including compact SMD chips, conventional axial through-hole and space-saving single-in-line (SIL) radial format.

This Application Note gives data, calculations, and typical products for use in high current and high voltage circuits. It should be read in conjunction with the full datasheets for each referenced product.

- **High Voltage Dividers**
- **High Voltage Balancing**
- **Current Sensing**
- **Emitter Ballasting**
- **Continuous voltage ratings up to 100 kV**
- **Ohmic values to 100 TΩ**
- **Ohmic values down to 1 mΩ with 1% accuracy**
- **SMD, axial, and SIL radial styles**

High Current Sensing

In this application, the designer is faced with conflicting goals:



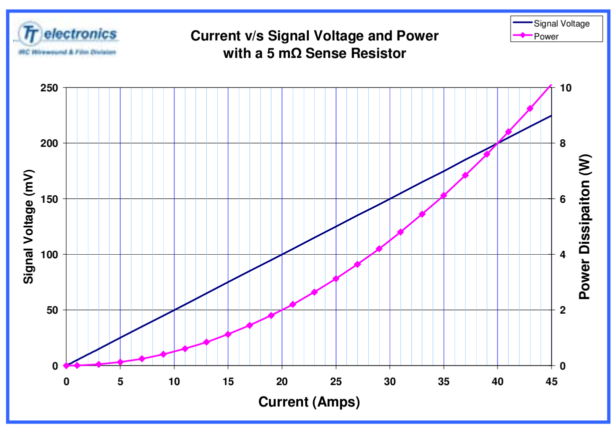
1. minimize the heat generation / power loss that is proportionate to resistance. ($P = I^2 R$)
2. maximize the voltage signal used to measure current ($V = I R$)

Simply put, lower resistance circuits run cooler and are more energy-efficient; higher resistance circuits provide output voltages that are easier to measure, especially important in electrically noisy environments.

Ohm's Law enables current to be calculated using the following equation, Current = Voltage / Resistance or $I = V / R$. As current flows through the resistor a voltage is created across the part, since the resistance value is known the current can be calculated. The power dissipated by the resistor can now be determined as well, using Power = Current^2 x Resistance or $P = I^2R$.

$P = (10\ \text{Amps})^2 \times 0.005\ \text{m}\Omega = 0.5\ \text{W}$ $\quad$ $P = (20\ \text{Amps})^2 \times 0.005\ \text{m}\Omega = 2\ \text{W}$

If you notice in the example problems that the only parameter that changed is the current through the resistor. If current increases by a factor of 2, dissipated power will increase by 4. The heat that is generated by the resistor must be dissipated through the air or through the circuit board via conduction or radiation, this is generally the limiting factor for surface mount resistor performance. The most common circuit board substrate is a sequence of layers of non-conductive fiberglass and epoxy with layers of copper conductor. Circuit board design features directly affects the heat dissipative qualities of the board and therfore the rating of the resistors. If the board can not dissipate the heat, then the solder joint between the resistor and the circuit board can become compromised. An example of a circuit board design that could dissipate more heat is a board with heavy copper traces, 4 ounces, as opposed to a board with light copper, 1 ounce. The copper will transfer more heat than the epoxy substrate material that is most common circuit boards design. The main point here is that capability of the resistor may be higher than the published power rating depending on the circuit board design.



As you can see from the previous paragraph, can be a challenge for the designer since dissipated power increases at an exponential rate as compared to the linear rate that signal level rises, refer to the graph at the right. This is why low resistance is favorable, however the signal strength may fall into background noise levels. This is where design compromises must be made, because a higher resistance may be required to cover the full range of current that the customer requires for the product.

Surface Mount: LRC, LRF, LRF3W, OAR, OARS, OARSXP, ULR, WA80Z, WSM, WSML
Through Hole: 2500, 4LPW, CSL, LOB, LPW, OAR, OAR-TP, PLO, PWRL

Example Products

OAR

Power (W):	1, 3, 5
Resistance:	2.5 mΩ - 100 mΩ
TCR (ppm):	20 – 450
Tolerance (%):	1 and 5

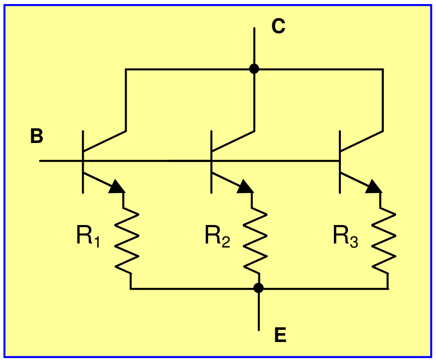
OARS and XP

Power (W):	1, 3, 5
Resistance:	1 mΩ - 50 mΩ
TCR (ppm):	20 – 240
Tolerance (%):	1 and 5

CSL

Power (W):	5
Resistance:	2.5 mΩ - 0.25mΩ
TCR (ppm):	< 55
Tolerance (%):	1

Emitter Resistors for High Current



In applications that require very high load currents it may be necessary to place multiple power FETs in parallel; either for cost reduction or reliability considerations. A lower current capable component may be significantly cheaper than a single MOSFET that is rated to handle the full load. Also a design that shares the load across multiple paths will increase the overall reliability of the power path by increasing redundancy and reducing thermal stresses to the solder joints and other electrical components.

During the periods outside of the switching transitions, the current in a parallel group of HEXFET Power MOSFETs will be distributed among the individual devices in inverse proportion to their ON resistance. The device with the lowest ON resistance will carry the highest current. This will, to an extent, be self-compensating, because the power loss in this device will be the highest. It will run hottest, and the increase in ON resistance due to heating will be more than that of the other devices, which will tend to equalize the current. However, the excessive temperatures can overstress other components and solder joints leading to premature component failure.

If the output current and / or power dissipation in the output transistors approaches more than about half their maximum rating, parallel transistors should be considered. If parallel transistors are used, balancing resistors should be installed in the emitter of each paralleled transistor as shown in the drawing. The value is determined by estimating the amount of difference between VBE between the transistors and having that amount, or a little more voltage, dropped across each resistor at the maximum output current.

The balancing resistors are chosen to offset any V_{BE} differences due to transistor variability, manufacture or temperature, etc. These voltage differences are usually less than 100 mV or so. Values of 0.01 Ω to 0.1 Ω are often used to provide a drop of 50 to 75 mV. They must be capable of handling the current and power dissipation. Assume ΔV_{BE} of 0.1 volt and an output of 30 amps. Each transistor and its associated emitter resistor must handle an I_c of 10 amps.

$R_{emitter}$ = 30 A / 3 = 10 A
$R_{emitter} = \Delta V_{BE}$ / IR = 0.1 / 10 = 0.01 Ω
Power Dissipated / Resistor – $R_{emitter} = I^2R = 10^2 * 0.01$ = 1 W

You may want to consider the following IRC product families based on their low resistance value and power capabilities, which are typically 1W – 5W with some as high as 15W.

Surface Mount: LRC, LRF, LRF3W, OAR, OARS, OARSXP, ULR, WA80Z, WSM, WSML
Through Hole: 2500, 4LPW, CSL, LOB, LPW, OAR, OAR-TP, PLO, PWRL

Example Products

ULR

Power (W):	1, 2, 2.5, 3
Resistance:	0.5 mΩ - 10 mΩ
TCR (ppm):	50 – 150
Tolerance (%):	1 and 5

OARS and XP

Power (W):	1, 3, 5
Resistance:	1 mΩ - 50 mΩ
TCR (ppm):	20 – 240
Tolerance (%):	1 and 5

SPH (Fail-safe)

Power (W):	2
Resistance:	0.1 Ω - 2400 Ω
TCR (ppm):	150, 180
Tolerance (%):	5 and 10

High Voltage Balancing Resistors

All aluminum electrolytic capacitors exhibit a leakage current when a DC voltage is connected across them. This may be modeled by a leakage resistance connected in parallel with the capacitor. This resistance is non-linear, that is, its value is a function of the applied voltage. Furthermore, the value is poorly defined, having a large degree of variation from one capacitor to another.

When building a capacitive reservoir for a high voltage DC bus it is common to use a series combination of two capacitors, each rated at half the bus voltage, as shown in Figure 4. If the capacitors are identical, the bus voltage will be shared equally between them. However, in practice the leakage resistances will differ, leading to uneven sharing and potential voltage overload on the capacitor with the higher leakage resistance. In other words, if Rl*a* (V*a*) < Rl*b* (V*b*) then the result will be V*b* > V*a* and possible failure of C*b*.

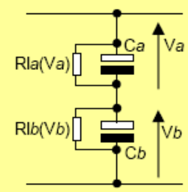


Figure 4
Voltage imbalance

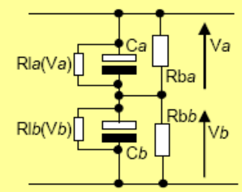


Figure 5
Balancing resistors

The solution is to use balancing resistors as shown in Figure 5. These are high value resistors rated at the appropriate voltage and matched in value to within a few percent. The value needs to be as high as possible to minimize power dissipation, but is generally chosen so that it is no more than 10% of the lowest value of leakage resistance at the rated voltage of the capacitor, Vr. In other words Rb*a* ≤ Rl*a* (Vr)/10. By this means the effect of the unbalanced internal capacitor leakage resistances are swamped by that of the balancing resistors and the voltages are approximately equalized, so V*a* ≈ V*b*.

In order to raise the total capacitance value, two or more pairs of capacitors may be connected in parallel. There are two configurations which may be used; either a bank of parallel connected capacitors may be balanced by a single pair of balancing resistors (Figure 6), or each pair of capacitors may be provided with its own pair of balancing resistors (Figure 7). Although clearly offering a lower component count, the first option suffers from a significantly lower reliability. This is because the effect of a short circuit failure of any one capacitor in the bank is that full bus voltage appears across the capacitors in the opposite half of the circuit. The circuit failure rate for **n** capacitors with a FIT of **F** is therefore **n**.**F**. The second option offers a superior reliability as a capacitor short failure will only cause failure of its twin. Depending on the acceptable level of degradation in smoothing, the FIT rate may therefore be <**F**.

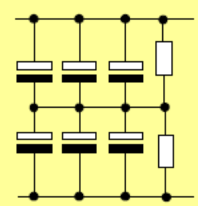


Figure 6
Parallel capacitors

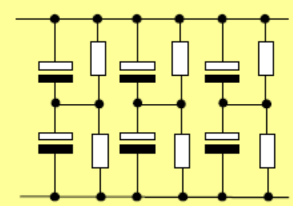
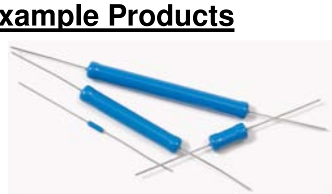


Figure 7
High reliability balancing of parallel capacitors

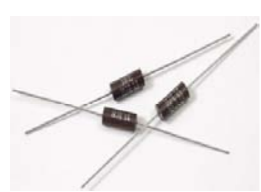
Surface Mount: HVC, SMHP
Through Hole: 3800, CGH, CMH, CGX, F43/F44, GC, GS-3, MH, MHP-TO-220, MHP-TO-247, T-44

Example Products



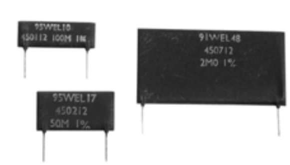
CGH and CMH (MIL R 49462)

Power (W):	0.25, 0.5, 1, 2, 3, 5
Voltage (kV):	0.75, 1.5, 3, 5, 10, 20
Resistance:	50 kΩ - 2 TΩ
TCR (ppm):	50, 100
Tolerance (%):	0.5, 1, 2, 5



GS3

Power (W):	3
Voltage (kV):	1
Resistance:	1 Ω - 3 MΩ
TCR (ppm):	50, 100
Tolerance (%):	1, 2, 5



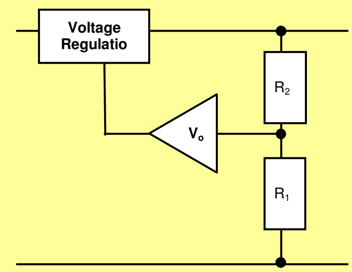
4500

Power (W):	1 – 4.5
Voltage (kV):	20
Resistance:	20 kΩ - 1.5 GΩ
TCR (ppm):	100, 150
Tolerance (%):	1, 2, 5

High Voltage Dividers

A common application for high voltage resistors is in voltage dividers for the measurement or control of high voltage rails. Figure 9 shows a typical application in which the output of a high voltage power supply is scaled down and fed back for regulation purposes. Assuming that the input impedance of the buffer is much greater than $\mathbf{R_1}$ the loading on the divider is negligible, so the voltage ratio is simply given by:

$$V_i / V_o = \frac{(R_1 + R_2)}{R_1} = 1 + R_2 / R_1$$

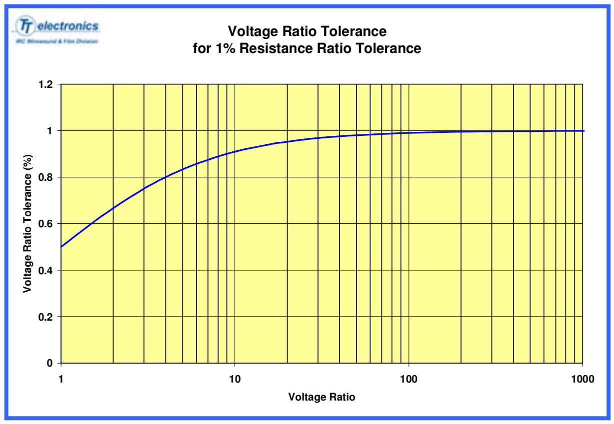


Voltage Divider

It should be noted that the voltage ratio is not the same as the resistance ratio $\mathbf{R_2}$ / $\mathbf{R_1}$ but is offset by one. Therefore, for example, for a voltage ratio of 1000:1 it is necessary to define a resistance ratio of 999:1. For a discrete resistor design it is preferable to select standard values, and some examples for decade voltage ratios are given in Table 1.

Decade Voltage Ratios using Standard Values

Target Voltage Ratio	R_2 / R_1	R1 (E24/96)	R2 (E12)	Actual Voltage Ratio	Nominal Error
10 : 1	9	9K1	82K	10.01	0.1%
100 : 1	99	4K75	470K	99.95	-0.05%
1000 : 1	999	6K81	6M8	999.5	-0.05%



Having selected nominal values, the next consideration is the tolerance needed. The tolerance in resistance ratio is simply the sum of the individual resistance tolerances. These are not necessarily the same; often it is most economical to elect a tighter tolerance on the low voltage part. For example, high voltage $\mathbf{R_2}$ at 1% and low voltage $\mathbf{R_1}$ at 0.1% gives a resistance ratio tolerance of 1.1%. The conversion of this to voltage ratio tolerance is shown in Figure 10, but for ratios above 50:1 they are effectively the same. For high precision applications the sources of error to be considered include finite loading of the divider by the buffer amplifier input, voltage coefficient of resistance (VCR) and temperature coefficient of resistance (TCR). The VCR is always negative and approximately linear over a limited voltage range and so may be compensated for to some extent. The effect of TCR, and, indeed, of tolerance, may be reduced by selecting matched sets or integrated dividers with a specified ratio tolerance and TCR tracking.

The CGH is often used in high voltage dividers, taking advantage of its precise resistance tolerance and low VCR. The GS3 series is an appropriate "tap resistor", the lower resistance component in the divider, because of its high voltage capabilities and stability.

Surface Mount: HVC, SMHP
Through Hole: 3800, CGH, CMH, CGX, F43/F44, GC, GS-3, MH, MHP-TO-220, MHP-TO-247, T-44

Example Products

T44, 43, and 48

Power (W): 1.5, 3.5, 10
Voltage (kV): 4 kV – 100 kV
Resistance: 1 kΩ - 45 GΩ
TCR (ppm): 25, 50, 100
Tolerance (%): 1, 2, 5

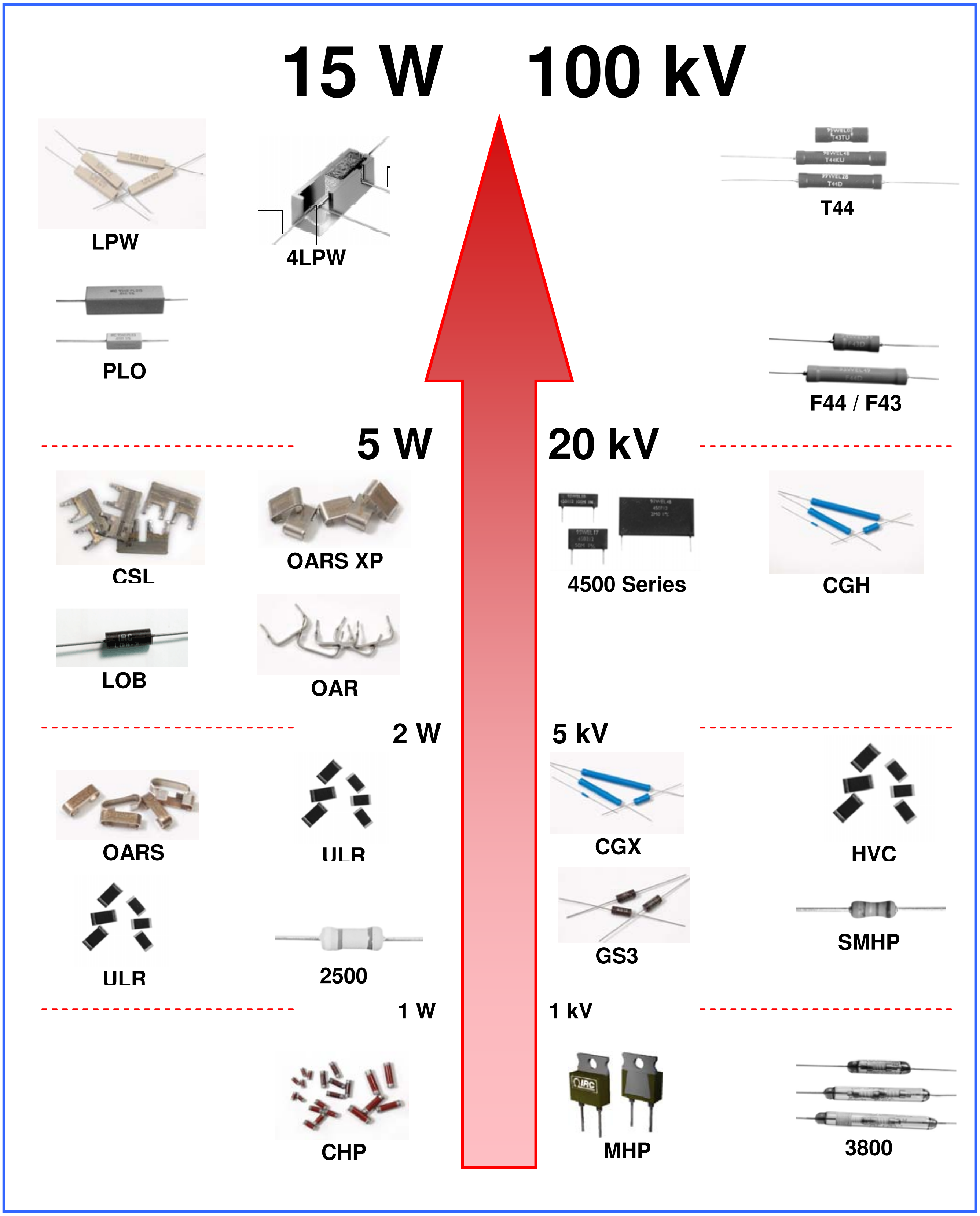
CGH and CMH (MIL R 49462)

Power (W): 0.25, 0.5, 1, 2, 3, 5
Voltage (kV): 0.75, 1.5, 3, 5, 10, 20
Resistance: 50 kΩ - 2 TΩ
TCR (ppm): 50, 100
Tolerance (%): 0.5, 1, 2, 5

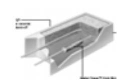
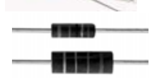
F43 and 44

Power (W): 0.7, 1.3
Voltage (kV): 4 – 28
Resistance: 1 MΩ - 150 GΩ
TCR (ppm): -2000
Tolerance (%): 2, 5, 10

Product Ranges



Summary Table

Product	Market: Aerospace	Automotive	Computer	High Voltage	Industrial	Medical	Military	Telecomm	Transmission	
4LPW						*		*		
AS	*		*			*	*	*		
CGH				*	*	*	*	*		
CHP	*		*				*			
CSL					*	*				
GS3		*	*	*	*	*		*		
HSF	*									
IBT						*		*		
LOB		*			*	*	*	*		
MH							*			
OAR		*	*		*	*		*		
OARS		*	*		*	*		*		
PWRG				*						
RLR	*		*				*	*	*	
SPH	*	*	*		*	*		*		

Note:
The table above illustrates the current product sales by market and should not be considered as the only products that may serve a customer's need. As a customer's technology evolves a different product may be more suitable than the existing sales by market segment.