Micrel's Guide to

Designing With Low-Dropout Voltage Regulators

Bob Wolbert

Applications Engineering Manager

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Micrel Semiconductor
1849 Fortune Drive
San Jose, CA 95131
Phone: + 1 (408) 944-0800
Fax: + 1 (408) 944-0970

Micrel, The High Performance Analog Power IC Company

Micrel Semiconductor designs, develops, manufactures, and markets high performance analog power integrated circuits on a worldwide basis. These circuits are used in a wide variety of electronic products, including those in cellular communications, portable and desktop computers, and in industrial electronics.

Micrel History

Since its founding in 1978 as an independent test facility of integrated circuits, Micrel has maintained a reputation for excellence, quality and customer responsiveness that is second to none.

In 1981 Micrel acquired its first independent semiconductor processing facility. Initially focusing on custom and specialty fabrication for other IC manufacturers, Micrel eventually expanded to develop its own line of semicustom and standard product Intelligent Power integrated circuits. In 1993, with the continued success of these ventures, Micrel acquired a new 57,000 sq. ft. facility and in 1995 expanded the campus into a 120,000 sq. ft. facility. The new Class 10 facility has allowed Micrel to extend its process and foundry capabilities with a full complement of CMOS/DMOS/Bipolar/NMOS/PMOS processes. Incorporating metal gate, silicon gate, dual metal, dual poly and feature sizes down to 1.5 micron, Micrel is able to offer its customers unique design and fabrication tools.

Micrel Today and Beyond

Building on its strength as an innovator in process and test technology, Micrel has expanded and diversified its business by becoming a recognized leader in the high performance analog power control and management markets.

The company's initial public offering in December of 1994 and recent ISO9001 compliance are just two more steps in Micrel's long range strategy to become the preeminent supplier of high performance analog power management and control ICs. By staying close to the customer and the markets they serve, Micrel will continue to remain focused on cost effective standard product solutions for an ever changing world.

The niche Micrel has carved for itself involves:

- **High Performance**.....precision voltages, high technology (Super βeta PNP™ process, patented circuit techniques, etc.) combined with the new safety features of overcurrent, overvoltage, and overtemperature protection
- **Analog**.....we control continuously varying outputs of voltage or current as opposed to digital ones and zeros (although we often throw in "mixed signal" i.e. analog with digital controls to bring out the best of both worlds)
- **Power ICs**.....our products involve high voltage, high current, or both

We use this expertise to address the following growing market segments:

1. Power supplies
2. Battery powered computer, cellular phone, and handheld instruments
3. Industrial & display systems
4. Desktop computers
5. Aftermarket automotive
6. Avionics
7. Plus many others

Some products in this book are protected by one or more of the following patents: 4,914,546; 4,951,101; 4,979,001; 5,034,346; 5,045,966; 5,047,820; 5,254,486; and 5,355,008. Additional patents are pending.

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Contributors:

Jerry Kmetz

Mike Mottola

Jim Cecil

Brian Huffman

Marvin Vander Kooi

Claude Smithson

Micrel Semiconductor
1849 Fortune Drive
San Jose, CA 95131
Phone: + 1 (408) 944-0800
Fax: + 1 (408) 944-0970

http://www.micrel.com

Section 1. Introduction: Low-Dropout Linear Regulators

What is a Linear Regulator?

IC linear voltage regulators have been around for decades. These simple-to-use devices appear in nearly every type of electronic equipment, where they produce a clean, accurate output voltage used by sensitive components.

Historically, linear regulators with PNP outputs have been expensive and limited to low current applications. However, Micrel Semiconductor's unique "Super βeta PNP™" line of low dropout regulators provides up to 7.5 amperes of current with dropout voltages less than 0.6V, guaranteed. A lower cost product line outputs the same currents with only 1V of dropout. These low dropout voltages guarantee the microprocessor gets a clean, well regulated supply that quickly reacts to processor-induced load changes as well as input supply variations.

The low dropout linear voltage regulator is a easy-to-use, low cost, yet high performance means of powering your systems.

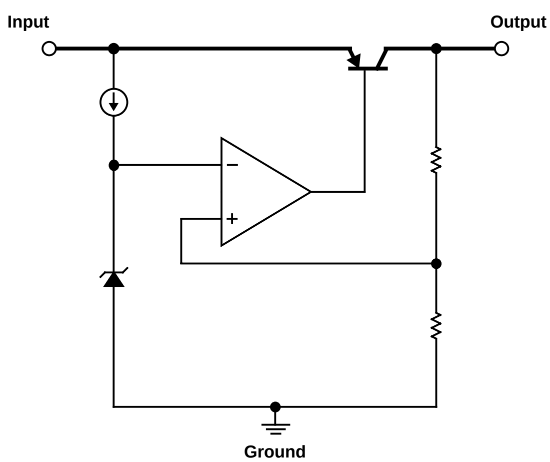


Figure 1-1. A basic linear regulator schematic.

A typical linear regulator diagram is shown in Figure 1-1. A pass transistor is controlled by an operational amplifier which compares the output voltage to a reference. As the output voltage drops, the op-amp increases drive to the pass element, which increases output voltage. Conversely, if the output rises above the desired set point, the op amp reduces drive. These corrections are performed continuously with the reaction time limited only by the speed of the op amp and output transistor loop.

Real linear regulators have a number of other features, including protection from short circuited loads and overtemperature shutdown. Advanced regulators offer extra features such as overvoltage shutdown, reversed-insertion and reversed polarity protection, and digital error indicators that signal when the output is not correct.

Why Use Regulators?

Their most basic function, voltage regulation, provides clean, constant, accurate voltage to a circuit. Voltage regulators are a fundamental block in the power supplies of most all electronic equipment.

Key regulator benefits and applications include:

- Accurate supply voltage
- Active noise filtering
- Protection from overcurrent faults
- Inter-stage isolation (decoupling)
- Generation of multiple output voltages from a single source
- Useful in constant current sources

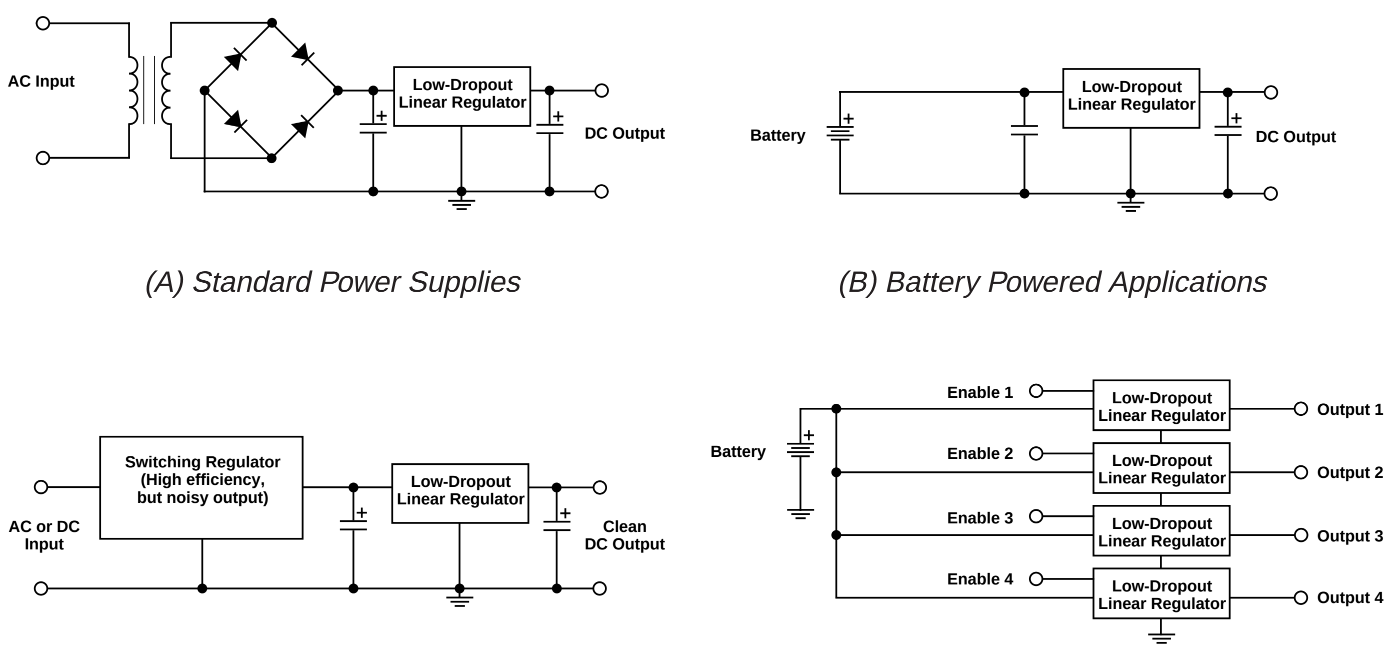
Figure 1-2 shows several typical applications for linear voltage regulators. A traditional AC to DC power supply appears in Figure 1-2(A). Here, the linear regulator performs ripple rejection, eliminating AC hum, and output voltage regulation. The power supply output voltage will be clean and constant, independent of AC line voltage variations. Figure 1-2(B) uses a low-dropout linear regulator to provide a constant output voltage from a battery, as the battery discharges. Low dropout regulators are excellent for this application since they allow more usable life from a given battery. Figure 1-2(C) shows a linear regulator configured as a "post regulator" for a switching power

supply. Switching supplies are known for excellent efficiency, but their output is noisy; ripple degrades regulation and performance, especially when powering analog circuits. The linear regulator following the switching regulator provides active filtering and greatly improves the output accuracy of the composite supply. As Figure 1-2(D) demonstrates, some linear regulators serve a double duty as both regulator and power ON/OFF control. In some applications, especially radio systems, different system blocks are often powered from different regulators—even if they use the same supply voltage—because of the isolation (decoupling) the high gain regulator provides.

Basic Design Issues

Let's review the most important parameters of voltage regulators:

- Output voltage is an important parameter, as this is the reason most designers purchase a regulator. Linear regulators are available in both fixed output voltage and adjustable configurations. Fixed voltage regulators offer enhanced ease-of-use, with their output voltages accurately trimmed at the factory—but only if your application uses an available voltage. Adjustables allow using a voltage custom-tailored for your circuit.
- Maximum output current is the parameter generally used to group regulators. Larger maximum output currents require larger, more expensive regulators.
- Dropout voltage is the next major parameter. This is the minimum additional voltage on the input that still produces a regulated output. For example, a Micrel 5.0V Super βeta PNP regulator will provide regulated output with an input voltage of 5.3V or above. The 300mV term is the dropout voltage. In the linear regulator world, the lower the dropout voltage, the better.
- Ground current is the supply current used by the regulator that does not pass into the load. An ideal regulator will minimize its ground current. This parameter is sometimes called quiescent current, but this usage is incorrect for PNP-pass element regulators.



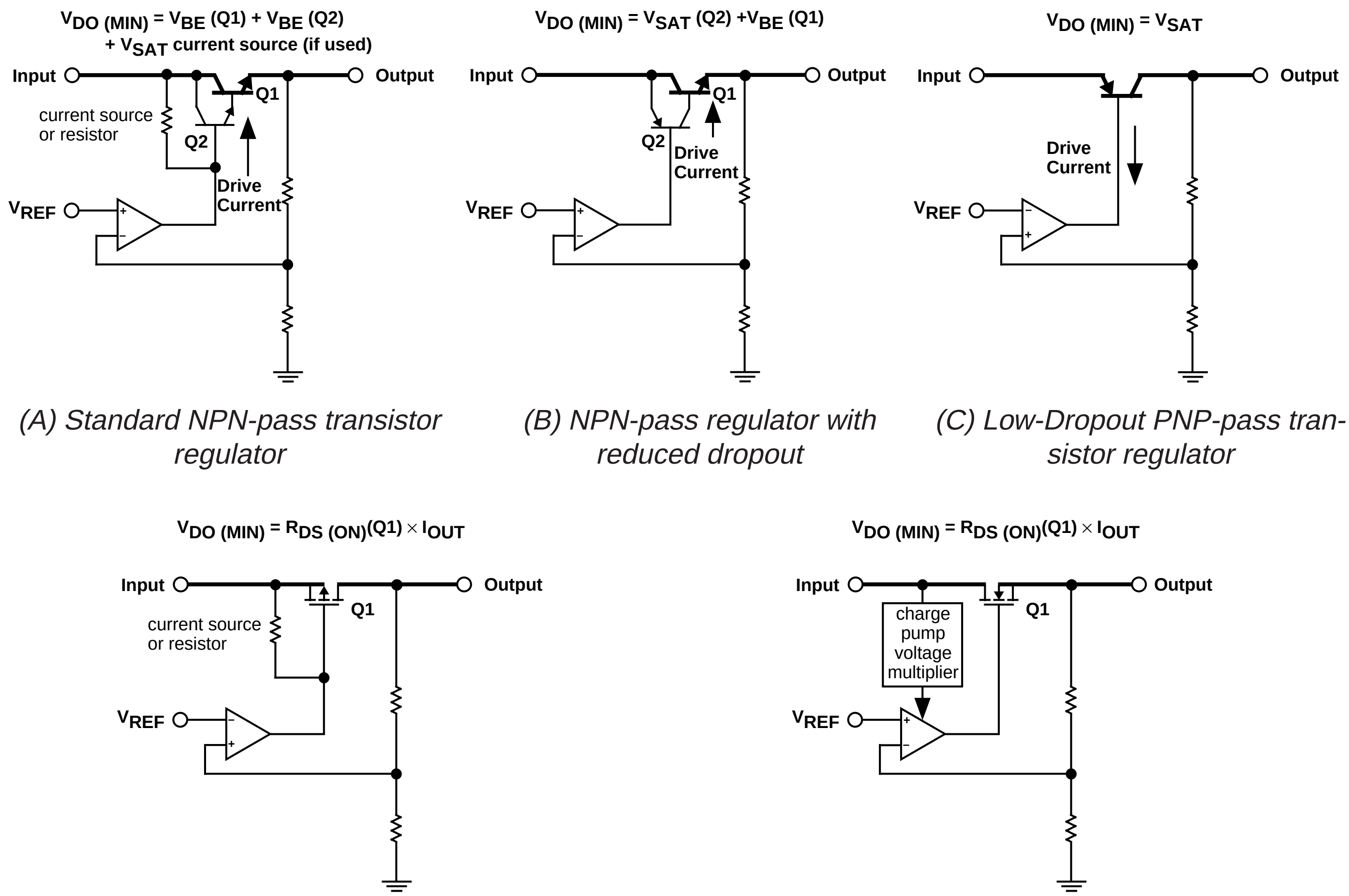
(A) Standard Power Supplies

(B) Battery Powered Applications

(C) Post-Regulator for Switching Supplies

(D) "Sleep-mode" and Inter Stage Isolation or Decoupling

Figure 1-2. Typical Linear Regulator Applications



(A) Standard NPN-pass transistor regulator

(B) NPN-pass regulator with reduced dropout

(C) Low-Dropout PNP-pass transistor regulator

(D) P-Channel MOSFET-pass transistor regulator

(E) N-Channel MOSFET-pass transistor regulator

Figure 1-3. The Five Major Types of Linear Regulators

- Efficiency is the amount of usable (output) power achieved from a given input power. With linear regulators, the efficiency is approximately the output voltage divided by the input voltage.

What is a "Low-Dropout" Linear Regulator?

A low dropout regulator is a class of linear regulator that is designed to minimize the saturation of the output pass transistor and its drive requirements. A low-dropout linear regulator will operate with input voltages only slightly higher than the desired output voltage. For example, "classic" linear regulators, such as the 7805 or LM317 need about 2.5 to 3V higher input voltage for a given output voltage. For a 5V output, these older devices need a 8V input. By comparison, Micrel's Super beta PNP low dropout regulators require only 0.3V of headroom, and would provide regulated output with only 5.3V of input.

Figure 1-3 shows the five major types of linear regulators:

A. "Classic" NPN-based regulators that require 2.5 to 3V of excess input voltage to function.
B. "Low Dropout NPN" regulators, with a NPN output but a PNP base drive circuit. These devices reduce the dropout requirement to 1.2 to 1.5V.
C. True low dropout PNP-based regulators that need 0.3V to 0.6V extra for operation.
D. P-channel CMOS output regulators. These devices have very low dropout voltages at low currents but require large die area (hence higher costly than bipolar versions) and have high internal drive current requirements when working with noisy inputs or widely varying output currents.

E. Regulator controllers. These are integrated circuits that provide the reference and control functions of a linear regulator, but do not have the pass element on board. They provide the advantage of optimizing die area and cost for higher current applications but suffer the disadvantage of being a multiple package solution.

If we graph the efficiency of the different classes of linear regulators we see very significant differences at low input and output voltages (see Figure 1-4). At higher voltages, however, these differences diminish. A 3.3V high current linear regulator controller such as the Micrel MIC5156 can approach 100% efficiency as the input voltage approaches dropout. But an LM317 set to 3.3V at 1A will have a miserable efficiency of only about 50% at its dropout threshold.

Linear Regulators vs. Switching Regulators

Linear regulators are less energy efficient than switching regulators. Why do we continue using them? Depending upon the application, linear regulators have several redeeming features:

- lower output noise is important for radios and other communications equipment
- faster response to input and output transients
- easier to use because they require only filter capacitors for operation
- generally smaller in size (no magnetics required)
- less expensive (simpler internal circuitry and no magnetics required)

Furthermore, in applications using low input-to-output voltage differentials, the efficiency is not all that bad! For example, in a 5V to 3.3V microprocessor application, linear regulator efficiency approaches 66%. And applications with low current subcircuits may not care that regulator efficiency is less than optimum as the power lost may be negligible overall.

Who Prefers Linear Low Dropout Regulators?

We see that price sensitive applications prefer linear regulators over their sampled-time counterparts. The design decision is especially clear cut for makers of:

- communications equipment
- small devices
- battery operated systems
- low current devices
- high performance microprocessors with sleep mode (fast transient recovery required)

As you proceed through this book, you will find numerous other applications where the linear regulator is the best power supply solution.

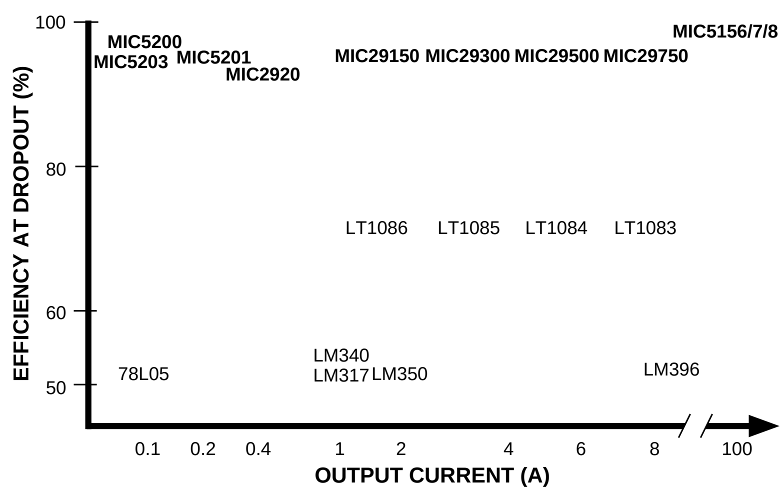


Figure 1-4. Linear Regulator Efficiency at Dropout

Section 2. Low-Dropout Regulator Design Charts

Regulator Selection Charts

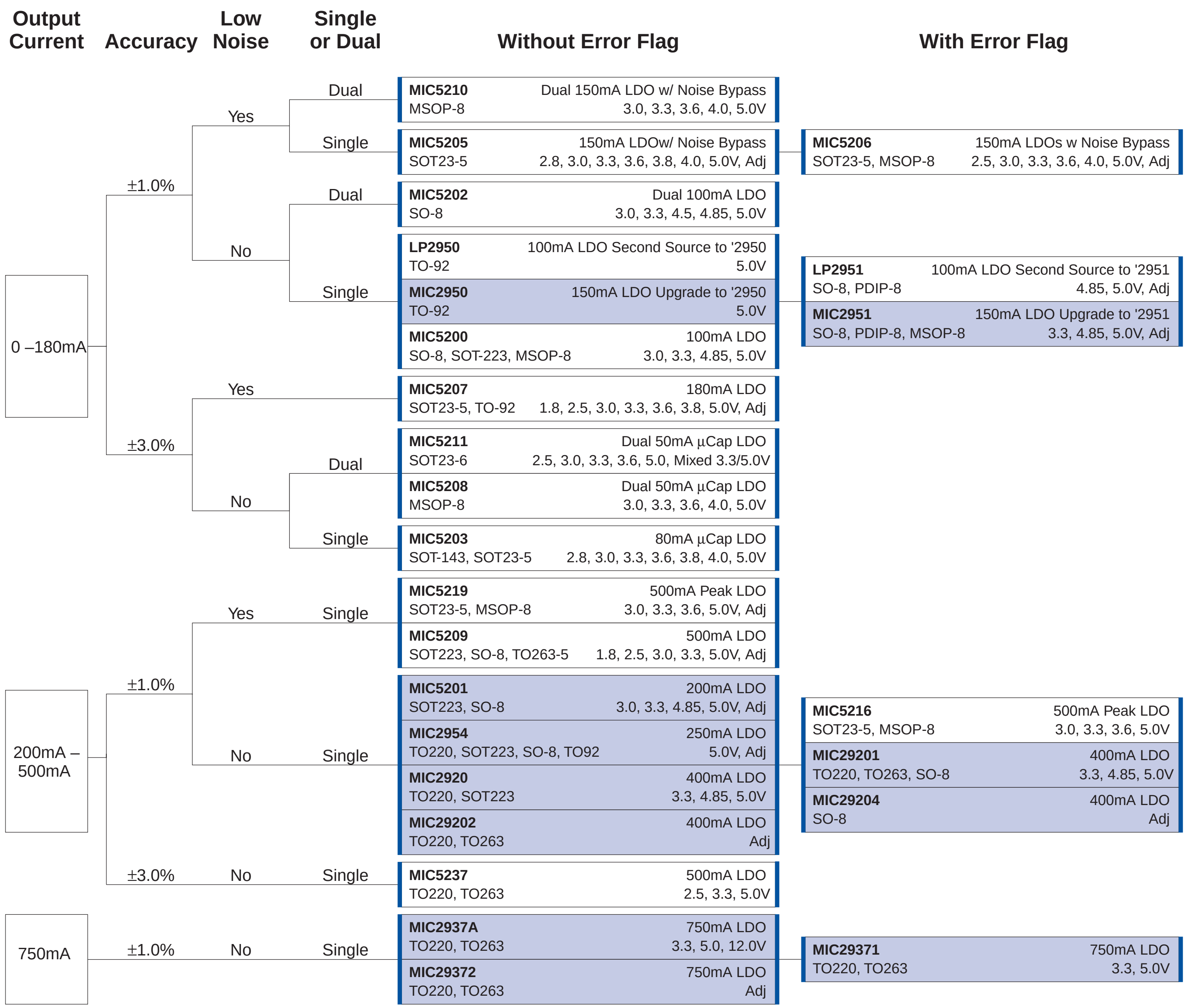


Figure 2-1a. 0 to 750mA LDO Regulator Selection Guide

Shaded boxes denote automotive load dump protected devices

Output Current	Accuracy	Error Flag	Low-Dropout Devices	Ultra-Low-Dropout Devices
1A – 1.5A	±1.0%	Yes	**MIC29151** 1.5A LDO TO220, TO263 3.3, 5.0, 12V	**MIC39151** 1.5A LDO TO263 1.8, 2.5V
		No	**MIC2940A** 1.25A LDO TO220, TO263 3.3, 5.0, 12V	
			MIC2941A 1.25A LDO TO220, TO263 Adj	**MIC39100** 1.0A LDO SOT223 1.8, 2.5, 3.3V
			MIC29150 1.5A LDO TO220, TO263 3.3, 5.0, 12.0V	**MIC39150** 1.5A LDO TO220, TO263 1.8, 2.5V
			MIC29152 1.5A LDO TO220, TO263 Adj	
3.0A	±1.0%	Yes	**MIC29301** 3.0A LDO TO220, TO263 3.3, 5.0, 12V	**MIC39301** 3.0A LDO TO263, TO220 1.8, 2.5V
			MIC29303 3.0A LDO TO220, TO263 Adj	
		No	**MIC29300** 3.0A LDO TO220, TO263 3.3, 5.0, 12.0V	
			MIC29302 3.0A LDO TO220, TO263 Adj	**MIC39300** 3.0A LDO TO220, TO263 1.8, 2.5V
			MIC29310 3.0A Low Cost LDO TO220, TO263 3.3, 5.0V	
			MIC29312 3.0A Low Cost LDO TO220, TO263 Adj	
5.0A –- 7.5A	±1.0%	Yes	**MIC29501** 5.0A LDO TO220, TO263 3.3, 5.0V	
			MIC29503 5.0A LDO TO220, TO263 Adj	
			MIC29751 7.5A LDO TO247 3.3, 5.0V	
		No	**MIC29500** 5.0A LDO TO220, TO263 3.3, 5.0V	
			MIC29502 5.0A LDO TO220, TO263 Adj	
			MIC29510 5.0A Low Cost LDO TO220 3.3, 5.0V	
			MIC29512 5.0A Low Cost LDO TO220 Adj	
			MIC29750 7.5A LDO TO247 3.3, 5.0V	
			MIC29752 7.5A Low Cost LDO TO247 Adj	
			MIC29710 7.5A LDO TO220 3.3, 5.0V	
			MIC29712 7.5A Low Cost LDO TO220 Adj	
>7.5A	±1.0%	Yes	**MIC5156** LDO Controller SO-8, PDIP-8 3.3, 5.0V, Adj	
			MIC5157 LDO Controller (w/Charge Pump) SO-14, PDIP-14 3.3, 5.0, 12V	
			MIC5158 LDO Controller (w/Charge Pump) SO-14, PDIP-14 5.0V, Adj	

Figure 2-1b. 1A to >7.5A LDO Regulator Selection Guide

Shaded boxes denote automotive load dump protected devices

MICREL

Regulator Selection Table

(Sorted by Output Current Rating)

Device	Output Current	Standard Output Voltage 1.8	2.5	2.8	3.0	3.3	3.6	3.8	4.0	4.75	4.85	5.0	12	Adj. (max.)	Accuracy	Dropout $(I_{MAX}, 25°C)$	Current Limit	Error Flag	Enable/ Shutdown	Thermal Shutdown	Rev. Input Protection	Load Dump	Packages
MIC5208	50mA × 2				•	•	•		•			•			3%	250mV	•		•	•	•		MSOP-8
MIC5211	50mA × 2		•		•	•	•					•			3%	250mV	•		•	•	•		SOT-23-6
MIC5203	80mA			•	•	•	•	•	•	•		•			3%	300mV	•		•	•	•		SOT-143, SOT-23-5
MIC5200	100mA				•	•					•	•			1%	230mV	•		•	•	•		SOP-8, SOT-223, MSOP-8
MIC5202	100mA × 2				•	•					•	•			1%	225mV	•		•	•	•		SOP-8
LP2950	100mA											•			½%,1%	380mV	•			•			TO-92
LP2951	100mA										•	•		29V	½%,1%	380mV	•	•	•	•			DIP-8, SOP-8
MIC2950	150mA											•			½%,1%	300mV	•			•	•	•	TO-92
MIC2951	150mA					•					•	•		29V	½%,1%	300mV	•	•	•	•	•	•	DIP-8, SOP-8, MSOP-8
MIC5205	150mA			•	•	•	•	•	•			•		16V	1%	165mV	•		•	•	•		SOT-23-5
MIC5206	150mA				•	•	•	•	•			•		16V	1%	165mV	•	•	•	•	•		SOT-23-5, MSOP-8
MIC5210	150mA × 2				•	•	•		•			•			1%	165mV	•		•	•	•		MSOP-8
MIC5207	180mV	•	•		•	•	•	•	•			•		16V	3%	165mA	•		•	•	•		SOT-23-5, TO-92^{SP}
MIC5201	200mA				•	•						•		16V	1%	270mV	•		•	•	•		SOP-8, SOT-223
MIC2954	250mA											•		29V	½%	375mV	•	•	•	•	•	•	TO-92,TO-220,SOT-223
MIC2920A	400mA					•					•	•	•		1%	450mV	•			•	•	•	TO-220, SOT-223
MIC29201	400mA					•					•	•	SP		1%	450mV	•	•	•	•	•	•	TO-220-5, TO-263-5
MIC29202	400mA													26V	1%	450mV	•		•	•	•	•	TO-220-5, TO-263-5
MIC29204	400mA											•		26V	1%	450mV	•	•	•	•	•	•	SOP-8, DIP-8
MIC5216	500mA[(1)]				•	•	•					•		12V	1%	300mV	•	•	•	•	•		SOT-23-5, MSOP-8
MIC5219	500mA[(1)]				•	•	•					•		12V	1%	300mV	•		•	•	•		SOT-23-5, MSOP-8
MIC5209	500mA	•	•		•	•	•					•		16V	1%	300mV	•		•	•	•		SOP-8, SOT-223, TO-263-5
MIC5237	500mA		•			•						•		16V	3%	300mV	•			•	•		TO-220, TO-263
MIC2937A	750mA					•						•	•		1%	370mV	•			•	•	•	TO-220, TO-263
MIC29371	750mA					•						•	SP		1%	370mV	•	•	•	•	•	•	TO-220-5, TO-263-5
MIC29372	750mA													26V	1%	370mV	•		•	•	•	•	TO-220-5, TO-263-5

Designing With LDO Regulators

Device	Output Current	1.8	2.5	2.8	3.0	3.3	3.6	3.8	4.0	4.75	4.85	5.0	12	Adj. (max.)	Accuracy	Dropout $(I_{MAX}, 25°C)$	Current Limit	Error Flag	Enable/ Shutdown	Thermal Shutdown	Rev. Input Protection	Load Dump	Packages
MIC2940A	1.25A					•						•	•		1%	400mV	•			•	•	•	TO-220, TO-263
MIC2941A	1.25A													26V	1%	400mV	•		•	•	•	•	TO-220-5, TO-263-5
MIC29150	1.5A					•						•	•		1%	350mV	•			•	•	•	TO-220, TO-263
MIC29151	1.5A					•						•	•		1%	350mV	•	•	•	•	•	•	TO-220-5, TO-263-5
MIC29152	1.5A													26V	1%	350mV	•		•	•	•	•	TO-220-5, TO-263-5
MIC29153	1.5A													26V[SP]	1%	350mV	•	•		•	•	•	TO-220-5, TO-263-5
MIC39150	1.5A		•												1%	350mV	•			•	•		TO-220, TO-263
MIC39151	1.5A		•												1%	350mV	•	•	•	•	•		TO-220-5, TO-263-5
MIC29300	3A					•						•	•		1%	370mV	•			•	•	•	TO-220, TO-263
MIC29301	3A					•						•	•		1%	370mV	•	•	•	•	•	•	TO-220-5, TO-263-5
MIC29302	3A													26V	1%	370mV	•		•	•	•	•	TO-220-5, TO-263-5
MIC29303	3A													26V	1%	370mV	•	•		•	•	•	TO-220-5, TO-263-5
MIC29310	3A					•						•			2%	600mV	•			•			TO-220, TO-263
MIC29312	3A													16V	2%	600mV	•		•	•			TO-220-5, TO-263-5
MIC39300	3A		•												1%	400mV	•			•	•		TO-220, TO-263
MIC39301	3A		•												1%	400mV	•	•	•	•	•		TO-220-5, TO-263-5
MIC29500	5A					•						•			1%	370mV	•			•	•	•	TO-220
MIC29501	5A					•						•			1%	370mV	•	•	•	•	•	•	TO-220-5, TO-263-5
MIC29502	5A													26V	1%	370mV	•		•	•	•	•	TO-220-5, TO-263-5
MIC29503	5A													26V	1%	370mV	•	•		•	•	•	TO-220-5, TO-263-5
MIC29510	5A					•						•			2%	700mV	•			•			TO-220, TO-263
MIC29512	5A													16V	2%	700mV	•		•	•			TO-220-5
MIC29710	7.5A					•						•			2%	700mV	•			•			TO-220
MIC29712	7.5A													16V	2%	700mV	•		•	•			TO-220-5
MIC29750	7.5A					•						•			1%	425mV	•			•	•	•	TO-247
MIC29751	7.5A					•						•			1%	425mV	•	•	•	•	•	•	TO-247-5
MIC29752	7.5A													26V	1%	425mV	•		•	•	•	•	TO-247-5
MIC5156	(2)					•						•		36V	1%	(2)	•	•	•	•			SOP-8, DIP-8
MIC5157	(2)					(3)						(3)	(3)		1%	(2)	•	•	•				SOP-14, DIP-14
MIC5158	(2)											(4)		(4)	1%	(2)	•	•	•				SOP-14, DIP-14

[SP] Special order. Contact factory.

[1] Output current limited by package and layout.

[2] Maximum output current and dropout voltage are determined by the choice of external MOSFET.

[3] 3.3V, 5V, or 12V selectable operation.

[4] 5V or Adjustable operation.

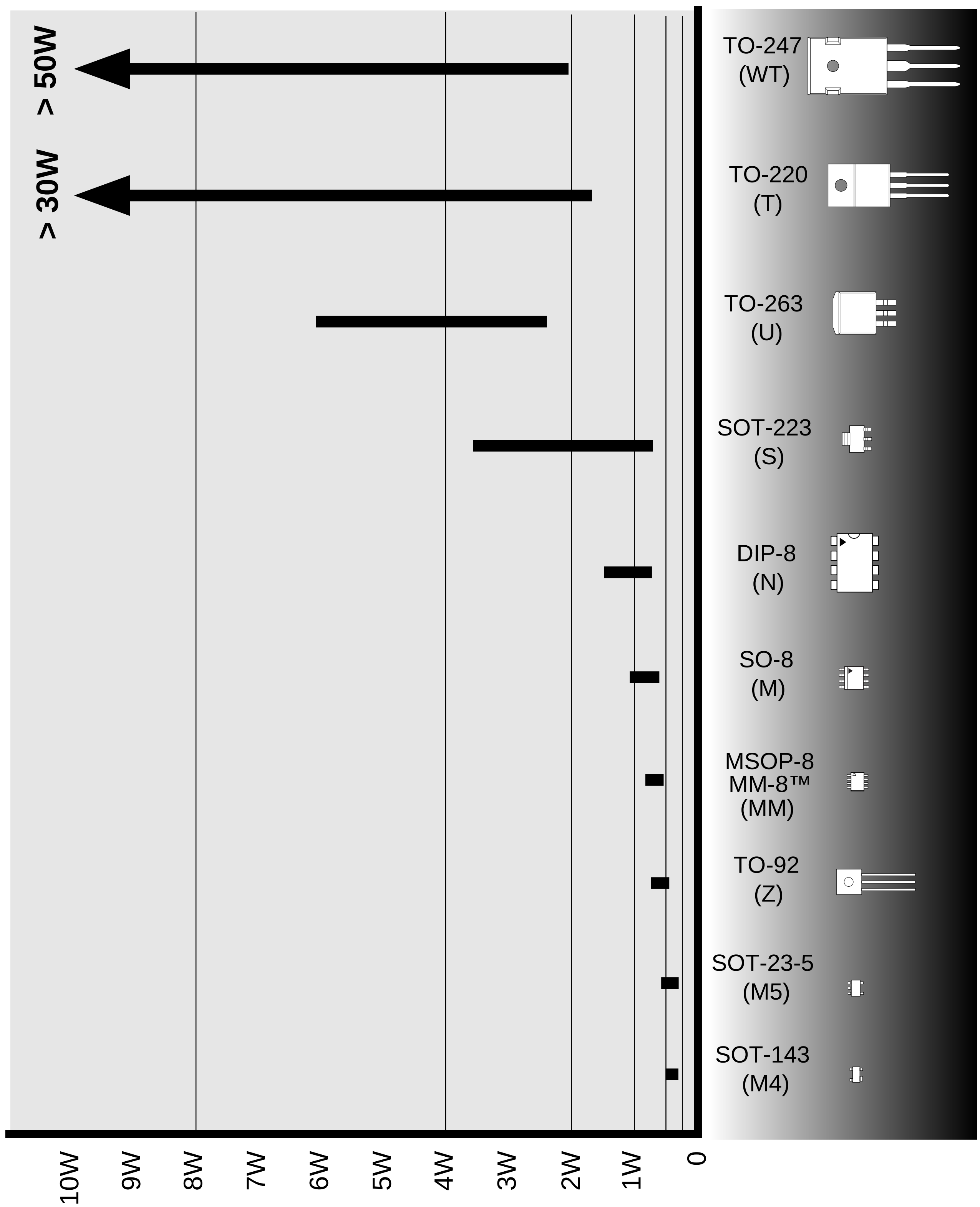


Figure 2-3 **Maximum Power Dissipation by Package Type**

The minimum point on each line of Figure 2-3 shows package power dissipation capability using "worst case" mounting techniques. The maximum point shows power capability with a very good (not infinite, though) heat sink. For example, through-hole TO-220 packages can dissipate a bit less than 2W without a heat sink, and over 30W with a good sink. The chart is approximate, and assumes an ambient temperature of 25°C. Packages are *not* shown in their approximate relative size.

Table 2-2. Typical Thermal Characteristics

Device	θ_{JC}	θ_{CS}	"Typical" heat sink θ_{JA}	Equivalent Thermal Graph (Figures 2-6, 2-7)
MIC5203BM4	—	—	250	A
MIC5200BM	—	—	160	B
MIC5200BS	15	—	50	E
MIC5202BM	—	—	160	B
LP2950BZ	—	—	160 – 180	B
LP2951BM	—	—	160	B
MIC2950BZ	—	—	160 – 180	D
MIC2951BM	—	—	160	D
MIC2951BN	—	—	105	
MIC5205BM5	—	—	220	C
MIC5206BM5	—	—	220	C
MIC5206BMM	—	—	200	C
MIC5207BM5	—	—	220	C
MIC5201BM	—	—	160	D
MIC5201BS	15	—	50	E
MIC2954BM	—	—	160	
MIC2954BS	15	—	50	
MIC2954BT	3	1	15 – 30	
MIC2954BZ	—	—	160 – 180	
MIC2920ABS	15	—	50	
MIC2920ABT	3	1	15 – 30	F
MIC29202BU	3	—	30 – 50	F
MIC29203BU	3	—	30 – 50	F
MIC29204BM	—	—	160	
MIC2937ABT	3	1	15 – 30	G
MIC2937ABU	3	—	30 – 50	G
MIC29371BT	3	1	15 – 30	G
MIC29371BU	3	—	30 – 50	G
MIC29372BT	3	1	15 – 30	G
MIC29372BU	3	—	30 – 50	G
MIC29373BT	3	1	15 – 30	G
MIC29373BU	3	—	30 – 50	G
MIC2940ABT	3	1	15 – 30	H
MIC2940ABU	3	—	30 – 50	
MIC2941BT	2	1	15 – 30	H
MIC2941BU	2	—	30 – 50	
MIC29150BT	2	1	10 – 30	H
MIC29150BU	2	—	30 – 40	
MIC29151BT	2	1	10 – 30	H
MIC29151BU	2	—	30 – 40	
MIC29152BT	2	1	10 – 30	H
MIC29152BU	2	—	30 – 40	
MIC29153BT	2	1	10 – 30	H
MIC29153BU	2	—	30 – 40	
MIC29300BT	2	1	10 – 30	I
MIC29300BU	2	—	30 – 40	
MIC29301BT	2	1	10 – 30	I
MIC29301BU	2	—	30 – 40	
MIC29302BT	2	1	10 – 30	I
MIC29302BU	2	—	30 – 40	
MIC29303BT	2	1	10 – 30	I
MIC29303BU	2	—	30 – 40	
MIC29310BT	2	1	10 – 30	I
MIC29312BT	2	1	10 – 30	I
MIC29500BT	2	1	5 – 15	J
MIC29500BU	2	—	20 – 30	
MIC29501BT	2	1	5 – 15	J
MIC29501BU	2	—	20 – 30	
MIC29502BT	2	1	5 – 15	J
MIC29502BU	2	—	20 – 30	
MIC29503BT	2	1	5 – 15	J
MIC29503BU	2	—	20 – 30	
MIC29510BT	2	1	5 – 15	J
MIC29512BT	2	1	5 – 15	J
MIC29710BT	2	1	5 – 15	K
MIC29712BT	2	1	5 – 15	K
MIC29750BWT	1.5	0.5	3 – 9	L
MIC29751BWT	1.5	0.5	3 – 9	L
MIC29752BWT	1.5	0.5	3 – 9	L

Output Current vs. Junction Temperature and Voltage Differential

(Figure 2-6)

These graphs show the junction temperature with a given output current and input-output voltage differential. Ambient temperature is 25°C. The thermal resistance used for the calculations is shown under each graph. This resistance assumes that a heat sink of suitable size for the particular regulator is employed; higher current regulator circuits generally require larger heat sinks. Refer to *Thermal Management*, in **Section 3**, for definitions and details.

For example, a MIC5203-3.3BM4, supplying 50mA and with 6.3V on its input ($V_{IN} – V_{OUT}$ = 3V), will have a junction temperature of approximately 63° (Figure 2-6 (A)).

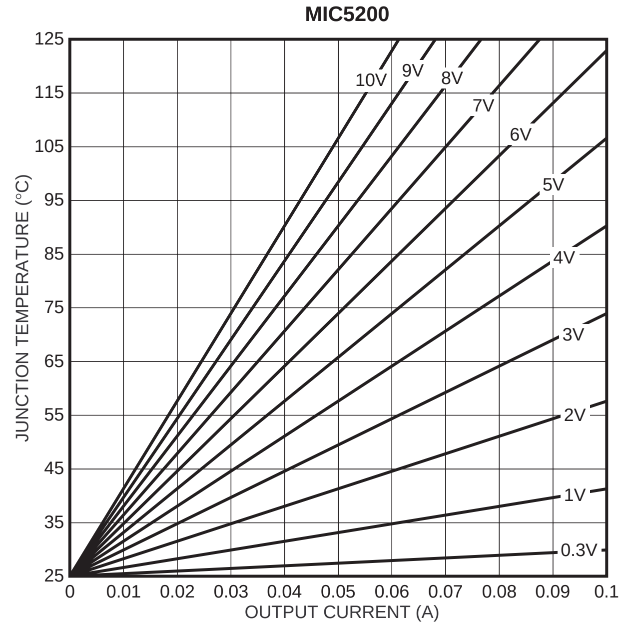


Figure 2-6 (B). SO-8 with θ_{JA} = 160°C/W

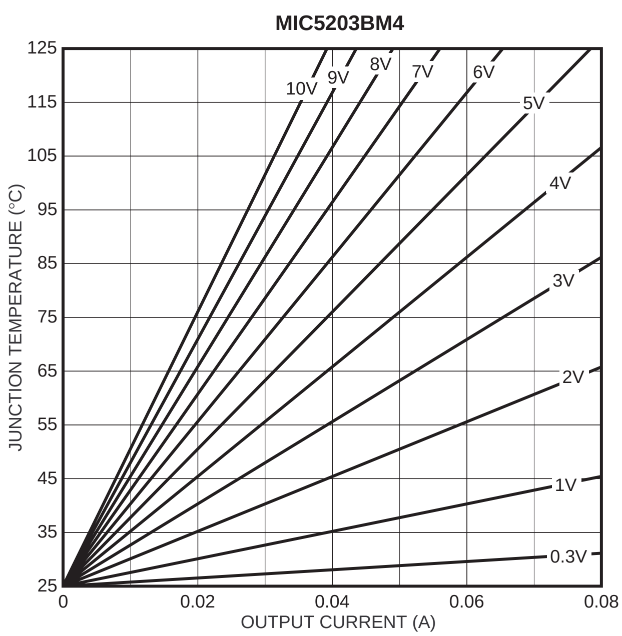


Figure 2-6 (A). SOT-143 with θ_{JA} = 250°C/W

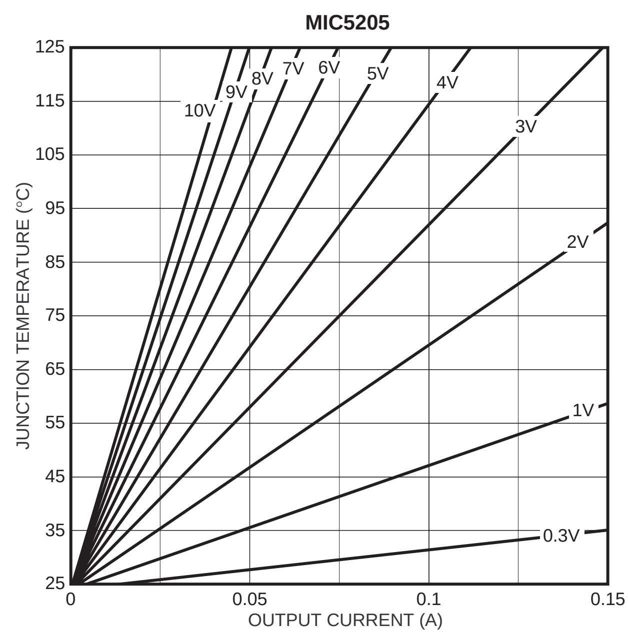


Figure 2-6 (C). SOT-23-5 with θ_{JA} = 220°C/W

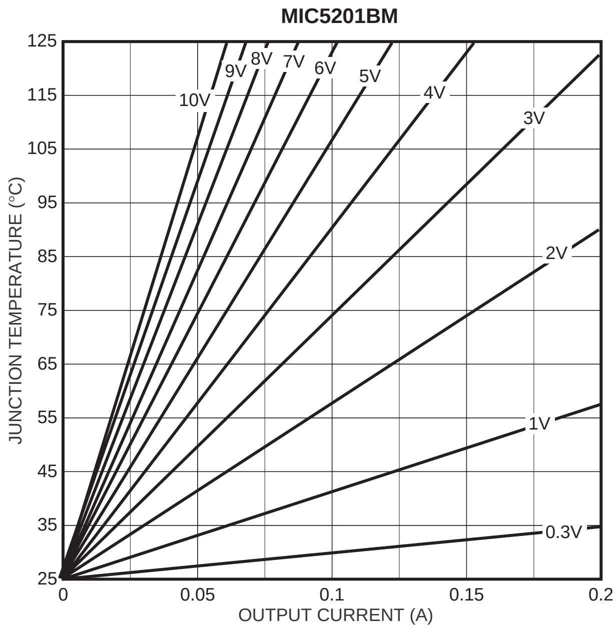


Figure 2-6 (D). High Current SO-8 with θ_{JA} = 160°C/W

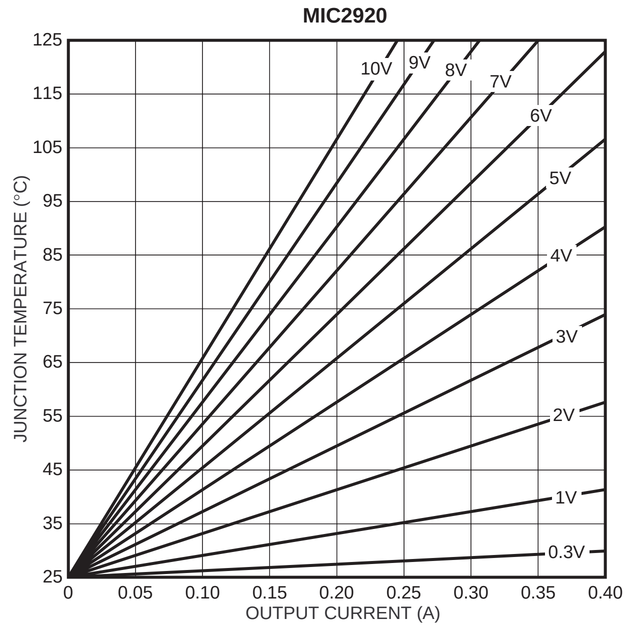


Figure 2-6 (F). TO-263 with θ_{JA} = 40°C/W

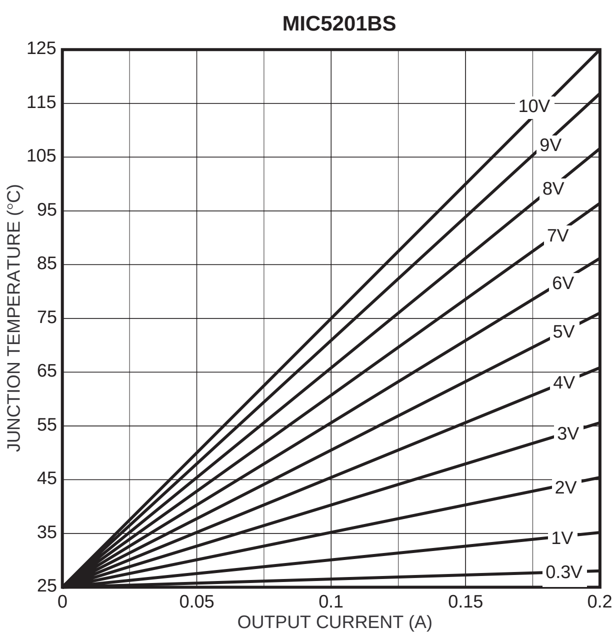


Figure 2-6 (E). SOT-223 with θ_{JA} = 50°C/W

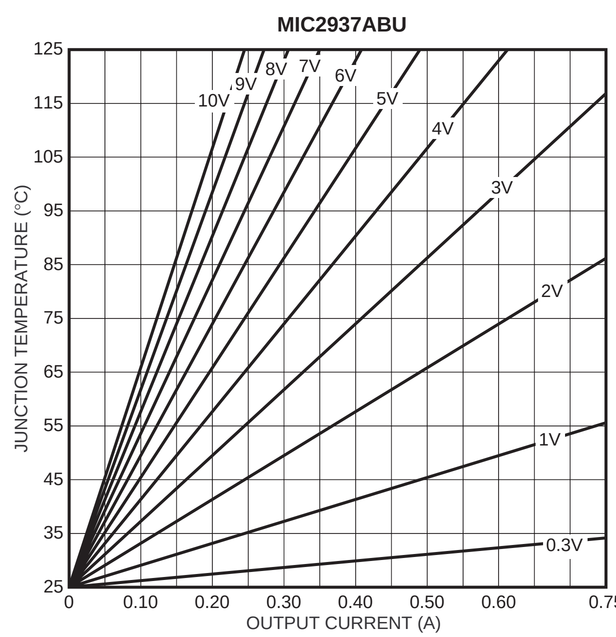


Figure 2-6 (G). TO-263 with θ_{JA} = 40°C/W

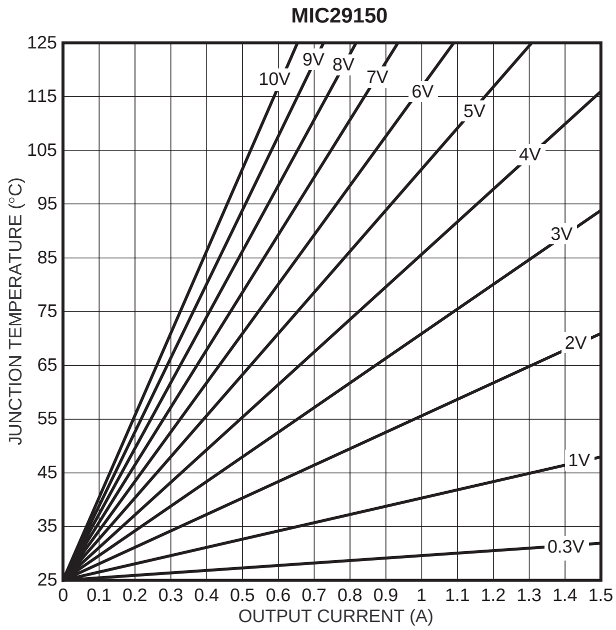


Figure 2-6 (H). TO-220 with θ_{JA} = 15°C/W

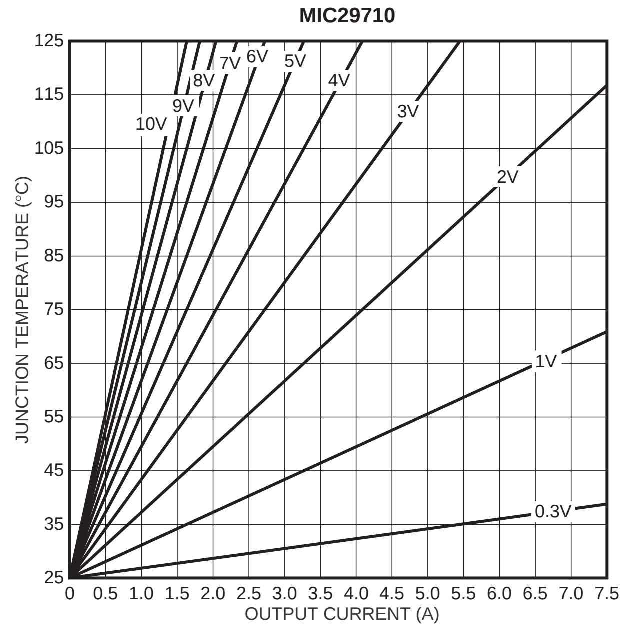


Figure 2-6 (K). TO-220 with θ_{JA} = 6°C/W

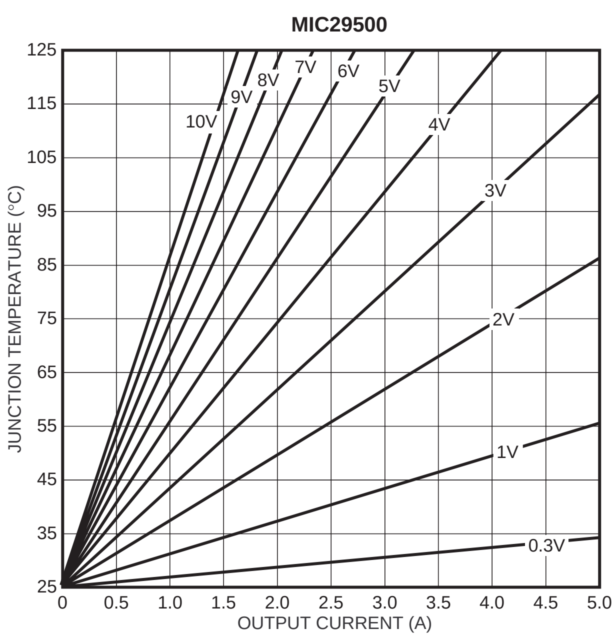


Figure 2-6 (J). TO-220 with θ_{JA} = 6°C/W

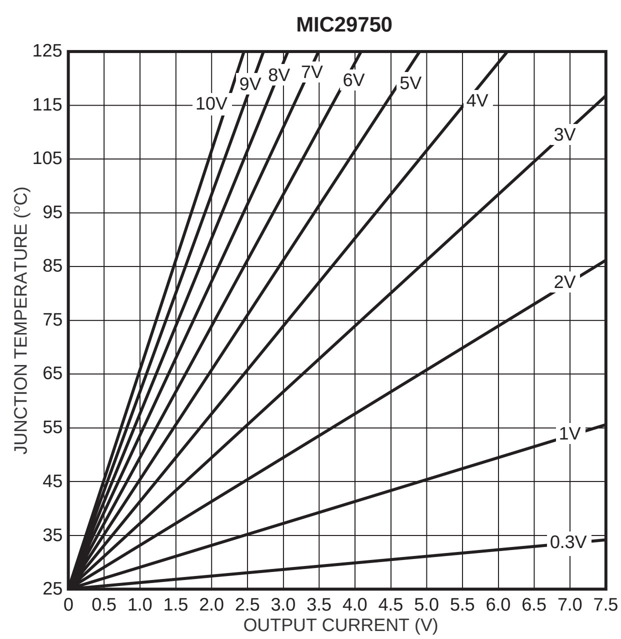


Figure 2-6 (L). TO-247 with θ_{JA} = 4°C/W

Junction Temperature Rise vs. Available Output Current and Differential Voltage

(Figure 2-7)

These graphs show the available thermally-limited steady-state output current with a given thermal resistance and input—output voltage differential. The assumed θ_{JA} (thermal resistance from junction to ambient) is shown below each graph. Refer to *Thermal Management* in **Section 3** for definitions and details.

For example, Figure 2-7 (C) shows that the MIC5205BM5, with 3V across it ($V_{IN} = V_{OUT} + 3V$) and supplying 120mA, will have a temperature rise of 80°C (when mounted normally).

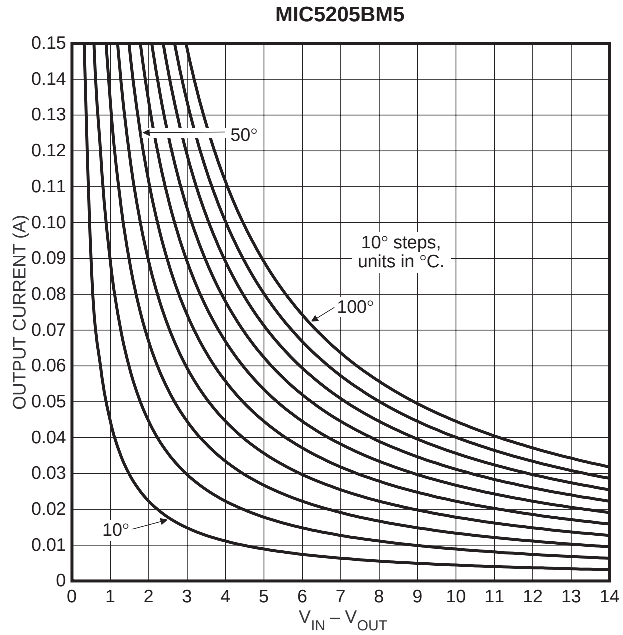


Figure 2-7 (C). SOT-23-5 with θ_{JA} = 220°C/W

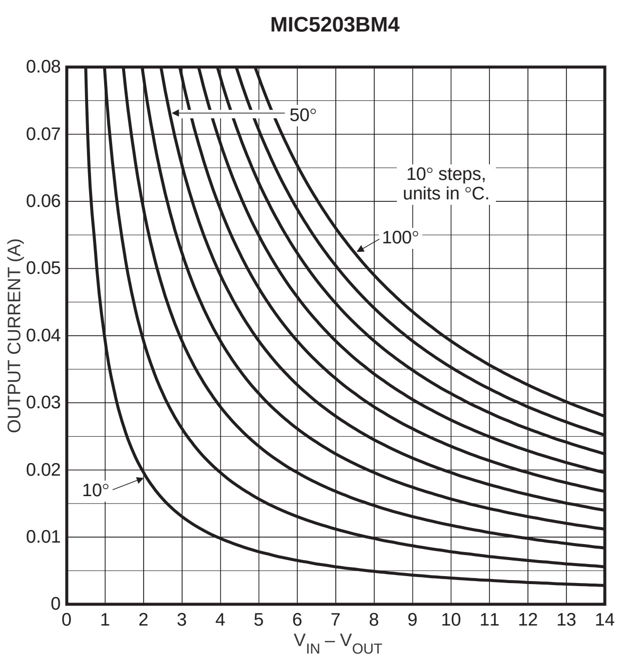


Figure 2-7 (A). SOT-143 with θ_{JA} = 250°C/W

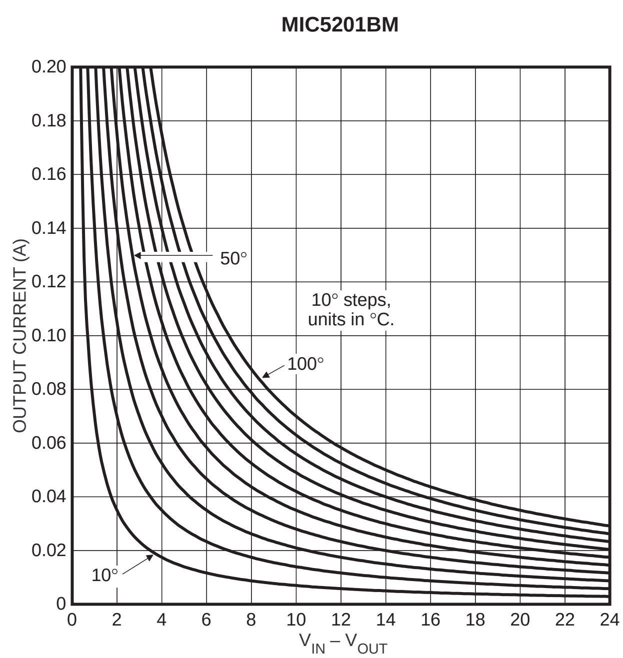


Figure 2-7 (D). SO-8 with θ_{JA} = 140°C/W

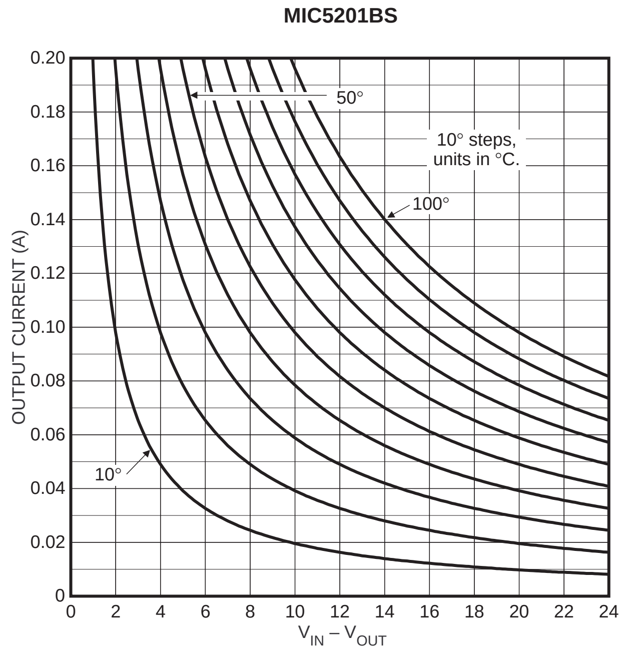


Figure 2-7 (E). SOT-223 with θ_{JA} = 50°C/W

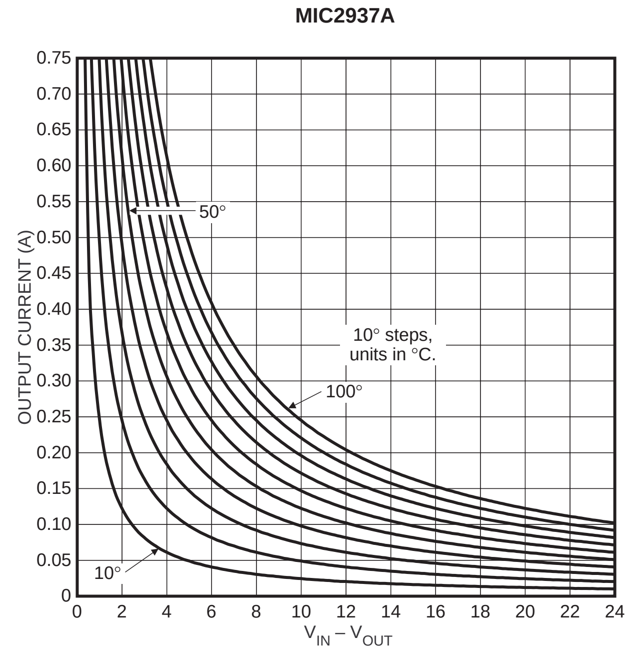


Figure 2-7 (G). TO-263 with θ_{JA} = 40°C/W

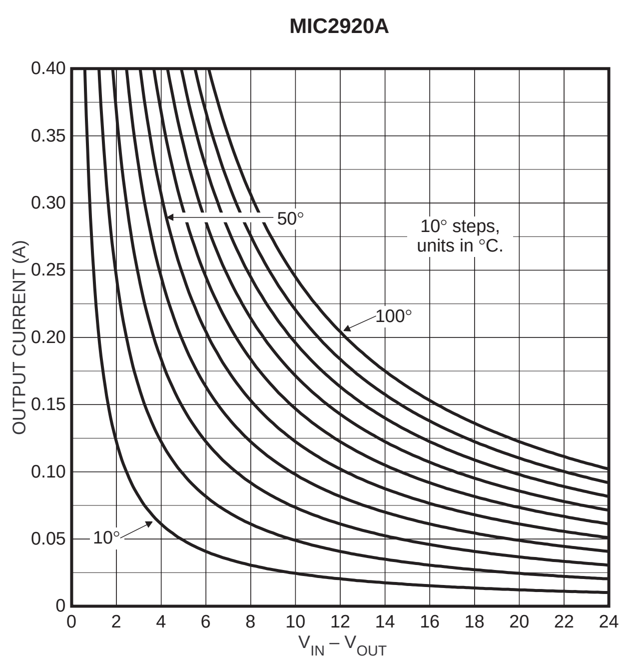


Figure 2-7 (F). TO-263 with θ_{JA} = 40°C/W

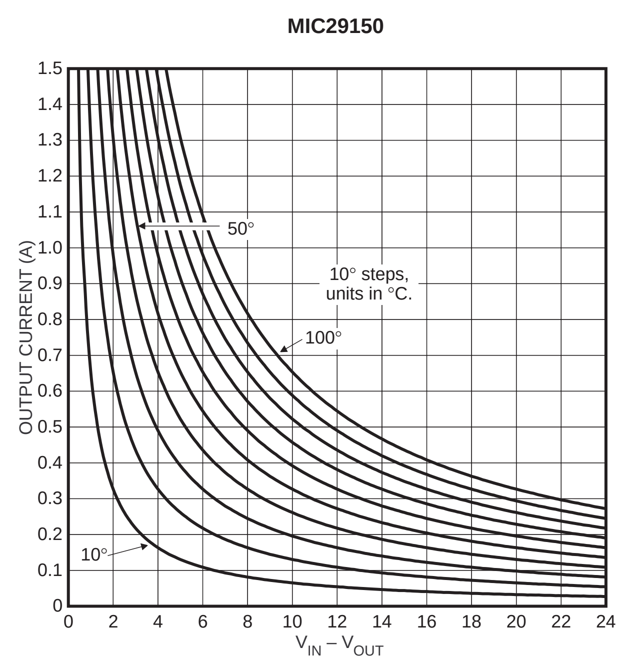


Figure 2-7 (H). TO-220 with θ_{JA} = 15°C/W

MIC29300

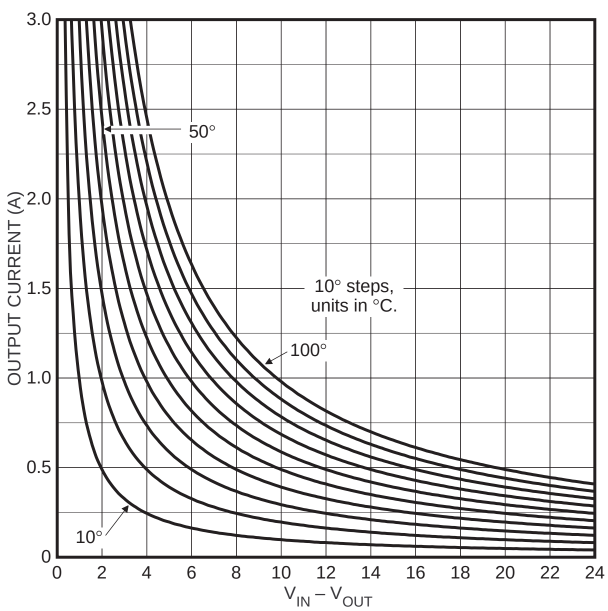


Figure 2-7 (I). TO-220 with θ_{JA} = 10°C/W

MIC29710

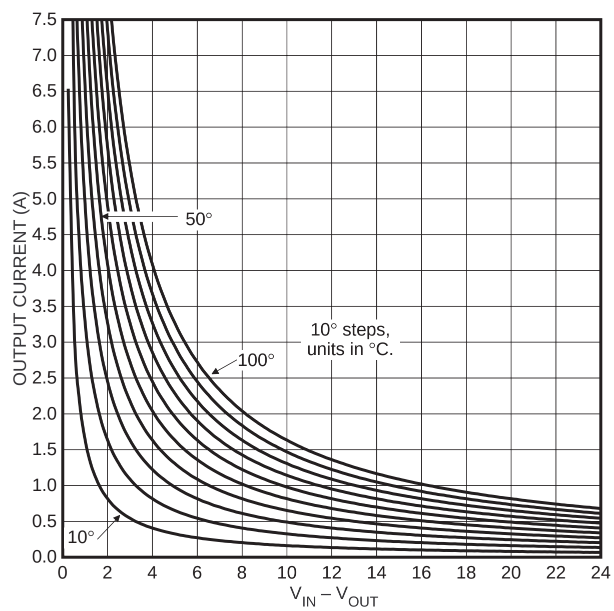


Figure 2-7 (K). TO-220 with θ_{JA} = 6°C/W

MIC29500

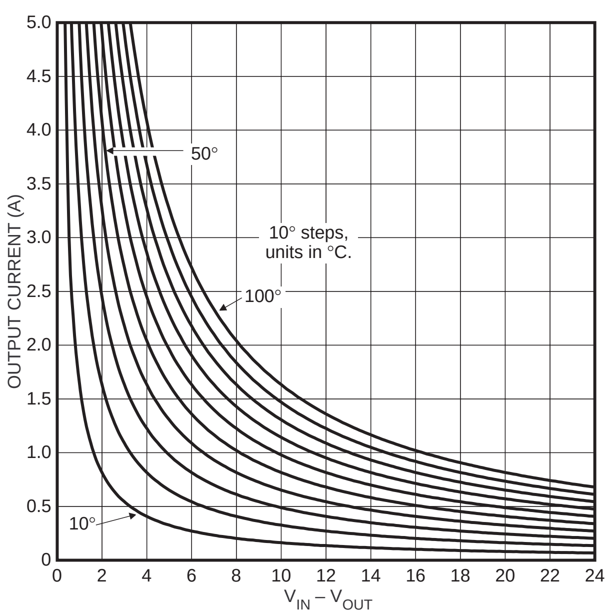


Figure 2-7 (J). TO-220 with θ_{JA} = 6°C/W

MIC29750

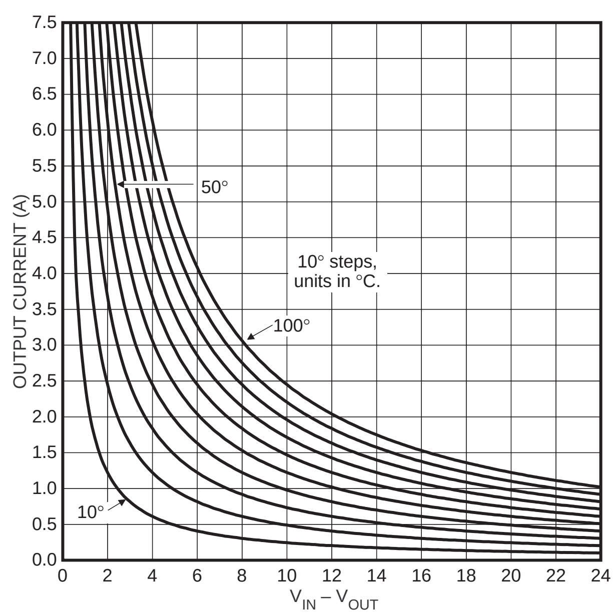


Figure 2-7 (L). TO-247 with θ_{JA} = 4°C/W

Section 3. Using LDO Linear Regulators

General Layout and Construction Considerations

Layout

Although often considered "just a D.C. Circuit", low-dropout linear regulators are actually built with moderately high frequency transistors because rapid response to input voltage or output current changes demand excellent high frequency performance. These characteristics place some requirements on bypass capacitors and board layout.

Bypass Capacitors

Low-dropout linear regulators need capacitors on both their input and output. The input capacitor provides bypassing of the internal op amp used in the voltage regulation loop. The output capacitor improves regulator response to sudden load changes, and in the case of the Super βeta PNP™ devices, provides loop compensation that allows stable operation.

The input capacitor for monolithic regulators should feature low inductance and generally good high frequency performance. Capacitance is not too critical except for systems where excessive input ripple voltage is present. The capacitor must, as a minimum, maintain the input voltage minimum value above the dropout point. Otherwise, the regulator ceases regulation and becomes merely a saturated switch. In an AC-line powered system, where the regulator is mounted within a few centimeters from the main filter capacitor, additional capacitors are often unnecessary. A 0.1µF ceramic directly adjacent to the regulator is always a good choice, however. If the regulator is farther away from the filter capacitor, local bypassing is mandatory.

With the high current MIC5157 and MIC5158 Super LDO™ regulator controllers, the input capacitor should be a medium sized (10µF or larger) low ESR (effective series resistance) type.

Output Capacitor

The Super βeta PNP regulators require a certain minimum value of output capacitance for operation—below this minimum value, the output may exhibit oscillation. The output capacitor is inside the voltage control loop and is necessary for loop stabilization. Minimum recommended values are listed on each device data sheet. There is *no* maximum value—the output capacitor may be increased without limit.[1]

Excellent response to high frequency load changes (load current transient recovery) demands low inductance, low ESR, high frequency filter capacitors. Stringent requirements are solved by paralleling multiple medium sized capacitors. Capacitors should be chosen by comparing their lead inductance, ESR, and dissipation factor. Multiple small or medium sized capacitors provide better high frequency characteristics than a single capacitor of the same total capacity since the lead inductance and ESR of the multiple capacitors is reduced by paralleling.

Although the capacitance value of the filter may be increased without limit, if the ESR of the paralleled capacitors drops below a certain (device family dependent) threshold, a zero in the transfer plot appears, lowering phase margin and decreasing stability. With some devices, especially the MIC5157 and MIC5158 Super LDO, this problem is solved by using a low ESR input decoupling capacitor. Worst-case situations may require changes to higher ESR output capacitors—perhaps increasing both the ESR and the capacitance by using a different chemistry—or, as a last resort, by adding a small series resistance (< 1Ω) between the regulator and the capacitor(s).

NOTE 1: Truly huge output capacitors will extend the start-up time, since the regulator must charge them. This time is determined by capacitor value and the current limit value of the regulator.

Circuit Board Layout

Stray capacitance and inductance may upset loop compensation and promote instability. Excessive input lead resistance increases the dropout voltage, and excessive output lead resistance reduces output load regulation. Ground loops also cause both problems. Careful layout is the solution.

Reduce stray capacitance and inductance by placing bypass and filter capacitors close to the regulator. Swamp parasitic reactances by using a 0.1µF ceramic capacitor (or equivalent) in parallel with the regulator input filter capacitor. Designers of battery-powered circuits often overlook the finite high-frequency impedance of their cells. The ceramic capacitor solves many unexpected problems.

Excessive lead resistance, causing unwanted voltage drops and ruining load regulation, is solved by merely increasing conductor size. Regulators with remote sensing capability—like all Micrel adjustables—may utilize a Kelvin-sense connection directly to the load. As Figure 3-1 shows, an additional pair of wires feeds back the load voltage to the regulator sense input.[2] This lets the regulator compensate for line drop. As the Kelvin sense leads carry only the small voltage-programming resistor current, they may be very narrow traces or small diameter wire. A judicious layout is especially important in remote-sensed designs, since these long, high impedance leads are susceptible to noise pickup.

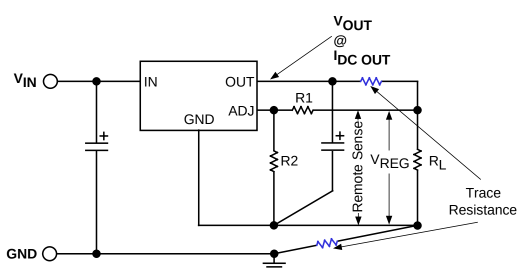


Figure 3-1. Remote Voltage Sense (Kelvin) Connections

A common ground loop problem occurs when rectifier ripple current flows through the regulator's ground lead on its way to the filter capacitor (see Figure 3-2). The ripple current, which is several times larger than the average DC current, may create a voltage drop in the ground line, raising its voltage relative to the load. As the regulator attempts to compensate, load regulation suffers. Solve the problem by ensuring rectifier current flows directly into the filter capacitor.

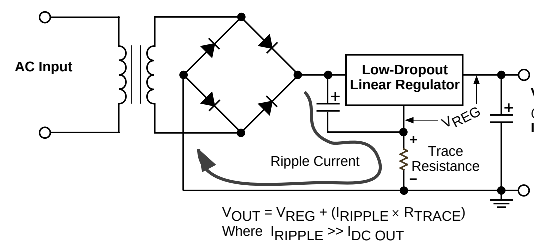


Figure 3-2. Ground Loop and Ripple Currents Degrade Output Accuracy

Figure 3-3 shows an ideal layout for remote-sensed loads. If a single point ground is not practical, load regulation is improved by employing a large ground plane.

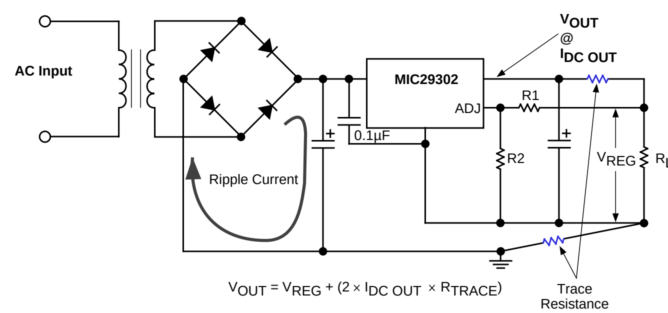


Figure 3-3. Regulator Layout With Remote Voltage Sensing

Assembly

Low power regulator circuits are built like any other analog system. Surface mounted systems are assembled using normal reflow (or similar), techniques. Larger leaded packages may require special lead bending before installation; specific lead bend options are available from Micrel, or the assembler may bend them. When power demands force the use of a heat sink, extra care must be applied during assembly and soldering. Our assembly discussion will focus on the popular TO-220 package but it is generally applicable to other package types.

NOTE 2: The internal reference in most Micrel regulators is positioned between the adjust pin and ground, unlike the older "classic" NPN regulator designs. This technique, while providing excellent performance with Micrel regulators, does not work with the older voltage regulators; in fact, it reduces their output voltage accuracy.

Lead Bending

If lead bending is necessary, use the standard bend options offered by Micrel whenever possible. These bending operations are performed on tooling developed specifically for this purpose and with the safety of the package, die, and internal wire bonds in mind. Custom lead bending is also available for a nominal charge.

For prototyping or other low quantity custom lead bending requirements, clamp the leads at the junction of the case with long nosed pliers. Using your fingers or another pair of pliers, bend the outer lead as desired. Please observe the following cautions:

- Do not spread or compress the leads
- Do not bend or twist the leads at the body junction: start the bend at least 3mm from the body
- Maintain a lead bend radius of approximately 1mm
- Do not re-bend leads multiple times

Micrel TO-220 packages are made from nickel-plated or tinned copper for best electrical and thermal performance. While rugged electrically, they are susceptible to mechanical stress and fatigue. Please handle them with care!

Heat Sink Attachment

TO-220 package applications at moderate (room) temperatures may not require heat sinking if the power dissipation is less than 2 watts. Otherwise, heat sinks are necessary. Use the minimum practical lead length so heat may travel more directly to the board, and use the board itself as a heat sink.

Attachment techniques vary depending upon the heat sink type, which in turn depends upon the power dissipated. The first consideration is whether or not electrical isolation is required. Micrel's Super ßeta PNP regulators all have a grounded tab, which usually means no insulation is necessary. This helps by reducing or eliminating one of the thermal resistances. Next, we determine heat sink size. See the *Thermal Management* chapter for details. If a standard commercial heat sink is chosen, we may generally assume minimal surface roughness or burrs.

Otherwise, machining the mounting pad may be necessary to achieve a flatness (peak-to-valley) of 4 mils per inch with a surface finish of ± 1.5µm or better for minimum thermal resistance.

Holes for the mounting screw should be drilled and deburred. Slightly oversized holes allow for slippage during temperature cycling and is generally recommended.

Heat sinks of bare aluminum or copper are not optimum heat radiators. Anodizing or painting improves heat radiation capability. For more details on heat sinks, see the *References*.

Thermal grease, thermal pads, or other thermally conductive interface between the package and the heat sink compensates for surface flatness errors, mounting torque reduction over time, air gaps, and other sins, and is recommended. Heat sink manufacturers offer a variety of solutions with widely varying prices, installation ease, and effectiveness.

Many heat sinks are available with mounting clips. These allow fast assembly and, when the clip also presses against the plastic body instead of only the metal tab, provide excellent heat contact area and low thermal resistance.

Machine screws are often used for heat sink attachment (see Figure 3-4). Proper torque is imperative; too loose and the thermal interface resistance is excessive; too tight and the semiconductor die will crack. The 0.68N-m specification applies to clean threads; ensure that the thermal grease does not interfere with the threads.

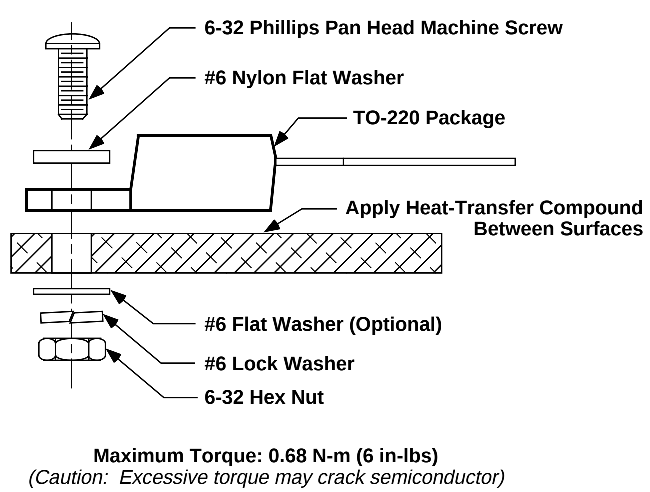


Figure 3-4. Mounting TO-220 Packages to Heat Sinks

Output Voltage Accuracy

Adjustable Regulator Accuracy Analysis

Micrel LDO Regulators are high accuracy devices with output voltages factory-trimmed to much better than 1% accuracy. Across the operating temperature, input voltage, and load current ranges, their worst-case accuracies are still better than ±2%. For adjustable regulators, the output also depends upon the accuracy of two programming resistors. Some systems require supply voltage accuracies better than ±2.5%—including noise and transients. While noise is generally not a major contributor to output inaccuracy, load transients caused by rapidly varying loads (such as high-speed microprocessors), are significant, even when using fast transient-response LDO regulators and high-quality filter capacitors.

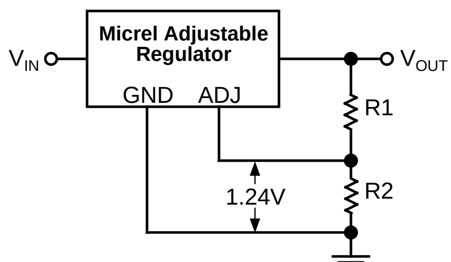


Figure 3-5. An adjustable linear regulator uses the ratio of two resistors to determine its output voltage.

Adjustable regulators use the ratio of two resistors to multiply the reference voltage to produce the desired output voltage (see Figure 3-5). The formula for output voltage from two resistors is presented as Equation 3-1.

$$V_{OUT} = V_{REF}\left(1+\frac{R1}{R2}\right) \quad (3\text{-}1)$$

The basic MIC29512 has a production-trimmed reference (V_{REF}) with better than ±1% accuracy at a fixed temperature of 25°C. It is guaranteed better than ±2% over the full operating temperature range, input voltage variations, and load current changes. Since practical circuits experience large temperature swings we should use the ±2% specification as our theoretical worst-case. This value assumes no error contribution from the programming resistors.

Referring to Figure 3-5 and Equation 3-1, we see that resistor tolerance (tol) must be added to the reference tolerance to determine the total regulator inaccuracy. A sensitivity analysis of this equation shows that the error contribution of the adjust resistors is:

$$\text{Error Contribution}\,\% = \left(\frac{2\times \text{tol}\%}{1-\left(\frac{\text{tol}\%}{100}\right)}\right)\times\left(1-\frac{V_{REF}}{V_{OUT}}\right) \quad (3\text{-}2)$$

Since the output voltage is proportional to the product of the reference voltage and the ratio of the programming resistors, at high output voltage, the error contribution of the programming resistors is the sum of each resistor's tolerance. Two standard ±1% resistors contribute as much as 2% to output voltage error. At lower voltages, the error is less significant. Figure 3-6 shows the effects of resistor tolerance on regulator accuracy from the minimum output voltage (V_{REF}) to 12V. At the minimum V_{OUT}, theoretical resistor tolerance has no effect on output accuracy. Resistor error increases proportionally with output voltage: at an output of 2.5V, the sensitivity factor is 0.5; at 5V it is about 0.75; and at 12V it is over 0.9. This means that with 5V of output, the error contribution of 1% resistors is 0.75 times the sum of the tolerances, or 0.75 × 2% = 1.5%. As expected, more precise resistors offer more accurate performance.

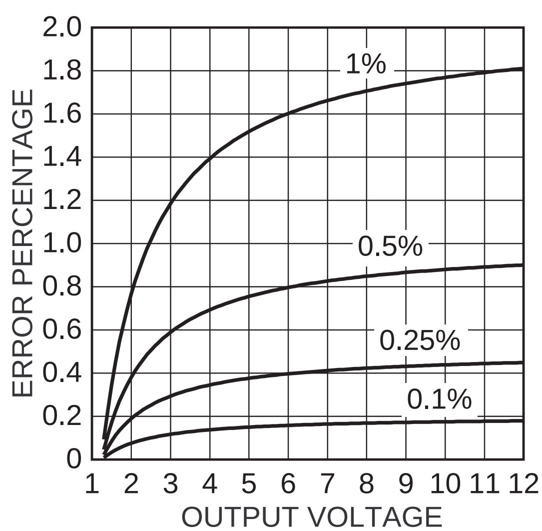


Figure 3-6. Resistor Tolerance Effects on Adjustable Regulator Accuracy

The output voltage error of the entire regulator system is the sum of reference tolerance and the resistor error contribution. Figure 3-7 shows this worst-case tolerance for the MIC29512 as the output volt-

age varies from minimum to 12V using ±1%, ±0.5%, ±0.25%, and ±0.1% resistors. The more expensive, tighter accuracy resistors provide improved tolerance, but it is still limited by the adjustable regulator's ±2% internal reference.

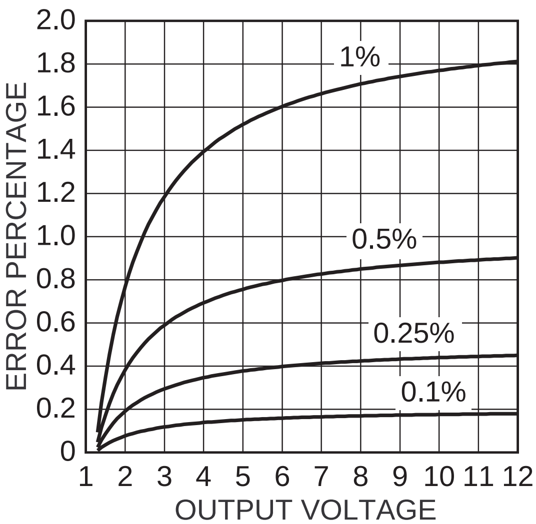


Figure 3-7. Worst-Case Output Tolerance

A better method is possible: increase the overall accuracy of the regulator by employing a precision reference in the feedback loop.

Improving Regulator Accuracy

Achieving a worst-case error of ±2.5%, including all D/C and A/C error terms, is possible by increasing the basic accuracy of the regulator itself, but this is expensive since high current regulators have significant self-heating. Its internal reference must maintain accuracy across a wide temperature range. Testing for this level of performance is time consuming and raises the cost of the regulator, which is unacceptable for extremely price-sensitive marketplaces. Some systems require better than ±2% accuracy. This high degree of accuracy is possible using Micrel's LM4041 voltage reference instead of one of the programming resistors (refer to Figure 3-8). The regulator output voltage is the sum of the internal reference and the LM4041's programmed voltage (Equation 3-3).

(3-3)
$$V_{OUT} = V_{REF\ Regulator} + V_{LM4041} = 1.240 + V_{LM4041}$$

The benefit of this circuit is the increased accuracy possible by eliminating the multiplicative effect of the regulator's internal reference. In normal configurations, the reference error is multiplied up by the resistor ratio, keeping the error percentage constant. With this circuit, the error voltage is within 25mV, absolute. Another benefit of this arrangement is that the LM4041 is not a dissipative device: there is only a small internal temperature rise to degrade accuracy. Additionally, both references are operating in their low-sensitivity range so we get less error contribution from the resistors. A drawback of this configuration is that the minimum output voltage is now the sum of both references, or about 2.5V. The adjustable LM4041 is available in accuracies of ±0.5% and ±1%, which allows better overall system output voltage accuracy.

Equation 3-4 presents the formula for the LM4041-ADJ output voltage. Note the output voltage has a slight effect on the reference. Refer to the LM4040 data sheet for full details regarding this second-order coefficient.

(3-4)
$$V_{LM4041} = \left[V_{OUT} \times \frac{\Delta V_{REF}}{\Delta V_{OUT}} + 1.233\right] \times \left[\frac{R1b}{R1a} + 1\right]$$

Actually, the voltage drop across R1b is slightly higher than that calculated from Equation 3-4. Approximately 60nA of current flows out of the LM4041 FB terminal. With large values of R1b, this current creates millivolts of higher output voltage; for best accuracy, compensate R1b by reducing its size accordingly. This error is +1mV with R1b = 16.5kΩ.

Equation 3-5 shows the nominal output voltage for the composite regulator of Figure 4.

(3-5)
$$V_{OUT} = \frac{1.233\left(\frac{R1b}{R1a} + 1\right)}{1.0013\left(\frac{0.0013R1b}{R1a}\right)} + \left(60nA \times R1b\right) + 1.240$$

Note that the tolerance of R2 has no effect on output voltage accuracy. It sets the diode reverse (operating) current and also allows the divider current from R1a and R1b to pass. With R2 = 1.2kΩ, 1mA of bias flows. If R2 is too small (less than about 105Ω, the maximum reverse current of the LM4041-ADJ is exceeded. If it is too large with respect to R1a and R1b then the circuit will not regulate. The recommended range for R2 is from 121Ω to $R1a/10$.

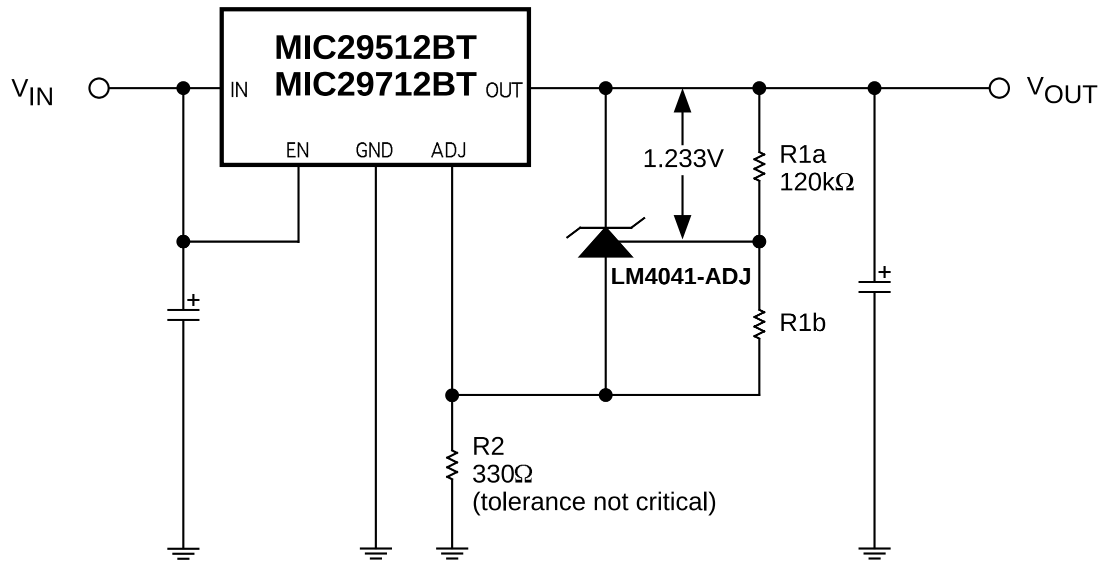


Figure 3-8. Improved Accuracy Composite Regulator Circuit

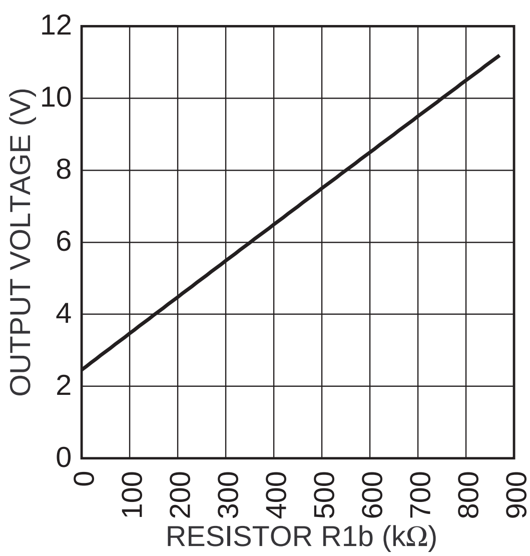


Figure 3-9. Output Voltage vs. R1b (See Figure 3-8)

Regulator & Reference Circuit Performance

With this circuit we achieve much improved accuracies. Our error terms are:

25mV	(constant) from the MIC29512
0.5%	from the LM4041C
+ 0 to 2%	from R1a and R1b
0.5% + 25mV to 2.5% + 25mV	Total Error Budget

Figure 3-10 shows the resistor error contribution to the LM4041C reference output voltage tolerance. Figure 3-11 shows the worst-case output voltage error of the composite regulator circuit using various resistor tolerances, when a 0.5% LM4041C reference is employed. The top four traces reflect use of 1%, 0.5%, 0.25%, and 0.1% resistors. Table 3-1 lists the production accuracy obtained with the low-cost LM4041C and standard 1% resistors as well as the improvement possible with 0.1% resistors.

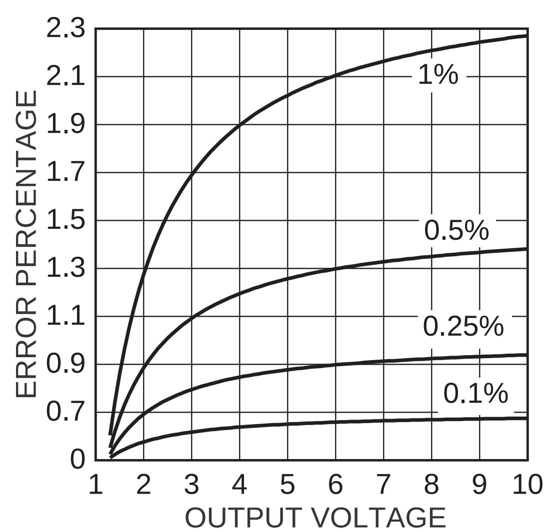


Figure 3-10. Resistor Tolerance Effects on LM4041 Voltage Reference Accuracy

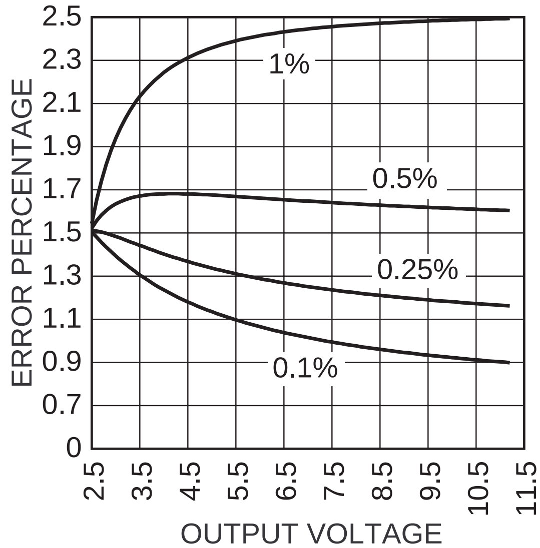


Figure 3-11. Composite Regulator Accuracy

What does the extra complexity of the composite regulator circuit of Figure 3-8 buy us in terms of extra accuracy? With precision components, we may achieve tolerances better than ±1% with the composite regulator, as compared to a theoretical best case of somewhat worse than 2% with the standard regulator and resistor configuration. Figure 3-12 and Table 3-2 show the accuracy difference between the circuits as the output voltage changes. The accuracy difference is the tolerance of the two-resistor circuit minus the tolerance of the composite circuit. Both tolerances are the calculated worst-case value, using 1% resistors. This figure shows the composite circuit is always at least 1% better than the standard configuration. Both the figure and the table assume standard ±1% resistors and the LM4041C-ADJ (0.5%) reference.

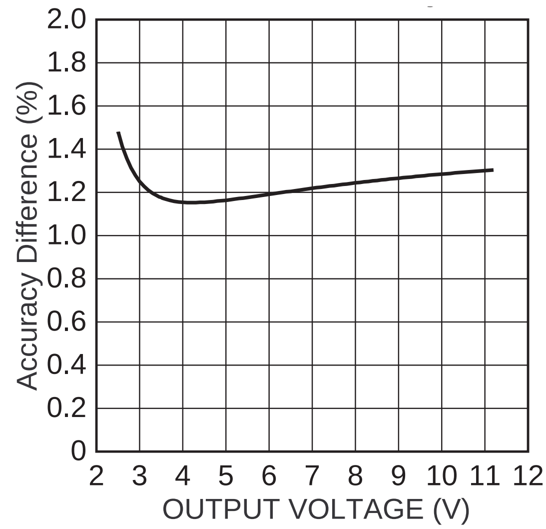


Figure 3-12. Accuracy difference between the Standard Two-Resistor Circuit and the Composite Circuit of Figure 3-8

V_{OUT}	1% Resistors	0.1% Resistors
2.50V	±1.54%	±1.50%
2.90V	±1.88%	±1.41%
3.00V	±1.94%	±1.39%
3.30V	±2.07%	±1.34%
3.45V	±2.12%	±1.31%
3.525V	±2.14%	±1.30%
3.60V	±2.16%	±1.29%
5.00V	±2.36%	±1.13%
6.00V	±2.41%	±1.07%
8.00V	±2.46%	±0.98%
10.00V	±2.49%	±0.92%
11.00V	±2.49%	±0.90%

Table 3-1. Worst-Case Output Voltage Error for Typical Operating Voltages Using the LM4040C (±0.5% Accuracy Version)

V_{OUT}	Composite Circuit	Standard Circuit
2.50V	±1.6%	±3.0%
3.00V	±1.9%	±3.2%
3.30V	±2.1%	±3.3%
3.50V	±2.1%	±3.2%
5.00V	±2.4%	±3.5%
6.00V	±2.4%	±3.6%
8.00V	±2.5%	±3.7%
10.00V	±2.5%	±3.8%
11.00V	±2.5%	±3.8%

Table 3-2. Comparing the Worst-Case Output Voltage Error for the Two Topologies With Typical Output Voltages

Design Issues and General Applications

Noise and Noise Reduction

Most of the output noise caused by a LDO regulator emanates from the voltage reference. While some of this noise may be shunted to ground by the output filter capacitor, bypassing the reference at a high impedance node provides more attenuation for a given capacitor value. The MIC5205 and MIC5206 use a lower noise bandgap reference and also provide external access to this reference. A small value (470pF or so) external capacitor attenuates output noise by about 10dB for a 5 volt output.

All of Micrel's adjustable regulators allow a similar technique. By shunting one of the voltage programming resistors with a small-value capacitor, the high frequency gain of the regulator is reduced which serves to reduce high frequency noise. The capacitor should be placed across the resistor connecting between the feedback pin and the output (R1 on data sheet schematics).

Stability

Low dropout linear regulators with a PNP output require an output capacitor for stable operation. See *Stability Issues* in **Section 4, Linear Regulator Solutions** for a discussion on stability with Super βeta PNP regulators.

The Super LDO is more stable than the monolithic devices and rarely needs much attention to guarantee stability. *Micrel's Unique "Super LDO"*, also in Section 4, discusses the few parameters requiring vigilance.

LDO Efficiency

The electrical efficiency of all electronic devices is defined as $P_{OUT} \div P_{IN}$. A close efficiency approximation for linear regulators is

$$\text{Eff} = \frac{V_{OUT}}{V_{IN}}$$

This approximation neglects regulator operating current, but is very accurate (usually within 1%) for Super βeta PNP and Super LDO regulators with their very low housekeeping power draw. The full formula is:

$$\text{Eff} = \frac{V_{IN} \times (I_{GND}) + (V_{IN} - V_{OUT}) \times I_{OUT}}{V_{OUT} \times I_{OUT}}$$

Building an Adjustable Regulator Allowing 0V Output

Some power supplies, especially laboratory power supplies and power systems demanding well-controlled surge-free start-up characteristics, require a zero-volt output capability. In other words, an adjustable laboratory power supply should provide a range than includes 0V. However, as shown in Figure 3-13, a typical adjustable regulator does not facilitate adjustment to voltages lower than V_{REF} (the internal bandgap voltage). Adjustable regulator ICs are designed for output voltages ranging from their reference voltage to their maximum input voltage (minus dropout); the reference voltage is generally about 1.2V. The lowest output voltage available from this circuit is provided when R1 = 0Ω. For the MIC29152 LDO regulator, V_{REF} = 1.240V, so $V_{OUT}(\text{min}) = V_{REF}(1+R1/R2)$, or 1.240V.

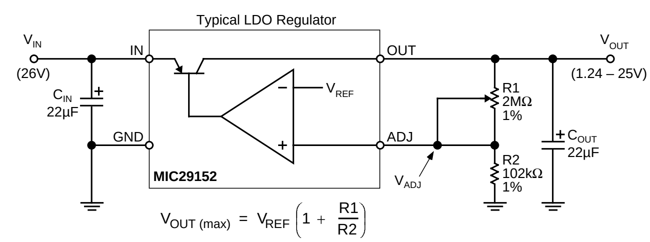


Figure 3-13. Typical Adjustable Regulator

Two designs work around the minimum output voltage limitation. The first uses a low-cost reference diode to create a "virtual" V_{OUT} that cancels the reference. The second uses op-amps to convince the regulator adjust pin that zero volts is a proper output level. In both cases, the feedback-loop summing junction must be biased at V_{REF} to provide linear operation.

Reference Generates a "Virtual V_{OUT}"

Figure 3-14 shows a simple method of achieving a variable output laboratory supply or a less-than-1.2V fixed-output supply. The circuit uses a second bandgap reference to translate the regulator's output up to a "virtual V_{OUT}" and then uses that virtual V_{OUT} as the top of a feedback divider. The output voltage adjusts from 0V to about 20V.

When R1 goes to 0Ω, the output is about 0V, the virtual V_{OUT} is one bandgap voltage above ground, and the adjust input is also one bandgap voltage above ground. The regulator's error amplifier loop is satisfied that both of its inputs are at one bandgap voltage and it keeps the output voltage constant at 0V. The virtual V_{OUT} tracks any increases in R1, remaining one bandgap voltage above the actual V_{OUT}, as the output rises from ground. The maximum possible V_{OUT} equals the regulator's maximum input voltage minus the approximately 2V housekeeping voltage required by the current-source FET and the external bandgap reference.

The current source, composed of a 2N3687 JFET and R3, is designed for about 77µA. Seven microamperes for the resistor string (about 100 times the nominal 60nA input current of the regulator's adjust input) and 70µA for the bandgap. R2 is optional, and is needed only if no load is present. It bleeds off the 70µA of reference current and satisfies the minimum load current requirement of the regulator.

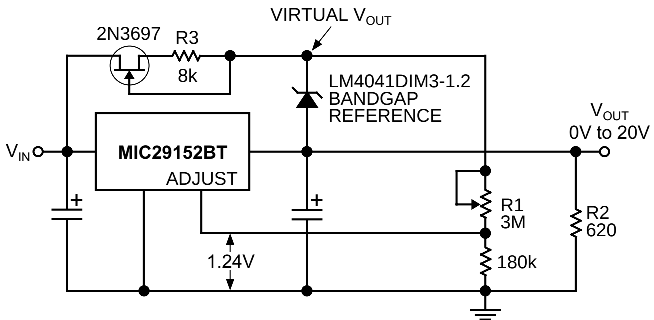


Figure 3-14. Adjust to Zero Volt Circuit Using a Reference Diode

A drawback of this simple design is that the voltage of the internal reference in the regulator must match the external (LM4041) voltage for the output to actually reach zero volts. In practice, the minimum output voltage from this simple circuit is a few millivolts.

Op-Amp Drives Ground Reference

The circuit of Figure 3-15 provides adjustability down to 0V by controlling the ground reference of the feedback divider. It uses the regulator's internal bandgap reference to provide both accuracy and economy. Non-inverting amplifier A2 senses V_{REF} (via V_{ADJ}) and provides a gain of just slightly more than unity. When R5 is adjusted to supply ground to voltage follower A1 then ground is also applied to the bottom of feedback voltage divider R1 and R2, and operation is identical to the standard adjustable regulator configuration, shown in Figure 3-13 (when adjusted to provide maximum output voltage). Conversely, when R5 is adjusted so the input to voltage follower A1 is taken directly from the output of amplifier A2 the bottom of voltage divider R1 and R2 is biased such that V_{ADJ} will equal V_{REF} when V_{OUT} is 0V. Rotation of R5 results in a smooth variation of output voltage from 0V to the upper design value, which is determined by R1 and R2.

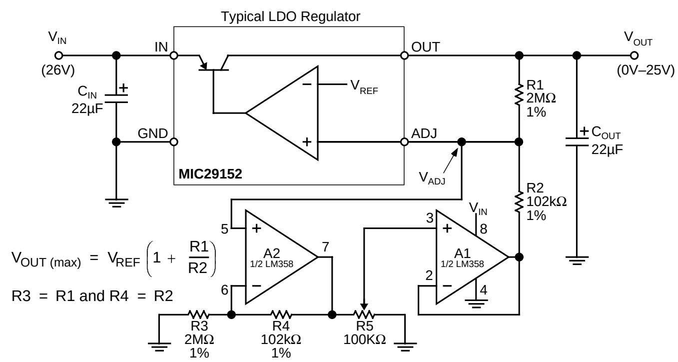


Figure 3-15. 0V-to-25V Adjustable Regulator

The gain of amplifier A2 is 1 + R4 / R3 = 1.05, in this example. Note that the portion of gain above unity is the reciprocal of the attenuation ratio afforded by feedback divider R1 and R2; i.e., R4 / R3 = 1 / (R1 / R2) To provide optimal ratio matching, resistors R3 and R4 have been chosen to be the same values and types as their counterparts R1 and R2, respectively.

Systems With Negative Supplies

A common start-up difficulty occurs if a regulator output is pulled below ground. This is possible in systems with negative power supplies. An easy fix is shown in Figure 3-16: adding a power diode, such as a 1N4001, from the regulator output to ground (with its anode to ground). This clamps the worst-case regulator output pin voltage to 0.6V or 0.7V and prevents start-up problems.

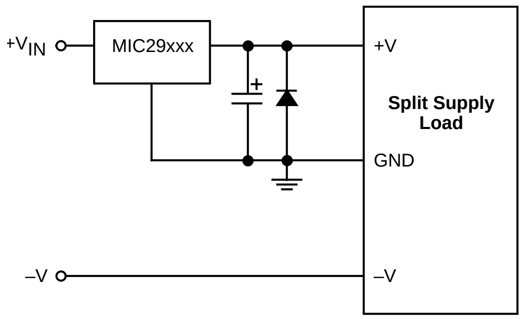


Figure 3-16. Diode Clamp Allows Start-Up in Split-Supply System

High Input Voltages

If the input voltage ranges above the maximum allowed by the regulator, a simple preregulator circuit may be employed, as shown in Figure 3-17. A preregulator is a crude regulator which drops extra voltage from the source to a value somewhat lower than the maximum input allowed by the regulator. It also helps thermal design by distributing the power dissipation between elements. The preregulator need not have good accuracy or transient response, since these parameters will be "cleaned up" by the final regulator.

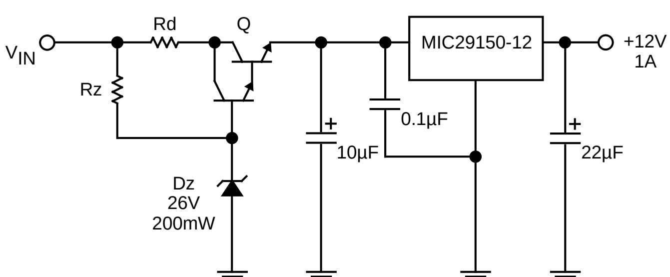


Figure 3-17. Preregulator Allows High Input Supply

Figure 3-17 shows the generic circuit. Table 3-3 provides component values for a typical application: +12V output at 1A. With up to 40V of input, no Rd is required. Above 40V, heat sinking is eased by power sharing with Rd. Note that a minimum input voltage is also listed; the composite regulator enters dropout below this minimum value. Assumptions made include a Q1 beta of 1000 and zener diode dissipation of 200mW. The MIC29150 dissipates a maximum of 13W; Q1 generates less than 15W of heat.

V_{MAX}	V_{MIN}	Rz	Rd
30V	15V	1.1kΩ	0
40V	17.5V	3.6kΩ	0
50V	23V	6.2kΩ	10Ω
60V	34V	8.87kΩ	20Ω

Table 3-3. Component Values for Figure 3-17

Controlling Voltage Regulator Turn-On Surges

When a power supply is initially activated, inrush current flows into the filter capacitors. The size of this inrush surge is dependent upon the size of the capacitors and the slew rate of the initial power-on ramp. Since this ramp plays havoc with the upstream power source, it should be minimized. Employing the minimum amount of capacitance is one method, but this technique does not solve the general problem. Slew rate limiting the power supply is a good solution to the general problem.

The turn-on time interval of a voltage regulator is essentially determined by the bandwidth of the regulator, its maximum output current (in current limit), and the load capacitance. To some extent, the rise time of the applied input voltage (which is normally quite short, tens of milliseconds, or less) also affects the turn-on time. However, the regulator output voltage typically steps abruptly at turn-on. Increasing the turn-on interval via some form of slew-limiting decreases the surge current seen by both the regulator and the system. These applications describe circuitry that changes the step-function to a smoother RC charge waveform.

Various performance differences exist between the three circuits that are presented. These are:

(1) whether stability is impacted

(2) whether start-up output voltage is 0V

(3) whether the circuit quickly recovers from a momentarily interrupted input voltage or a shorted output.

Table 3-4 summarizes each circuit's features.

Circuit Figure	Stability Impacted?	Start-Up Pedestal?	V_{IN} Interrupt Recovery?	V_{OUT} Short Recovery?
3-18	yes	1.2V	no	no
3-20	no	1.8V	no	yes
3-22	no	0V	yes	no

Table 3-4. Slow Turn-On Circuit Performance Features

The Simplest Approach

Figure 3-18 illustrates a typical LDO voltage regulator, the MIC29152, with an additional capacitor (C_T) in parallel with the series leg (R1) of the feedback voltage divider. Since the voltage (V_{ADJ}) will be maintained at V_{REF} by the regulator loop, the output of this circuit will still rapidly step to V_{REF} (and then rise slowly). Since V_{REF} is usually only about 1.2V, this eliminates a large part of the surge current.

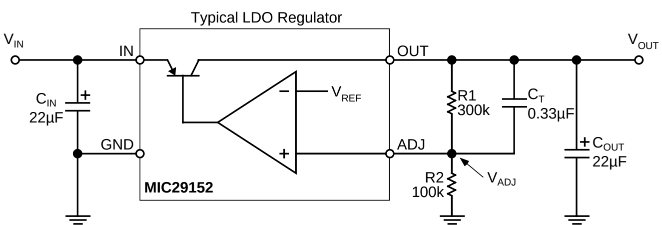


Figure 3-18. Simplest Slow Turn-On Circuit

As C_T charges, the regulator output (V_{OUT}) asymptotically approaches the desired value. If a turn-on time of 300 milliseconds is desired then about three time constants should be allowed for charge time: $3t = 0.3s$, or $t = 0.1s = R1 \times C_T = 300k\Omega \times 0.33\mu F$.

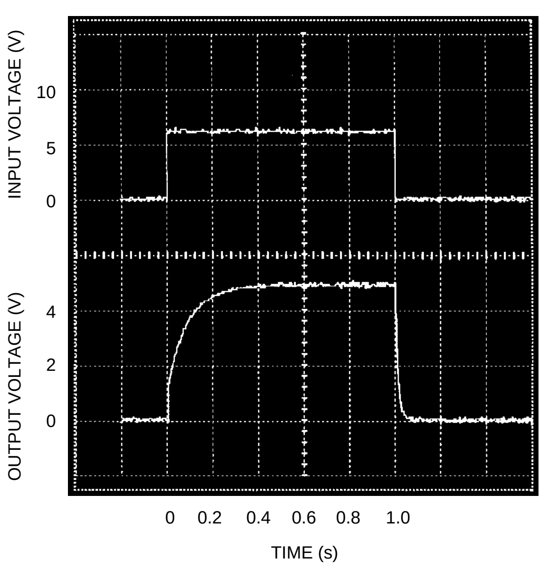


Figure 3-19. Turn-On Behavior for Circuit of Figure 3-18

Figure 3-19 shows the waveforms of the circuit of Figure 3-18. This circuit has three shortcomings: (1) the approximately 1.2V step at turn-on, (2) the addition of capacitor C_T places a zero in the closed-loop transfer function (which affects frequency and transient responses and can potentially cause stability problems) and (3) the recovery time associated with a momentarily short-circuited output may be unacceptably long[3].

Improving the Simple Approach

Figure 3-20 addresses the problems of potential instability and recovery time. Diode D1 is added to the circuit to decouple the (charged) capacitor from the feedback network, thereby eliminating the effect of C_T on the closed-loop transfer function. Because of the non-linear effect of D1 being in series with C_T, there is a slightly longer "tail" associated with approaching the final output voltage at turn-on. In the event of a momentarily shorted output, diode D2 provides a low-impedance discharge path for C_T and thus assures the desired turn-on behavior.

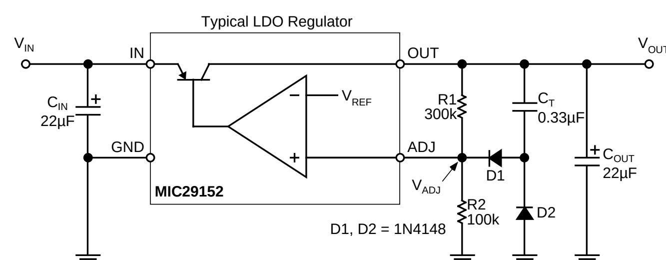


Figure 3-20. Improved Slow Turn-On Circuit

Figure 3-21 shows the waveforms of the circuit of Figure 3-20. Note that the initial step-function output is now 0.6V higher than with the circuit of Figure 3-18. This (approximately) 1.8V turn-on pedestal may

NOTE 3: This is because when the output is shorted, C_T is discharged only by R2; if the short is removed before C_T is fully discharged the regulator output will not exhibit the desired turn-on behavior.

be objectionable, especially in applications where the desired final output voltage is relatively low.

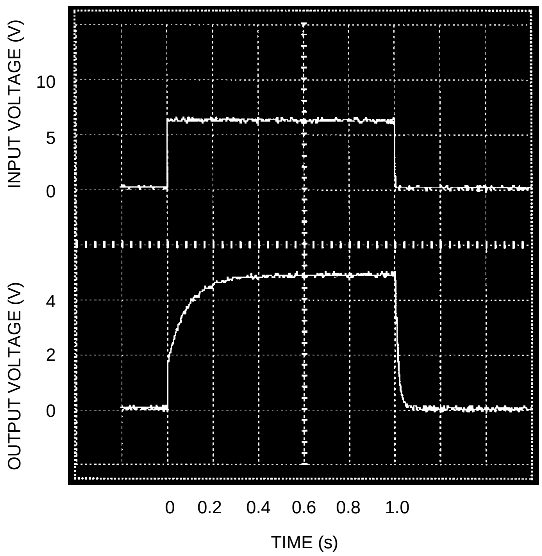


Figure 3-21. Turn-On Behavior of Figure 3-20

Eliminating Initial Start-Up Pedestal

The circuits of Figures 3-18 and 3-19 depend upon the existence of an output voltage (to create V_{ADJ}) and, therefore, produce the initial step-function voltage pedestals of about 1.2V and 1.8V, as can be seen in Figures 3-19 and 3-21, respectively. The approach of Figure 3-22 facilitates placing the output voltage origin at zero volts because $V_{CONTROL}$ is derived from the input voltage. No reactive component is added to the feedback circuit. The value of R_T should be considerably smaller than R3 to assure that the junction of R_T and C_T acts like a voltage source driving R3 and so R_T is the primary timing control. If sufficient current is introduced into the loop summing junction (via R3) to generate $V_{ADJ} \geq V_{REF}$, then V_{OUT} will be zero volts. As R_T charges C_T, $V_{CONTROL}$ decays, which would eventually result in $V_{ADJ} < V_{REF}$. In normal operation, $V_{ADJ} = V_{REF}$, so V_{OUT} becomes greater than zero volts. The process continues until $V_{CONTROL}$ decays to V_{REF} + 0.6V and V_{OUT} reaches the desired value. This circuit requires a regulator with an enable function, (such as the MIC29152) because a small (< 2V) spike is generated coincident with application of a step-function input voltage. Capacitor C1 and resistor R4 provide a short hold-off timing function that eliminates this spike.

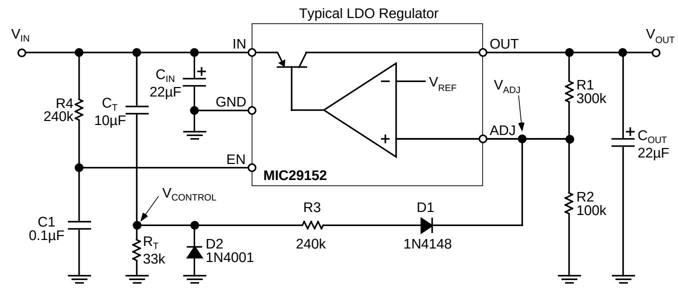


Figure 3-22. Slow Turn-On Without Pedestal Voltage

Figure 3-23 illustrates the timing of this operation. The small initial delay (about 40 milliseconds) is the time interval during which $V_{ADJ} > V_{REF}$. Since V_{IN} is usually fairly consistent in value R3 may be chosen to minimize this delay. Note that if R3 is calculated based on the minimum foreseen V_{IN} (as described below), then higher values of V_{IN} will produce additional delay before the turn-on ramp begins. Conversely, if V_{IN}(max) is used for the calculation of R3, then lower values of V_{IN} will not produce the desired turn-on characteristic; instead, there will be a small initial step-function prior to the desired turn-on ramp. Recovery from a momentarily shorted output is not addressed by this circuit, but interrupted input voltage is handled properly. Notice that the buildup of regulator output voltage differs from the waveforms of Figures 3-19 and 3-21 in that it is more ramp-like (less logarithmic). This is because only an initial portion of the RC charge waveform is used; i.e., while $V_{CONTROL} > V_{REF}$ + 0.6V. The actual time constant used for Figure 3-22 is 0.33 second, so 3t is one second. As shown by Figure 3-23, this provides about 600 milliseconds of ramp time, which corresponds to the first 60% of the capacitor RC charge curve. R3 is calculated as follows:

at turn-on time force V_{ADJ} = 1.5V

(*just slightly higher than* V_{REF})

then $$I_{CONTROL} = \frac{1.5V}{\left(\frac{R1 \times R2}{R1 + R2}\right)}$$

and $$R3 = \frac{V_{IN\,min} - 0.6V}{I_{CONTROL}}$$

Since the MIC29152 is a low-dropout regulator, 6V was chosen for V_{IN}(min). This corresponds to the small (approximately 40msec) delay before the out-

put begins to rise. With 7V input the initial delay is considerably more noticeable.

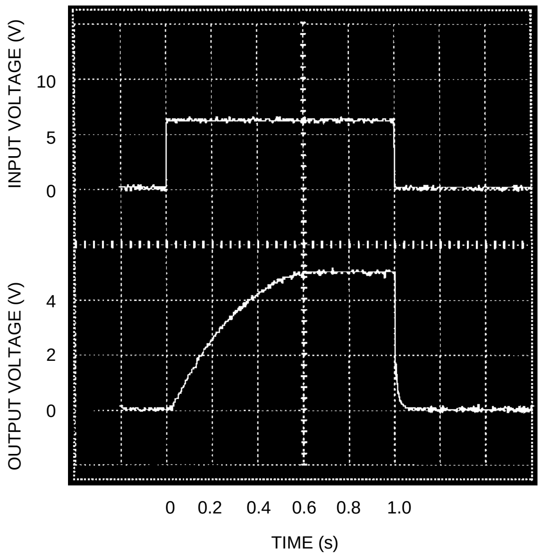


Figure 3-23. Turn-On Behavior of Figure 3-22

Current Sources

Another major application for voltage regulators is current sources. Among other uses, most rechargeable batteries need some type of constant current chargers.

Simple Current Source

Several techniques for generating accurate output currents exist. The simplest uses a single resistor in the ground return lead (Figure 3-24). This technique works with all Micrel adjustable regulators except for the MIC5205 or the MIC5206. The output current is $V_{REF} \div R$. A drawback of this simple circuit is that power supply ground and load ground are not common. Also, compliance ranges from 0V to only $V_{OUT} - (V_{DO} + V_{REF})$.

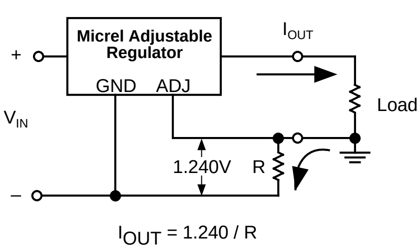


Figure 3-24. Simple Current Source Uses Reference Resistor in –V Return

The Super LDO Current Source

The adjustable Super LDOs, MIC5156 and MIC5158, feature linear current limiting. This is referenced to an internal 35mV source. A simple, high efficiency, high output current source may be built (Figure 3-25). Current source compliance is excellent, ranging from zero volts to V_{IN} – dropout, which is only $I_{OUT} \times R_{DS\,(ON)}$ + 35mV (generally only a few hundred millivolts even at 10A). Output current is

$$I_{OUT} = 35mV \div Rs$$

This circuit suffers from relatively poor accuracy, however, since the 35mV threshold is not production trimmed. R1 and R2 allow clamping the output voltage to a maximum value, if desired.

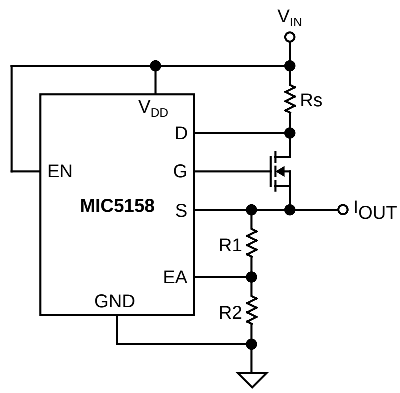


Figure 3-25. Simple Current Source Using the Super LDO

Accurate Current Source Using Op Amps

High accuracy and maintaining a common ground are both possible with an alternative circuit using two op amps and a low current MOSFET (Figure 3-26). This technique works with all Micrel adjustable regulators except for the MIC52xx series. Compliance is from 0V to $V_{IN} - V_{DO}$.

A Low-Cost 12V & 5V Power Supply

Taking advantage of the low-dropout voltage capability of Micrel's regulators, we may build a dual output 12V & 5V linear power supply with excellent efficiency using a low cost 12.6V center-tapped "filament" transformer.

Figure 3-27 shows the schematic for the simple power supply. Using a single center-tapped transformer and one bridge rectifier, both 12V and 5V outputs are available. Efficiency is high because the transformer's RMS output voltage is only slightly above our desired outputs. The 12.6V center tapped

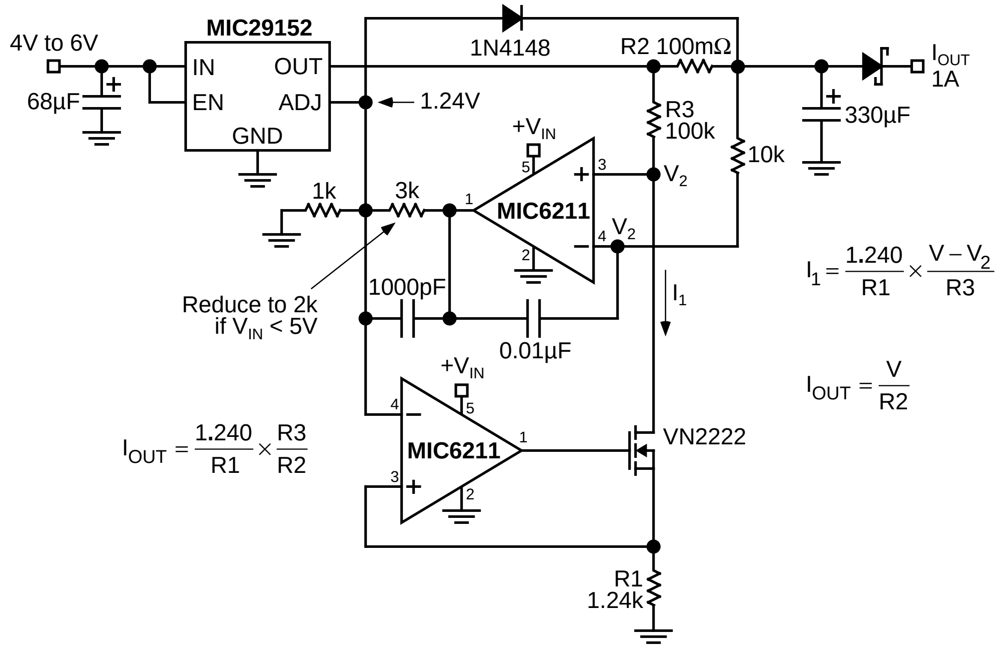


Figure 3-26. Current Source Using a Pair of Op-Amps

filament transformer is a decades-old design originally used for powering vacuum tube heaters. It is perhaps the most common transformer made. The outside windings feed the bridge rectifier and filter capacitor for the 12V output. A MIC29150-12 produces the regulated 12V output. The transformer center tap feeds the 5V filter capacitor and the MIC29150-5.0 directly—*no rectifier diode is needed.*

This circuit may be scaled to other output currents as desired. Overall efficiency is extremely high due to the low input voltage, so heat sinking requirements are minimal. A final benefit: since the power tabs of the TO-220 packages are at ground potential, a single non-isolated, non-insulated heat sink may be used for both regulators.

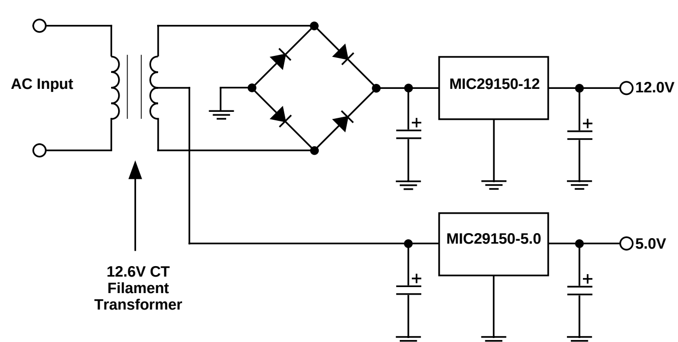


Figure 3-27. A Dual-Output Power Supply From a Single Transformer and Bridge Rectifier

Computer Power Supplies

The decreasing silicon geometries of microprocessors and memory have forced a reduction in operating voltage from the longtime standard of 5V. This rise of sub-5V microprocessors, logic, and memory components in personal computer systems created demand for lower voltage power supplies. Several options exist for the desktop computer system designer. One of these options is to provide both 3.3V and 5.0V from the main system power supply. Another is to use the existing high current 5V supply and employ a low dropout (LDO) linear regulator to provide 3.3V.

The low-cost, production proven desktop computer power supplies output ±5V and ±12V—but not 3V. Redesigning the system power supply would increase cost and break the long standing power supply to motherboard connector standard which has no provision for 3V. Further complicating matters is that “3V” is not really defined. Microprocessor manufacturers produce devices requiring 2.9V, 3.3V, 3.38V, 3.45V, 3.525V, 3.6V, and several other similar voltages. No single standard has been adopted. Designing and stocking dedicated power supplies for all of these different voltages would be extremely difficult and expensive. Also, motherboard makers want to maximize their available market by allowing as many different microprocessors as possible on each board; this means they must design an on-board supply that produces all of the most popular voltages to remain competitive. This is even more important for the motherboard vendors who sell boards sans-microprocessor. They must not only provide the expected voltages, they must simplify the selection process so that all system integrators—and even some end users—may configure the voltage properly. With too low an operating voltage, the microprocessor will generate errors; too high a voltage is fatal.

Instead, system integrators use motherboards with an on-board power supply, which converts the readily available +5V source into the required low voltage output. The simplest, lowest cost solution for this problem is the modern, very low dropout version of the venerable linear regulator. This is a low cost option, requiring only quick design work and little motherboard space. Linear regulators provide clean, accurate output and do not radiate RFI, so government certification is not jeopardized. Adjustable linear regulators allow voltage selection by means of jumper-selected resistors. They are fast starting, and may optionally provide ON/OFF control and an error flag that indicates power system trouble.

Dropout Requirements

While linear regulators are extremely easy to use, one design factor must be considered: dropout voltage. For example, a regulator with 2 volts of dropout producing a 3.3V output requires over 5.3 volts on its input. Furthermore, reliable circuit operation requires operating a linear regulator above its dropout region—in other words, with a higher than minimum input voltage. In dropout, the regulator is not regulating and it responds sluggishly to load changes.

What is the required dropout voltage performance? Let’s assume we have a 5V supply and need to provide 3.525V to our microprocessor. The worst case occurs when the input voltage from the 5V supply is at its minimum and the output is at its maximum. An example will illustrate.

V_{IN} =	5V – 5% =	4.75V
V_{OUT} =	3.525V + 2% =	3.60V
Maximum Allowable Dropout Voltage:		1.15V

This simplified example does not include the effects of power supply connector, microprocessor socket, or PC board trace resistances, which would further subtract from the required dropout voltage. Fast response to load current changes (from a processor recovering from “sleep” mode, for example) occurs only when the regulator is away from its dropout point. In real systems, a maximum dropout voltage between 0.6V to 1V is ideal. Achieving this performance means the output device must be either a PNP bipolar transistor or a MOSFET.

Historically, linear regulators with PNP outputs have been expensive and limited to low current applications. However, Super ßeta PNP low dropout regulators provide up to 7.5 amperes of current with dropout voltages less than 0.6V, guaranteed. A lower cost product line outputs the same currents with only 1V of dropout. These low dropout voltages guarantee the microprocessor gets a clean, well regulated supply that quickly reacts to processor-induced load changes as well as input supply variations.

The low dropout linear voltage regulator is an easy-to-use, low cost, yet high performance means

of powering high performance low voltage microprocessors. By selecting a modern low dropout regulator, you assure reliable operation under all working conditions.

5V to 3.xV Conversion Circuits

Recommended circuits for on-board desktop computer power supplies follow. Due to the high speed load changes common to microprocessors, fast load transient response is crucial. This means circuit layout and bypass and filter capacitor selection is also critical. At low current levels, thermal considerations are not difficult; however, at currents of above 3 amperes, the resulting heat may be troublesome.

Method 1: Use a Monolithic LDO

The simplest method of providing a second V_{CC} on a computer motherboard is by using a monolithic regulator. If the required voltage is a standard value, a fixed-voltage regulator is available. In this ideal situation, your electrical design consists of merely specifying a suitable output filter capacitor. If the output voltage is not available from a fixed regulator, adjustables are used. They use two resistors to program the output voltage but are otherwise similar to the fixed versions. Figure 3-28 and 3-29 show fixed and adjustable regulator applications.

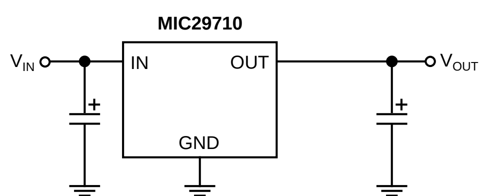
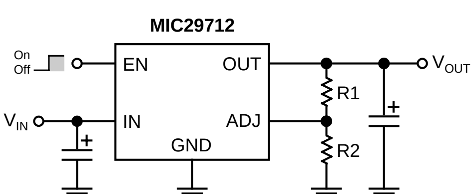


Figure 3-28. Fixed Regulator Circuit Suitable for Computer Power Supply Applications



$$V_{OUT} = 1.240\left(\frac{R1}{R2}+1\right)$$

Figure 3-29. Adjustable Regulator Circuit Suitable for Computer Power Supply Applications

Method 2: The MIC5156 "Super LDO"

The Micrel MIC5156 is a linear regulator controller that works with a low cost N-Channel power MOSFET to produce a very low dropout regulator system. The MIC5156 is available in a small 8-pin SOIC or in a standard 8-pin DIP, and offers fixed 3.3V, 5.0V, or user selectable (adjustable) voltage outputs. Figure 2 shows the entire schematic—two filter capacitors, a MOSFET, and a printed circuit board trace about a centimeter long (used as a current sense resistor) is all you need for the fixed voltage version. For the adjustable part, add two resistors. The MIC5156 requires an additional power supply to provide gate drive for the MOSFET: use your PC's 12V supply—the current drawn from the 12V supply is very small; approximately one milliampere. If a 12V supply is not available, the MIC5158 generates its own bias and does not need an additional supply.

Figure 3-30 shows a typical 3.3V and 5V computer power supply application. The MIC5156 provides regulated 3.3V using Q1 as the pass element and also controls a MOSFET switch for the 5V supply.

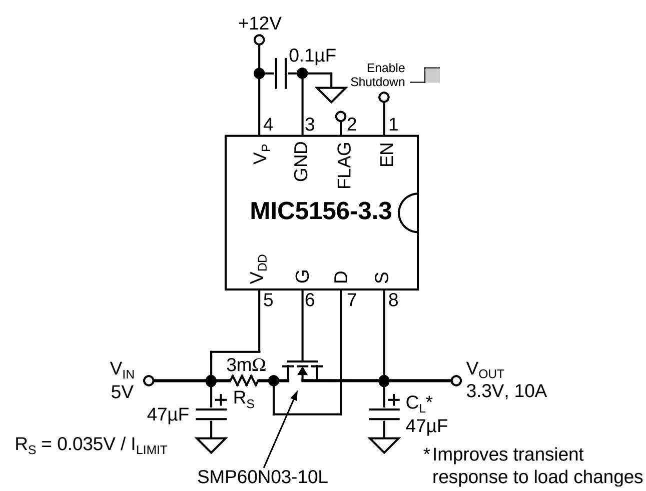


Figure 3-30. MIC5156 5V-to-3.3V Converter

When the 3.3V output has reached regulation, the FLAG output goes high, enhancing Q2, which switches 5V to Load 2. This circuit complies with the requirements of some dual-voltage microprocessors that require the 5V supply input to remain below 3.0V until the 3.3V supply input is greater than 3.0V.

An optional current limiting sense resistor (R_S) limits the load current to 12A maximum. For less costly designs, the sense resistor's value and function can be duplicated using one of two techniques: A solid piece of copper wire with appropriate length and di-

ameter (gauge) makes a reasonably accurate low-value resistor. Another method uses a printed circuit trace to create the sense resistor. The resistance value is a function of the trace thickness, width, and length. See *Alternative Resistors*, in **Section 4**, for current sense resistor details.

NOTE: the tab of the power MOSFET is connected to +5V. Use an insulator between the MOSFET and the heat sink, if necessary.

Method 3: The MIC5158 "Super LDO"

Like the MIC5156, the MIC5158 is a linear regulator controller that works with a low cost N-Channel power MOSFET to produce a very low dropout regulator system. The MIC5158, however, generates the bias voltage required to drive the N-channel MOSFET and does not require a 12V supply. Its on-board charge pump uses three capacitors and takes care of the level shifting. Figure 3-31 shows the MIC5158 circuit.

An idea for the motherboard manufacturer: build the MIC5158 circuit on a plug-in daughterboard with three or five pins that allow it to mount on the system board like a monolithic regulator.

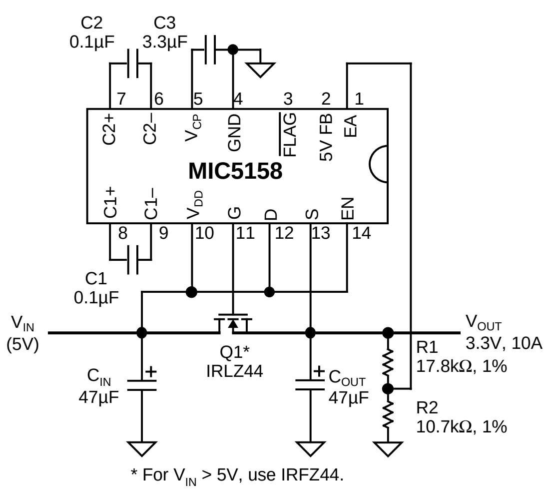


Figure 3-31. MIC5158 5V-to-3.3V Converter

Method 4: Current Boost a MIC2951

The 150mA MIC2951 gets a capacity boost to several amperes by using an external PNP transistor. Figure 3-32 shows the MIC2951 driving a DH45H8 or equivalent PNP transistor to achieve a 3A output. This circuit has a number of problems, including poor stability (a large output capacitor is required to squelch oscillations), poor current limiting characteristics, poor load transient response, no overtemperature shutdown protection, and requires numerous external components. It is not recommended.

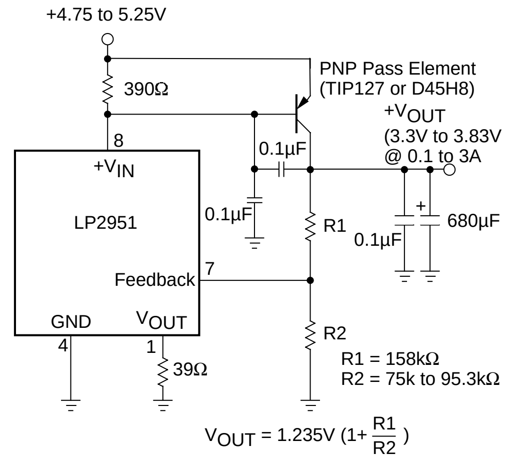


Figure 3-32. PNP Transistor Boosts Current Output From MIC2951 Regulator

Adjust Resistor Values

Table 3-5 shows recommended resistor values for various voltages. The values shown represent the calculated closest-match for the desired voltage using standard 1% tolerance resistors. Since Micrel's adjustable regulators use a high impedance feedback stage, large value adjust resistors are generally recommended. Valid resistor values range from a few ohms to about 500kΩ.

While the MIC29152/29302/29502 have a 1.240V reference, the Super LDO and current boosted MIC2951 circuits use a 1.235V reference.

	Figs. 3-28 & 29 (V_{REF} = 1.240V)		Figs. 3-30, 31, & 32 (V_{REF} = 1.235V)	
Voltage	**R1**	**R2**	**R1**	**R2**
1.5	80.6k	16.9k	53.6k	11.5k
1.8	237k	107k	301k	137k
2.85	287k	221k	187k	143k
2.9	162k	121k	137k	102k
3.0	102k	71.5k	150k	105k
3.1	158k	105k	154k	102k
3.15	191k	124k	158k	102k
3.3	196k	118k	178k	107k
3.45	221k	124k	191k	107k
3.6	102k	53.6k	383k	200k
3.8	221k	107k	221k	107k
4.0	255k	115k	115k	51.1k
4.1	316k	137k	232k	100k
4.5	137k	52.3k	107k	40.2k

Table 3-5. Suggested Adjust Resistor Values

3.3V to 2.xV Conversion

Like the 5V to 3.3V conversion discussed above, dropping to voltages below 3.3V from a 3.3V rail is a useful application for LDO regulators. Here, the regulator dropout voltage is much more critical. Applications using 2.9V only have 400mV of headroom when powered from a perfect 3.3V supply. For the standard 3.3V supply tolerance of ±300mV, the headroom drops to only 100mV. For this situation, the most reasonable solution is one of the Super LDO circuits shown in Figures 3-30 and 3-31. These circuits feature excellent efficiency—approximately 88%. Monolithic LDO solutions powered from a standard 3.3V ± 300mV supply become tenable with output voltages of 2.5V or below.

Improving Transient Response

Modern low-voltage microprocessors have multiple operating modes to maximize both performance and minimize power consumption. They switch between these modes quickly, however, which places a strain on their power supply. Supply current variations of several orders of magnitude in tens of nanoseconds are standard for some processors—and they still require that their supply voltage remain within specification throughout these transitions.

Micrel low-dropout regulators have excellent response to variations in input voltage and load current. By virtue of their low dropout voltage, these devices do not saturate into dropout as readily as similar NPN-based designs. A 3.3V output Super βeta PNP LDO will maintain full speed and performance with an input supply as low as 4.2V, and will still provide some regulation with supplies down to 3.8V, unlike NPN devices that require 5.1V or more for good performance and become nothing more than a resistor under 4.6V of input. Micrel's PNP regulators provide superior performance in "5V to 3.3V" conversion applications, especially when all tolerances are considered.

Figure 3-33 is a test schematic using the Intel® Pentium™ Validator. The Validator is a dynamic load which simulates a Pentium processor changing states at high speed. Using Figure 3-33, the MIC29512 (Figure 3-34) was tested with fast 200mA to 5A load transitions. The MIC29712 was tested with fast transitions between 200mA and 7.5A (Figure 3-35).

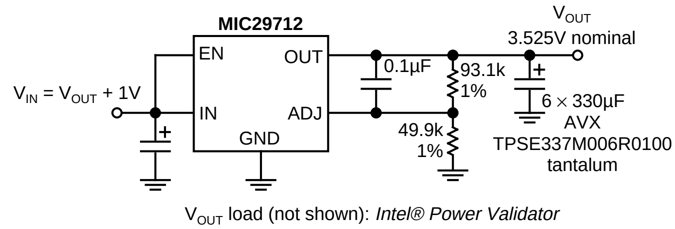


Figure 3-33. Load Transient Response Test Circuit. Super LDO System Driving an Intel Pentium "Validator" Test System

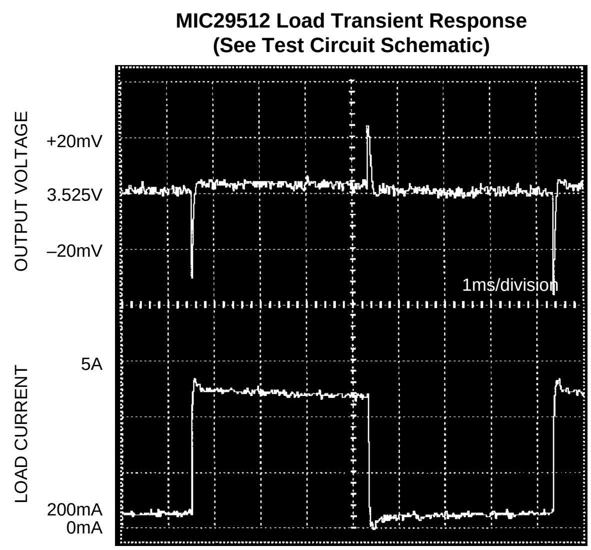


Figure 3-34. MIC29512 Load Transient Response

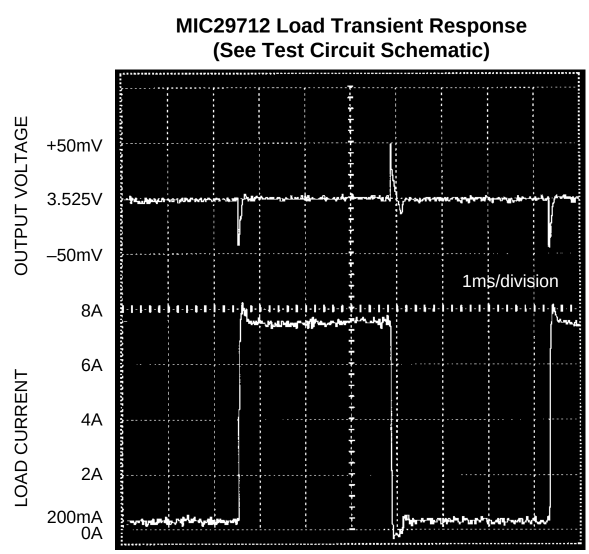


Figure 3-35. MIC29712 Load Transient Response. Load Varies from 200mA to 7.5A

The following photographs show the transient response of the MIC5156 Super LDO with an IRL3103 power MOSFET ($R_{DS (ON)} \leq 14m\Omega$, Ciss = 1600pF) driving the Intel Pentium™ Validator. Figure 3-36 shows the performance with four (4) 330µF AVX surface mount capacitors. The peak transient response voltage is –55mV on attack and +60mV on turn-off. Figure 3-37 shows the tremendous improvement another four 330µF capacitors make: with eight (8) 330µF AVX capacitors, the transient peaks drop to only approximately ±25mV. These measurements are made with V_{DD} = 5.0V, V_P = 12.0V, and a single 330µF bypass capacitor on the V_{DD} input to the MIC5156. As both the 5156 and the MIC5158 use the same error amplifier circuit, their transient response should be similar. Furthermore, the transient response of the MIC5156 does not change as the input voltage (V_{DD}) decreases from 5.0V down to nearly dropout levels (a bit less than 3.6V input with the 3.525V output).

Accuracy Requirements

Microprocessors have various voltage tolerance requirements. Some are happy with supplies that swing a full ±10%, while others need better than ±2.5% accuracy for proper operation. Fixed 3.3V devices operate well with any of these microprocessors, since Micrel guarantees better than ±2% across the operating load current and temperature ranges. Locating the regulator close to the processor to minimize lead resistance and inductance is the only design consideration that is necessary. Microprocessors that use nonstandard or varying voltages have a problem: while the basic adjustable regulator offers ±1% accuracy and ±2% worst case over temperature extremes, any error in the external programming resistors (either in tolerance or compromise in resistance ratio that is unavoidable when using standardized resistor values) directly appears as output voltage error. The error budget quickly disappears. See *Adjustable Regulator Accuracy Analysis*, in this section, for a discussion of voltage tolerance and sensitivity.

When any trace resistance effects are considered, it is painfully apparent that this solution will not provide the needed ±2.5% accuracy. Resistors of 0.1% tolerance are one step. Other ideas are presented in *Improving Regulator Accuracy*, also in this section.

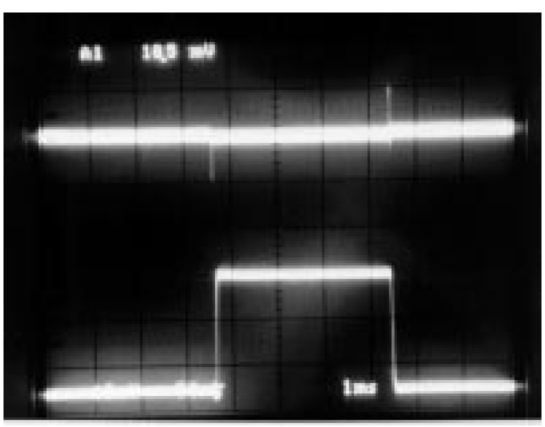


Figure 3-36. Transient response of the MIC5156 Super LDO driving an Intel Pentium "Validator" microprocessor simulator. Output capacitance is 4 × 330µF.

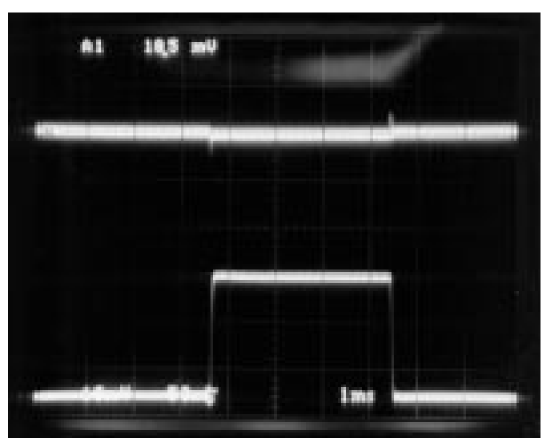


Figure 3-37. Transient response of the MIC5156 Super LDO driving an Intel Pentium "Validator" microprocessor simulator. Output capacitance is 8 × 330µF.

Multiple Output Voltages

Another design parameter computer motherboard designers cope with is the need to support different types of microprocessors with one layout. Since processors in a single family may require different voltages, it is no surprise that different processor types also may need various supply voltages. Since it is expensive to provide multiple variable outputs from the system power supply, the economical solution to this problem is to generate or switch between supplies directly on the motherboard.

Occasionally, a designer will get lucky and some motherboard options can use a standard voltage from the power supply. In this case, we may switch the higher voltage around the LDO generating the lower voltage, as shown in Figure 3-38. This circuit was designed to allow Intel DX4Processors™, running on 3.3V, to operate in the same socket as a standard 5V 486. A pin on the DX4Processor is hard wired to ground, which provides the switching needed for automatically selecting the supply voltage. Standard 486 processors have no connection to this pin.

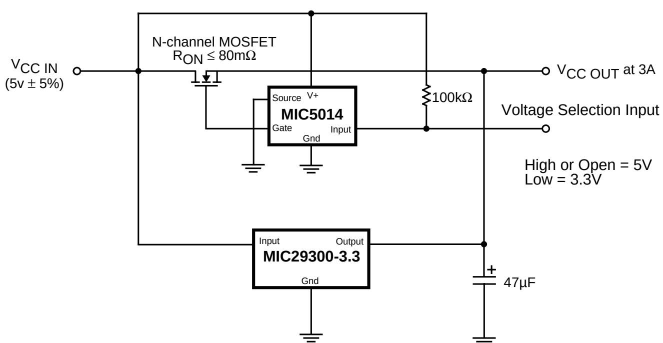


Figure 3-38. Switching 5V or 3.3V to a Microprocessor

This circuit capitalizes on the reversed-battery protection feature built into Micrel's Super βeta PNP regulators. The regulators survive a voltage forced on their output that is higher than their programmed output. In this situation, the regulator places its pass transistor in a high impedance state. Only a few microamperes of current leaks back into the regulator under these conditions, which should be negligible. Note that an adjustable regulator could be used in place of the fixed voltage version shown.

An adjustable regulator and an analog switch will perform this task, as shown in Figure 3-39. Only one supply (of the maximum desired output voltage, or higher) is necessary.

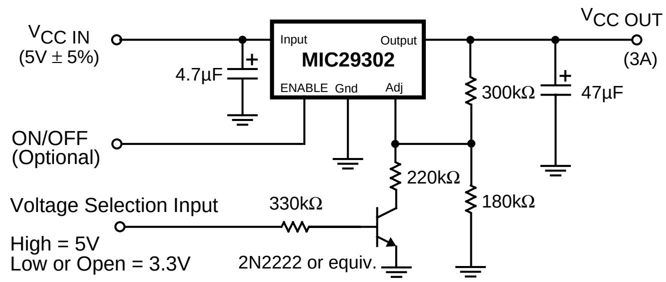


Figure 3-39. Adjustable LDO and analog switch provides selectable output voltages

Another method of providing two or more output voltages to a socket with the higher of the two provided is by using the Super LDO. Program the adjustable MIC5156 or MIC5158 as shown in Figure 3-40. When the higher of the two voltages is chosen, the regulator simply acts as a low-loss switch. Use a transistor switch to select the lower voltage. This technique may be expanded to any number of discrete voltages, if desired. The MIC5158 will operate from a single input supply of 3.0V or greater. The MIC5156 needs a low current 12V supply to provide gate bias for the pass MOSFET, but if this is available, it is smaller than the MIC5158 and requires no charge pump capacitors.

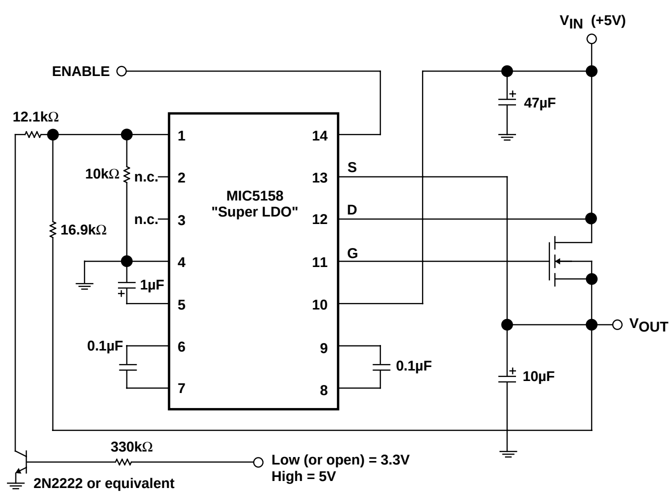
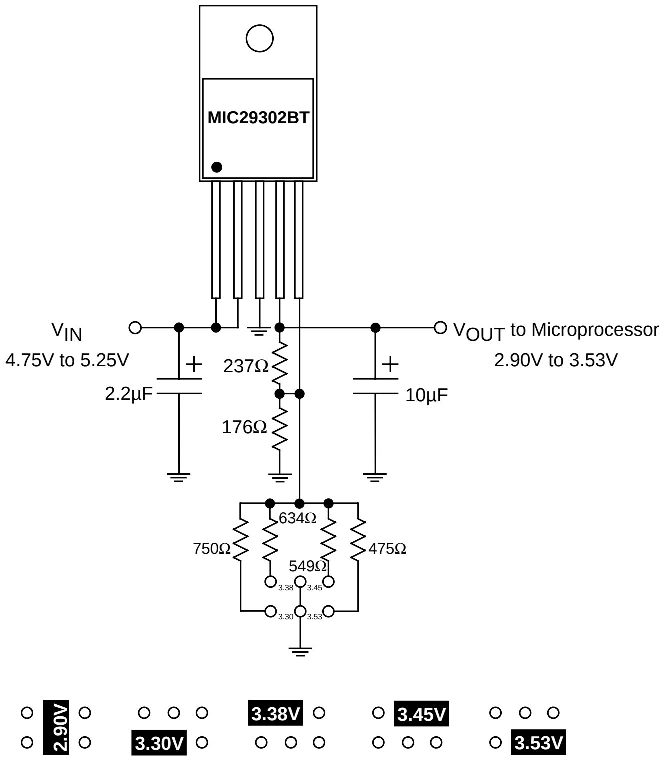


Figure 3-40. MIC5158 with Selectable Output Voltages

Figure 3-41 is a switched voltage PNP regulator that relies on jumpers for output voltage programming. While perhaps not as "elegant" as the previous techniques, it provides full functionality and flexibility. This circuit was designed so if all jumpers are accidentally removed, the output voltage drops to its lowest value. By configuring the jumpers as shown, the system is relatively safe—if someone inadvertently removes all



Voltage Jumper Positions

Figure 3-41. Jumper Selectable Output Voltages

the jumpers, the output voltage drops to a low value. While the system may be error-prone or nonfunctional with this low voltage, at least the microprocessor will survive.

Multiple Supply Sequencing

Some microprocessors use multiple supply voltages; a voltage for the core, another for the cache memory, and a different one for I/O, for example. Sequencing these supplies may be critical to prevent latch-up. Figure 3-42 shows an easy way of guaranteeing this sequencing using Micrel's regulators with an enable control. As the output voltage of Supply 1 rises above 2V, the regulator for Supply 2 starts up. Supply 2 will never be high until Supply 1 is active. Supply 1 need not be the higher output voltage; it must only be 2.4V or above (necessary to assure the second regulator is fully enabled). Note that Supply 1 may not need an enable pin.

This technique works with the MIC29151 through MIC29752 monolithic regulators as well as with the Super LDO (MIC5156/57/58). It also is applicable for systems requiring any number of sequenced supplies, although for simplicity we only show two supplies here.

Thermal Design

Once the electrical design of your power system is complete, we must deal with thermal issues. While they are not terribly difficult, thermal design is lightly covered in most electrical engineering curriculum. Properly addressing thermal issues is imperative to LDO system reliability, and is covered in detail in *Thermal Management*, later in this section.

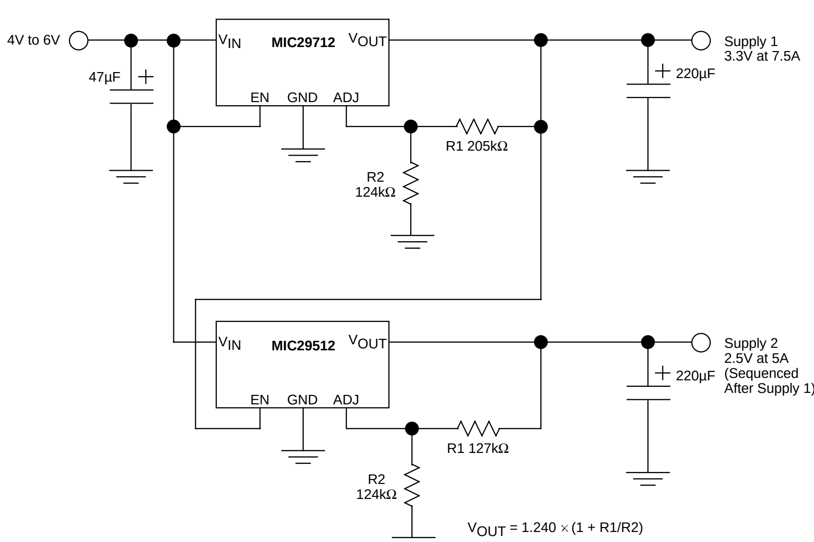


Figure 3-42. Multiple Supply Sequencing

Portable Devices

Voltage regulators are necessary in almost all electronic equipment, and portable devices are no exception. Portable equipment includes cellular and “wireless” telephones, radio receivers and handheld transceivers, calculators, pagers, notebook computers, test equipment, medical appliances and most other battery operated gear.

Design Considerations

Portable electronics are characterized by two major distinguishing features:

- Small size
- Self-contained power source (batteries)

Beyond these similarities, portable equipment power requirements vary as much as their intended application.

Small Package Needed

Portable devices are, by definition, relatively small and lightweight. Most circuitry is surface mounted and power dissipation is normally minimized.

Self Contained Power

Most portable equipment is battery powered. Batteries are often the largest and heaviest component in the system, and may account for 80% or more of the total volume and mass of the portable device. Power conservation is an important design consideration. Low power components are used and power management techniques, such as “sleep mode”, help maximize battery life. Just as one is never too rich, one’s batteries never last long enough!

Yet another battery-imposed limitation is that batteries are available in discrete voltages, determined by their chemical composition. Converting these voltages into a constant supply suitable for electronics is the regulator’s most important task.

Low Current (And Low Voltage)

The regulators used in portable equipment are usually low output current devices, generally under 250mA, since their loads are also (usually) low current. Few portable devices have high voltage loads[4] and those that do need little current.

Low Output Noise Requirement

Cellular telephones, pagers, and other radios have frequency synthesizers, preamplifiers, and mixers that are susceptible to power supply noise. The frequency synthesizer voltage controlled oscillator (VCO), the block that determines operating frequency, may produce a noisy sine wave output (a wider bandwidth signal) if noise is present on V_{CC}. Making matters worse for portable equipment designers, lower powered/lower cost VCOs are generally more susceptible to V_{CC} noise.

Ideal VCOs produce a single spectral line at the operating frequency. Real oscillators have sideband skirts; poor devices have broad skirts. Figure 3-43 shows the measured phase noise from a free running Murata MQE001-953 VCO powered by a MIC5205 low-noise regulator. Note the significant improvement when using the noise bypass capacitor. Regulators not optimized for noise performance produce skirts similar to or worse than the MIC5205 without bypass capacitors.

Broad oscillator skirts decrease the noise figure and the strong signal rejection capability of receivers (reducing performance) and broaden the transmitted signal in transmitters (possibly in violation of spectral purity regulations).

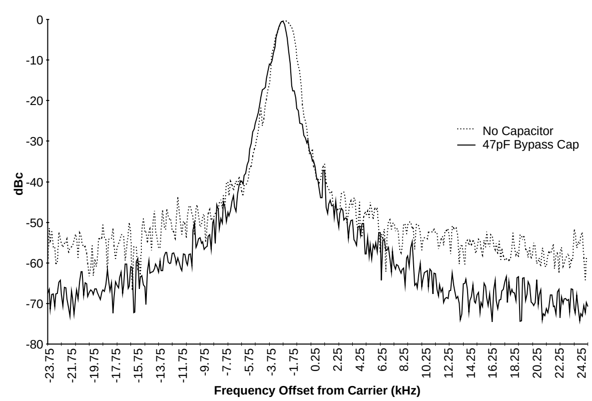


Figure 3-43. A Low-Noise LDO (MIC5205) Reduces VCO Phase Noise

Although not as susceptible to noise as VCOs, preamplifiers and mixers operating from noisy supplies also reduce receiver and transmitter performance in similar ways.

NOTE 4: The notable exceptions to this statement are the fluorescent backlights in notebook computers and the electroluminescent lamps in telephones, watches, etc. These lamps must be driven with a switching regulator that boosts the battery voltage—something a linear regulator cannot do.

Dropout and Battery Life

Low dropout regulators allow more operating lifetime from batteries by generating usable output to the load well after standard regulators would be saturated. This allows discharging batteries to lower levels or—in many cases—eliminating a cell or two from a series string. Compared to older style regulators with 2 to 3V of dropout, Micrel's 0.3V to 0.6V LDOs allow eliminating one to two alkaline, NiCd, or NiMH cells.

Ground Current and Battery Life

The quiescent, or ground, current of regulators employed inside portable equipment is also important. This current is yet another load for the battery, and should be minimized.

Battery Stretching Techniques

Sleep Mode Switching

Sleep mode switching is an important technique for battery powered devices. Basically, sleep mode switching powers down system blocks not immediately required. For example, while a cellular phone must monitor for an incoming call, its transmitter is not needed and should draw no power; it can be shut off. Likewise, audio circuits may be powered down. Portable computers use sleep mode switching by spinning down the hard disk drive and powering down the video display backlight, for example. Simpler devices like calculators automatically turn off after a certain period of inactivity.

Micrel's LDO regulators make sleep mode implementation easy because each family has a version with logic-compatible shutdown control. Many families feature "zero power" shutdown—when disabled, the regulator fully powers down and draws virtually zero current.[5] Designers updating older systems that used MOSFETs for switching power to regulators may now eliminate the MOSFET. The regulator serves as switch, voltage regulator, current limiter, and overtemperature protector. All are important features in any type of portable equipment.

Power Sequencing

A technique related to Sleep Mode Switching is Power Sequencing. This is a power control technique that enables power blocks for a short while and then disables them. For example, in a cellular telephone awaiting a call, the receiver power may be pulsed on and off at a low-to-medium duty cycle. It listens for a few milliseconds each few hundred milliseconds.

Multiple Regulators Provide Isolation

The close proximity between different circuit blocks naturally required by portable equipment increases the possibility of interstage coupling and interference. Digital noise from the microprocessor may interfere with a sensitive VCO or a receiver preamplifier, for example. A common path for this noise is the common supply bus. Linear regulators help this situation by providing active isolation between load and input supply. Noise from a load that appears on the regulator's output is greatly attenuated on the regulator's input.

Figure 3-44 shows a simplified block diagram of a cellular telephone power distribution system. Between five and seven regulators are used in a typical telephone, providing regulation, ON/OFF (sleep mode) switching, and active isolation between stages.

NOTE 5: In the real world, there is no such thing as zero, but Micrel's regulators pass only nanoamperes of device leakage current when disabled—"virtually zero" current.

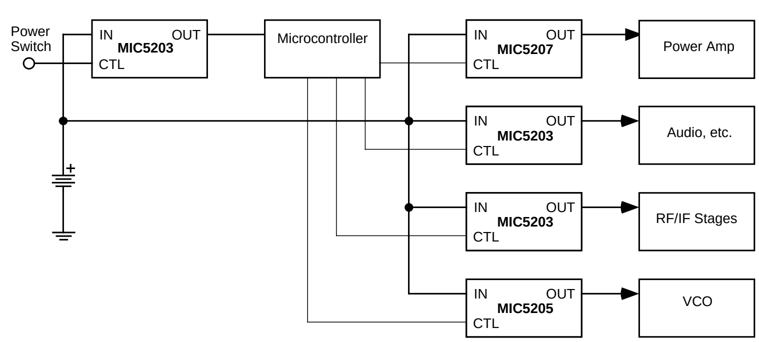


Figure 3-44. Cellular Telephone Block Diagram

Thermal Management

A Thermal Primer

Micrel low dropout (LDO) regulators are very easy to use. Only one external filter capacitor is necessary for operation, so the electrical design effort is minimal. In many cases, thermal design is also quite simple, aided by the low dropout characteristic of Micrel's LDOs. Unlike other linear regulators, Micrel's LDOs operate with dropout voltages of 300mV–often less. The resulting Voltage × Current power loss can be quite small even with moderate output current. At higher currents and/or higher input-to-output voltage differentials, however, selecting the correct heat sink is an essential "chore".

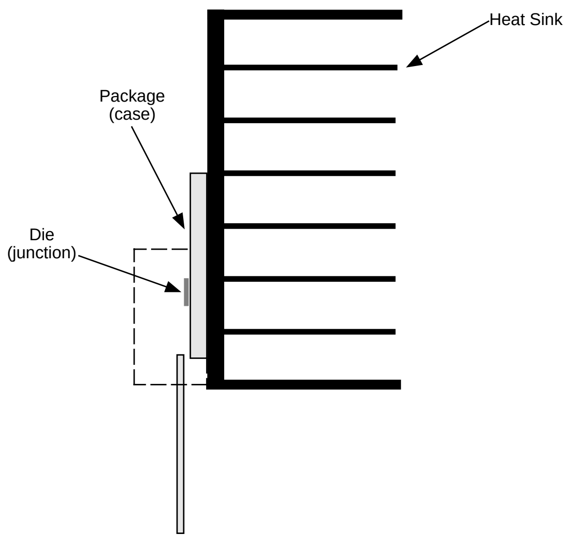


Figure 3-45. Regulator Mounted to a Heat Sink

Thermal Parameters

Before working with thermal parameters, we will define the applicable symbols and terms.

ΔT	Temperature rise (temperature difference, °C)
q	Heat flow (Watts)
θ	Thermal resistance (°C/W)
P_D	Power Dissipation (Watts)
θ_{JA}	Thermal resistance, junction (die) to ambient (free air)
θ_{JC}	Thermal resistance, junction (die) to the package (case)
θ_{CS}	Thermal resistance, case (package) to the heat sink
θ_{SA}	Thermal resistance, heat sink to ambient (free air)
T_A	Ambient temperature
T_J	Junction (die) temperature
$T_{J(MAX)}$	Maximum allowable junction temperature

Figure 3-46 shows the thermal terms as they apply to linear regulators. The "junction" or "die" is the active semiconductor regulator; this is the heat source. The package shown is the standard TO-220; the "case" is the metal tab forming the back of the package which acts as a heat spreader. The heat sink is the interface between the package and the ambient environment. Between each element—junction, package, heat sink, and ambient—there exists interface thermal resistance. Between the die and the package is the junction to case thermal resistance, θ_{JC}. Between the package and the heat sink is the case-to-sink thermal resistance, θ_{CS}. And between the heat sink and the external surroundings is the heat sink to ambient thermal resistance, θ_{SA}. The total path from the die to ambient is θ_{JA}.

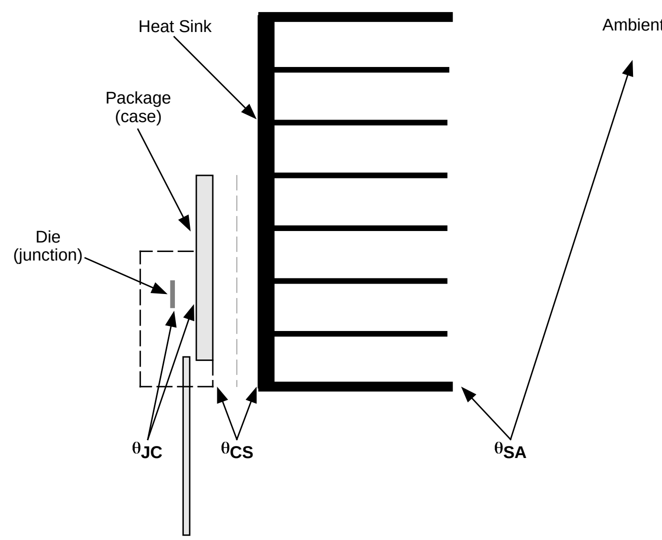


Figure 3-46. Thermal Parameters

Thermal/Electrical Analogy

For those of us more comfortable with the laws of Kirchhoff and Ohm than those of Boyle or Celsius, an electrical metaphor simplifies thermal analysis. Heat flow and current flow have similar characteristics. Table 3-6 shows the general analogy.

Thermal Parameter	Electrical Parameter
Power (q)	Current (I)
Thermal Resistance (θ)	Resistance (R)
Temperature Difference (ΔT)	Voltage (V)

Table 3-6. Thermal/Electrical Analogy

The formula for constant heat flow is:

$\theta = \Delta T / q$

The equivalent electrical (Ohm's Law) form is:

$I = \Delta V / R$

Electrically, a voltage difference across a resistor produces current flow. Thermally, a temperature gradient across a thermal resistance creates heat flow. From this, we deduce that if we dissipate power as heat and need to minimize temperature rise, we must minimize the thermal resistance. Taken another way, if we have a given thermal resistance, dissipating more power will increase the temperature rise.

Thermal resistances act like electrical resistances: in series, they add; in parallel, their reciprocals add and the resulting sum is inverted. The general problem of heat sinking power semiconductors may be simplified to the following electrical schematic (Figure 3-47).

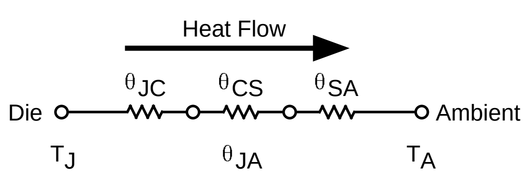


Figure 3-47. Heat flow through the interface resistances.

Summing these resistances, the total thermal path for heat generated by the regulator die is:

$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$

Calculating Thermal Parameters

Two types of thermal parameters exist; those we may control and those fixed by the application (or physics). The application itself determines which category the parameters fit—some systems have a specific form factor dictated by other factors, for example. This serves to limit the maximum heat sink size possible.

Parameter	Extenuating Circumstances
θ_{SA}	Set by heat sink size, design and air flow
θ_{JC}	Set by regulator die size and package type
θ_{CS}	Set by mounting technique and package type
$T_{J(MAX)}$	Set by regulator manufacturer and lifetime considerations
Power dissipation	Set by V_{IN}, V_{OUT}, and I_{OUT}

Each regulator data sheet specifies the junction to case thermal resistance, θ_{JC}. Heat sink manufacturers specify θ_{SA}, (often graphically) for each product. And θ_{CS} is generally small compared to θ_{JC}. The maximum die temperature for Micrel regulators is generally 125°C, unless specified otherwise on the data sheet. The last remaining variable is the regulator power dissipation.

Power dissipation in a linear regulator is:

$P_D = [(V_{IN} - V_{OUT}) I_{OUT}] + (V_{IN} \times I_{GND})$

Where:

P_D = Power dissipation

V_{IN} = Input voltage applied to the regulator

V_{OUT} = Regulator output voltage

I_{OUT} = Regulator output current

I_{GND} = Regulator biasing currents

Proper design dictates use of worst case values for all parameters. Worst case V_{IN} is high supply. Worst case V_{OUT} for thermal considerations is the lowest possible output voltage, subtracting all tolerances from the nominal output. I_{OUT} is taken at its highest steady-state value. The ground current value comes from the device's data sheet, from the graph of I_{GND} vs. I_{OUT}.

Calculating Maximum Allowable Thermal Resistance

Given the power dissipation, ambient operating temperature, and the maximum junction temperature of a regulator, the maximum allowable thermal resistance is readily calculated.

$$\theta_{JA} \le (T_{J(MAX)} - T_A) / P_D$$

Maximum heat sink thermal resistance is

$$\theta_{SA} \le \theta_{JA} - (\theta_{JC} + \theta_{CS})$$

We calculate the thermal resistance (θ_{SA}) required of the heat sink using the following formula:

$$\theta_{SA} = \frac{T_J - T_A}{P_D} - (\theta_{JC} + \theta_{CS})$$

Why A Maximum Junction Temperature?

Why do semiconductors, including LDO regulators, have a maximum junction temperature (T_J)? Heat is a natural enemy of most electronic components, and regulators are no exception. Semiconductor lifetimes, statistically specified as mean time to failure (MTTF) are reduced significantly when they are operated at high temperatures. The junction temperature, the temperature of the silicon die itself, is the most important temperature in this calculation. Device manufacturers have this lifetime-versus-operating temperature trade-off in mind when rating their devices. Power semiconductor manufacturers must also deal with the inevitable temperature variations across the die surface, which are more extreme for wider temperature-range devices. Also, the mechanical stress induced on the semiconductor, its package, and its bond wires is increased by temperature cycling, such as that caused by turning equipment on and off. A regulator running at a lower maximum junction temperature has a smaller temperature change, which creates less mechanical stress.

The expected failure rate under operating conditions is very small, and expressed in FITs (failures in time), which is defined as failures per one billion device hours. Deriving the failure rate from the operating life test temperature to the actual operating temperature is performed using the Arrhenius equation:

$$\frac{100}{FR2} = \frac{MTTF2}{MTTF1} = e^{\left(\frac{Ea}{k}\right)\left(\frac{1}{T2} - \frac{1}{T1}\right)}$$

Where:

FR1 is the failure rate at temperature T1 (Kelvin)
FR2 is the failure rate at temperature T2
MTTF1 is the mean time to failure at T1
MTTF2 is the mean time to failure at T2
Ea is the activation energy in electron volts (eV)
k is Boltzmann's constant (8.617386×10^{-5} eV/K)

The activation energy is determined by long-term burn-in testing. An average value of 0.62eV is determined, after considering all temperature-related failure mechanisms, including silicon-related failure modes and packaging issues, such as the die attach, lead bonding, and package material composition. Using a reference temperature of 125°C (498K) and normalizing to 100 FITs, the formula becomes:

$$\frac{100}{FR2} = e^{\left(\frac{0.62}{k}\right)\left(\frac{1}{T2} - \frac{1}{498}\right)}$$

The standard semiconductor reliability versus junction temperature characteristic is shown in Figure 3-48. We see that a device operating at 125°C has a relative lifetime of 100. For each 15°C rise in junction temperature, the MTTF halves. At 150°C, it drops to about 34. On the other hand, at 100°C, its life is more than tripled, and at 70°C, it is 1800.

As a designer of equipment using LDOs, the most important rule to remember is "cold is cool; hot is not". Minimizing regulator temperatures will maximize your product's reliability.

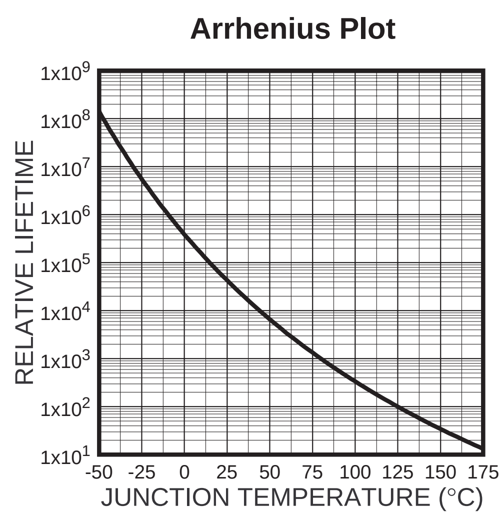


Figure 3-48. Typical MTTF vs. Temperature Curve

Heat Sink Charts for High Current Regulators

The heat sink plays an important role in high current regulator systems, as it directly affects the safe operating area (SOA) of the semiconductor. The following graphs, Figure 3-49 through 3-53, show the maximum output current allowable with a given heat sink for different input-output voltages at an ambient temperature of 25°C. Three curves are shown: no heat sink, nominal heat sink, and infinite heat sink (θ_{SA} = 0). Additional thermal design graphs appear in **Section 2**.

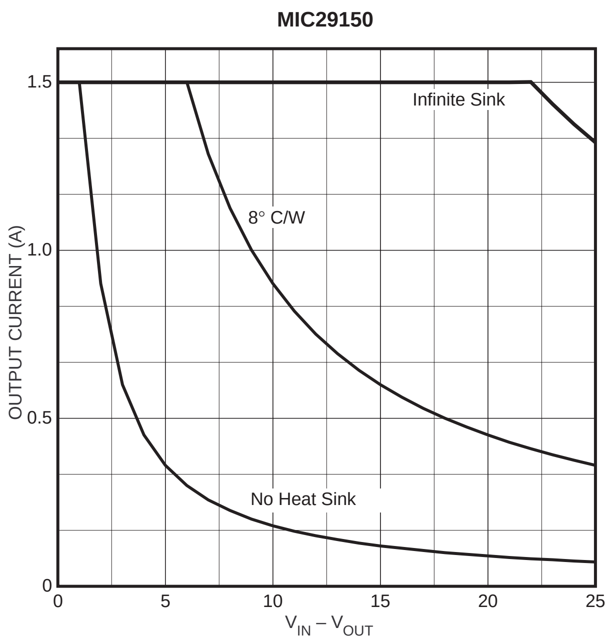


Figure 3-49. Maximum Output Current With Different Heat Sinks, MIC29150 Series

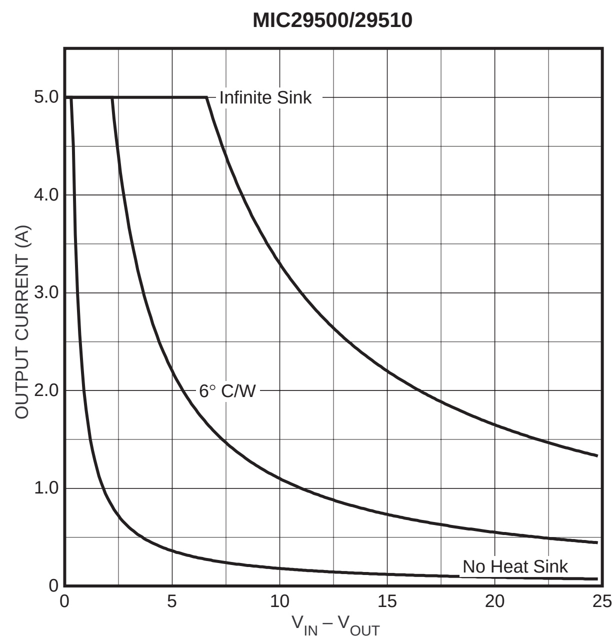


Figure 3-51. Maximum Output Current With Different Heat Sinks, MIC29500 Series

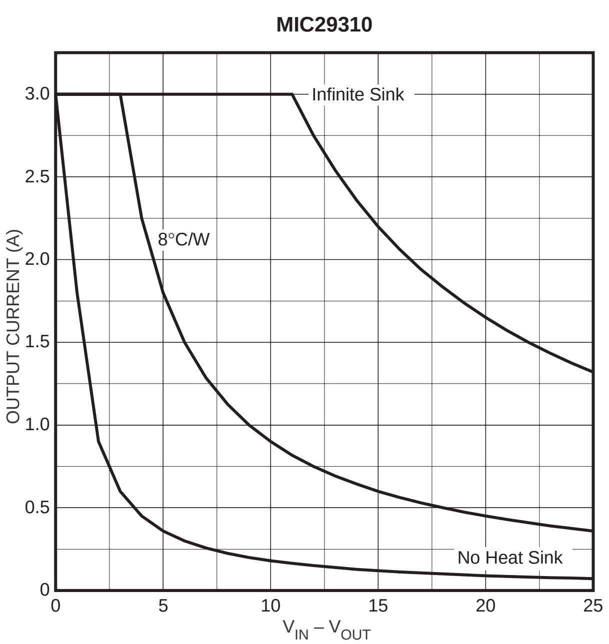


Figure 3-50. Maximum Output Current With Different Heat Sinks, MIC29300 Series

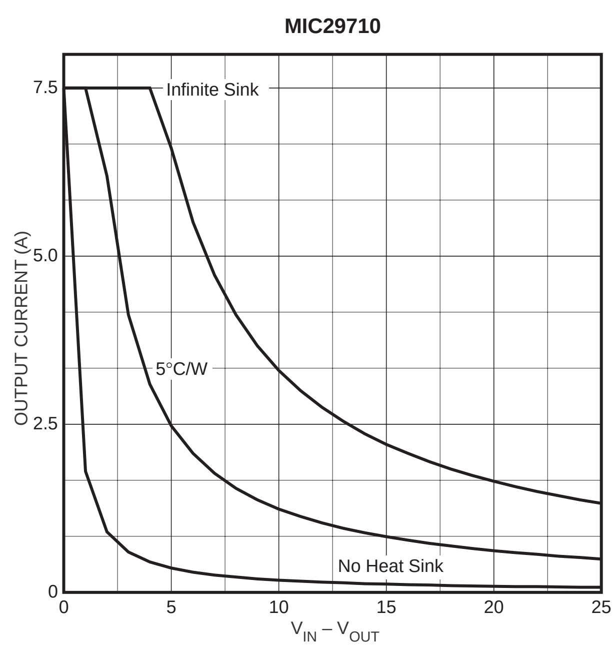


Figure 3-52. Maximum Output Current With Different Heat Sinks, MIC29710/MIC29712

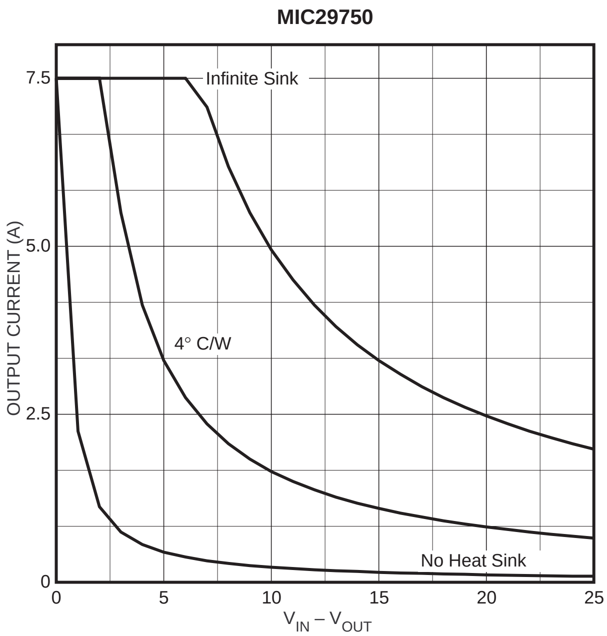


Figure 3-53. Maximum Output Current With Different Heat Sinks, MIC29750/MIC29752

Thermal Examples

Let's do an example. We need to design a power supply for a low voltage microprocessor which requires 3.3V at up to 3A. It will get its input from a 5V ±5% supply. We choose a MIC29300-3.3BT for our regulator. The worst case V_{IN} is high supply; in this case, 5V + 5%, or 5.25V. The LDO has a maximum die temperature of 125°C in its TO-220 package with a θ_{JC} of 2°C/W and a mounting resistance (θ_{CS}) of 1°C/W[2], and will operate at an ambient temperature of 50°C. Worst case V_{OUT} for thermal considerations is minimum, or 3.3V – 2% = 3.234V.[5] I_{OUT} is taken at its highest steady-state value. The ground current value comes from the device's data sheet, from the graph of I_{GND} vs. I_{OUT}.

Armed with this information, we calculate the thermal resistance (θ_{SA}) required of the heat sink using the previous formula:

$$\theta_{SA} = \frac{125 - 50°C}{10.5W} - (2 + 1°C/W) = \mathbf{4.1\ °C/W}$$

NOTE 5: Most Micrel regulators are production trimmed to better than ±1% accuracy under standard conditions. Across the full temperature range, with load current and input voltage variations, the device output voltage varies less than ±2%.

Performing similar calculations for 1.25A, 1.5A, 2.0A, 2.5A, 3.0A, 4.0A, and 5.0A gives the results shown in Table 3-7. We choose the smallest regulator for the required current level to minimize cost.

Regulator	I_{OUT}	P_D (W)	θ_{SA}(°C/W)
MIC29150	1.25A	2.6	25
MIC29150	1.5A	3.2	21
MIC29300	2.0A	4.2	15
MIC29300	2.5A	5.2	11
MIC29300	3.0A	6.3	8.8
MIC29500	4.0A	8.4	5.9
MIC29500	5.0A	10.5	4.1

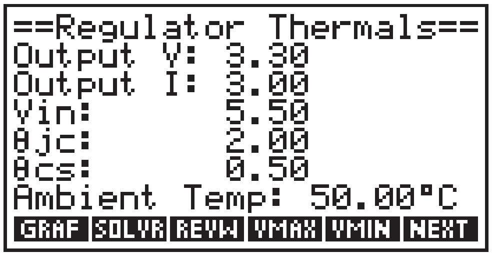
Table 3-7. Micrel LDO power dissipation and heat sink requirements for various 3.3V current levels.

Table 3-8 shows the effect maximum ambient temperature has on heat sink thermal properties. Lower thermal resistances require physically larger heat sinks. The table clearly shows cooler running systems need smaller heat sinks, as common sense suggests.

Output	**Ambient Temperature**		
	40°C	**50°C**	**60°C**
1.5A	24°C/W	21°C/W	17°C/W
5A	5.1°C/W	4.1°C/W	3.2°C/W

Table 3-8. Ambient Temperature Affects Heat Sink Requirements

Although routine, these calculations become tedious. A program written for the HP 48 calculator is available from Micrel that will calculate any of the above parameters and ease your design optimization process. It will also graph the resulting heat sink characteristics versus input voltage. See Appendix C for the program listing or send e-mail to Micrel at `apps@micrel.com` and request program "LDO SINK for the HP48".



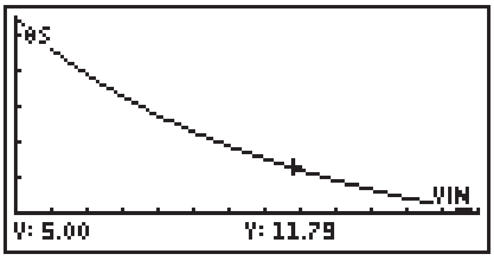


Figure 3-54. "LDO SINK" Calculator Program Eases Tedious Thermal Calculations (See Appendix C)

Heat Sink Selection

With this information we may specify a heat sink. The worst case is still air (natural convection). The heat sink should be mounted so that at least 0.25 inches (about 6mm) of separation exists between the sides and top of the sink and other components or the system case. Thermal properties are maximized when the heat sink is mounted so that natural vertical motion of warm air is directed along the long axis of the sink fins.

If we are fortunate enough to have some forced airflow, reductions in heat sink cost and space are possible by characterizing air speed–even a slow air stream significantly assists cooling. As with natural convection, a small gap allowing the air stream to pass is necessary. Fins should be located to maximize airflow along them. Orientation with respect to vertical is not very important, as airflow cooling dominates the natural convection.

As an example, we will select heat sinks for 1.5A and 5A outputs. We consider four airflow cases: natural convection, 200 feet/minute (1m/sec), 300 feet/minute (1.5m/sec), and 400 feet/minute (2m/sec). Table 3 shows heat sinks for these air velocities; note the rapid reduction in size and weight (fin thickness) when forced air is available. Consulting manufacturer's charts, we see a variety of sinks are made that are suitable for our application. At 5A (10.5W worst case package dissipation) and natural convection, sinks are sizable, but at 1.5A (3.2W worst case package dissipation) and 400 feet/minute airflow, modest heat sinks are adequate.

	Output Current	
Airflow	**1.5A**	**5A**
400 ft./min. (2m/sec)	Thermalloy 6049PB	Thermalloy 6232 Thermalloy 6034 Thermalloy 6391B
300 ft./min. (1.5m/sec)		AAVID 504222B AAVID 563202B AAVID 593202B AAVID 534302B Thermalloy 7021B Thermalloy 6032 Thermalloy 6234B
200 ft./min. (1m/sec)	AAVID 577002 Thermalloy 6043PB Thermalloy 6045B	AAVID 508122 AAVID 552022 AAVID 533302 Thermalloy 7025B Thermalloy 7024B Thermalloy 7022B Thermalloy 6101B
Natural Convection (no forced airflow)	AAVID 576000 AAVID 574802 592502 579302 Thermalloy 6238B Thermalloy 6038 Thermalloy 7038	AAVID 533602B (v) AAVID 519922B (h) AAVID 532802B (v) Thermalloy 6299B (v) Thermalloy 7023 (h)

Table 3-9. Commercial Heat Sinks for 1.5A and 5.0A Applications [Vertical Mounting Denoted by (V); (H) Means Horizontal Mounting]

Reading Heat Sink Graphs

Major heat sink manufacturers provide graphs showing their heat sink characteristics. The standard graph (Figure 3-55) depicts two different data: one curve is the heat sink thermal performance in still air (natural convection); the other shows the performance possible with forced cooling. The two graphs should be considered separately since they do not share common axes. Both are measured using a single device as a heat source: if multiple regulators are attached, thermal performance improves by as much as one-third (see *Multiple Packages on One Heat Sink*, below).

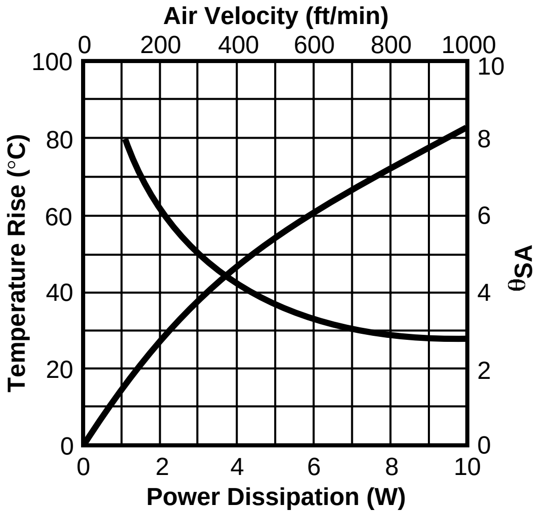


Figure 3-55. Typical Heat Sink Performance Graph

Figure 3-56 shows the natural convection portion of the curve. The x-axis shows power dissipation and the y-axis represents temperature rise over ambient. While this curve is nearly linear, it does exhibit some droop at larger temperature rises, representing increased thermodynamic efficiency with larger ΔT. At any point on the curve, the θ_{SA} is determined by dividing the temperature rise by the power dissipation.

Figure 3-57 shows the thermal resistance of the heat sink under forced convection. The x-axis (on top, by convention) is air velocity in lineal units per minute. The y-axis (on the right side) is θ_{SA}.

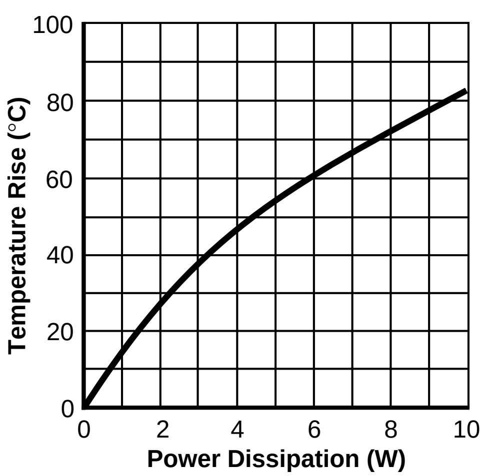


Figure 3-56. Natural Convection Performance

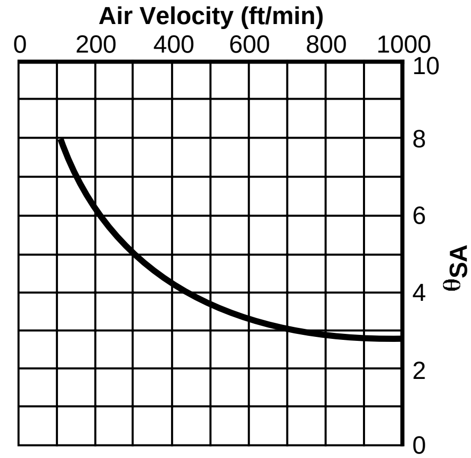


Figure 3-57. Forced Convection Performance

Power Sharing Resistor

The heat sink required for 5A applications in still air is massive and expensive. There is a better way to manage heat problems: we take advantage of the very low dropout voltage characteristic of Micrel's Super ßeta PNP™ regulators and dissipate some power externally in a series resistance. By distributing the voltage drop between this low cost resistor and the regulator, we distribute the heating and reduce the size of the regulator heat sink. Knowing the worst case voltages in the system and the peak current requirements, we select a resistor that drops a portion of the excess voltage without sacrificing performance. The maximum value of the resistor is calculated from:

$$R_{MAX} = \frac{V_{IN\,(MIN)} - (V_{OUT\,(MAX)} + V_{DO})}{I_{OUT\,(PEAK)} + I_{GND}}$$

Where: $V_{IN\,(MIN)}$ is low supply (5V – 5% = 4.75V)

$V_{OUT\,(MAX)}$ is the maximum output voltage across the full temperature range (3.3V + 2% = 3.366V)

V_{DO} is the worst case dropout voltage across the full temperature range (600mV)

$I_{OUT\,(PEAK)}$ is the maximum 3.3V load current

I_{GND} is the regulator ground current.

For our 5A output example:

$$R_{MAX} = \frac{4.75 - (3.366 + 0.6)\ V}{5 + 0.08\ A} = \frac{0.784V}{5.08A} = 0.154\Omega$$

The power drop across this resistor is:

$$P_{D\ (RES)} = (I_{OUT\ (PEAK)} + I_{GND})^2 \times R$$

or 4.0W. This subtracts directly from the 10.5W of regulator power dissipation that occurs without the resistor, reducing regulator heat generation to 6.5W.

$$P_{D(Regulator)} = P_{D(R\ =\ 0\Omega)} - P_{D\ (RES)}$$

Considering 5% resistor tolerances and standard values leads us to a 0.15Ω ± 5% resistor. This produces a nominal power savings of 3.9W. With worst-case tolerances, the regulator power dissipation drops to 6.8W maximum. This heat drop reduces our heat sinking requirements for the MIC29500 significantly. We can use a smaller heat sink with a larger thermal resistance. Now, a heat sink with 8.3°C/W thermal characteristics is suitable—nearly a factor of 2 better than without the resistor. Table 3-10 lists representative heat sinks meeting these conditions.

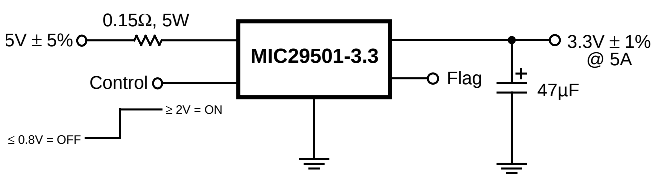


Figure 3-58. Resistor Power Sharing Reduces Heat Sink Requirement

For the 1.5A output application using the MIC29150, we calculate a maximum R of 0.512Ω. Using R = 0.51Ω, at least 1.1W is saved, dropping power dissipation to only 2.0W—a heat sink is probably not required. This circuit is shown in Figure 3-59.

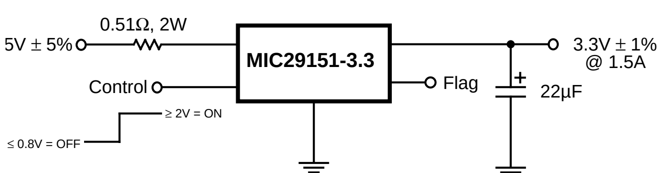


Figure 3-59. Power Sharing Resistor Eliminates Need for Separate Heat Sink

Another option exists for designers of lower current systems. The MIC29150 and MIC29300 regulators are available in the surface mount derivative of the TO-220 package, the TO-263, which is soldered directly to the PC board. No separate heat sink is necessary, as copper area on the board acts as the heat exchanger. For further information, refer to *Heat Sinking Surface Mount Packages*, which follows.

Airflow	Heat Sink Model
400 ft./min. (2m/sec)	AAVID 530700 AAVID 574802 Thermalloy 6110 Thermalloy 7137, 7140 Thermalloy 7128
300 ft./min. (1.5m/sec)	AAVID 57302 AAVID 530600 AAVID 577202 AAVID 576802 Thermalloy 6025 Thermalloy 6109 Thermalloy 6022
200 ft./min. (1m/sec)	AAVID 575102 AAVID 574902 AAVID 523002 AAVID 504102 Thermalloy 6225 Thermalloy 6070 Thermalloy 6030 Thermalloy 6230 Thermalloy 6021, 6221 Thermalloy 7136, 7138
Natural Convection (no forced airflow)	AAVID 563202 AAVID 593202 AAVID 534302 Thermalloy 6232 Thermalloy 6032 Thermalloy 6034 Thermalloy 6234

Table 3-10. Representative Commercial Heat Sinks for the 5.0A Output Example Using a Series Dropping Resistor (Assumptions: T_A = 50°C, R = 0.15Ω ±5%, $I_{OUT\ MAX}$ = 5.0A, θ_{JC} = 2°C/W, θ_{CS} = 1°C/W, resulting in a required θ_{SA} = 8.0°C/W)

Multiple Packages on One Heat Sink

The previous calculations assume the power dissipation transferred to the heat sink emanates from a single point source. When multiple heat sources are applied, heat sink thermal performance (θ_{SA}) improves. Two mechanisms decrease the total effective thermal resistance:

1. Paralleling multiple devices reduces the effective θ_{JS}.
2. Heat sink efficiency is increased due to improved heat distribution

Paralleled θ_{JC} and θ_{CS} terms lead to a reduction in case temperature of each regulator, since the power dissipation of each semiconductor is reduced proportionally. Distributing the heat sources, instead of a single-point source, minimizes temperature gra-

dients across the heat sink, resulting in lower conduction loss. As much as a 33% reduction in θ_{SA} is possible with distributed heat sources.

Micrel's Super Beta PNP regulators are a natural for multiple package mounting on a single heat sink because their mounting tabs are all at ground potential. Thus, no insulator is needed between the package and the heat sink, allowing the best possible θ_{CS}.

Paralleled Devices on a Heat Sink Example

An example will clarify this concept. Given a regulator that must dissipate 30W of heat, operating at an ambient temperature of 25°C, what heat sink θ_{SA} is needed? Given the following parameters:

$T_{J(MAX)} = 125°C$

$\theta_{JC} = 2°C/W$

$\theta_{CS} = 1°CW$

Case 1: Single Regulator

This configuration is shown graphically in Figure 3-60.

$$\theta_{SA} = \Delta T/W - (\theta_{JC} + \theta_{CS})$$
$$= (125° - 25°) / 30W - (2 + 1)\ °C/W$$

$$\theta_{SA} = 0.33°C/W$$

This is a very large heat sink.

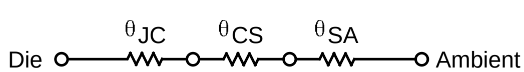


Figure 3-60. Single Heat Source Thermal "Circuit"

Case 2: Two Paralleled Regulators

This configuration is shown graphically in Figure 3-61. The effective θ_{JS} is reduced because the thermal resistances are connected in parallel.

$\theta_{JC'} = 1/((1/\theta_{JC1}) + (1/\theta_{JC2}))$

Assuming $\theta_{JC1} = \theta_{JC2}$, then

$\theta_{JC'} = \theta_{JC1} \div 2 \quad = 1°C/W$

$\theta_{CS'} = 1/((1/\theta_{CS1} + (1/\theta_{CS2}))$

Assuming $\theta_{CS1} = \theta_{CS2}$, then

$\theta_{CS}' = \theta_{CS1} \div 2 \quad = 0.5°C/W$

now

$\theta_{SA} = \Delta T/W - (\theta_{JC}' + \theta_{CS}') \quad = 1.83°C/W$

With the 33% efficiency gain, we could use a heat sink with a θ_{SA} rating as high as 2.4°C/W. This represents a tremendous reduction in heat sink size.

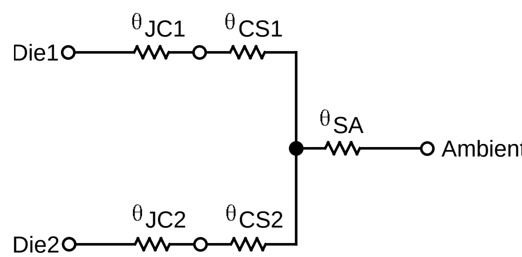


Figure 3-61. Dual Heat Source Thermal "Circuit"

Case 3: Multiple Paralleled Regulators

This configuration is shown graphically in Figure 3-62. For the condition of "n" paralleled heat sources, the θ_{JC} and θ_{CS} are reduced to 1/n their per-unit value. The heat sink needs the following rating:

$$\theta_{SA} = \Delta T/W - ((\theta_{JC1}/n) + (\theta_{CS1}/n))$$

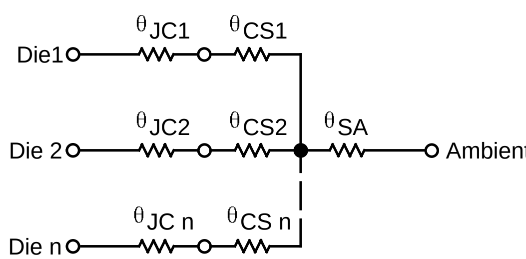


Figure 3-62. "n" Heat Source Thermal Circuit

Table 3-11 shows the reduction in heat sink performance allowed by paralleled regulators.

n	θ_{SA}
1	0.33
2	1.83
3	2.33
4	2.58
5	2.73
6	2.83

Table 3-11. Paralleled Regulators Allow Smaller (Physical Size) Heat Sinks. T_A = 25°C

Another way of looking at this situation is to ask what is the increase in maximum ambient temperature paralleled regulators allow?

$$T_A = T_{J(MAX)} - W \times [\theta_{SA} + (\theta_{JC}/n) + (\theta_{CS}/n)]$$

Table 3-12 shows the highest allowable T_A using the 0.33°C/W heat sink of Case 1.

n	T_A (°C)
1	25
2	70
3	85
4	92
5	97
6	100

Table 3-12. Highest Allowable Ambient Temperature With a 0.33°C/W Heat Sink

Heat Sinking Surface Mount Packages

System designers increasingly face the restriction of using all surface-mounted components in their new designs—even including the power components. Through-hole components can dissipate excess heat with clip-on or bolt-on heat sinks keeping things cool. Surface mounted components do not have this flexibility and rely on the conductive traces or pads on the printed circuit board for heat transfer. We will address the question “How much PC board pad area does my design require?”

Example 1: TO-263 Package

We will determine if a Micrel surface mount low dropout linear regulator may operate using only a PC board pad as its heat sink. We start with the circuit requirements.

System Requirements:

V_{OUT} = 5.0V

$V_{IN\ (MAX)}$ = 9.0V

$V_{IN\ (MIN)}$ = 5.6V

I_{OUT} = 700mA

Duty cycle = 100%

T_A = 50°C

This leads us to choose the 750mA MIC2937A-5.0BU voltage regulator, which has these characteristics:

V_{OUT} = 5V ± 2% (worst case over temperature)

$T_{J\ MAX}$ = 125°C

θ_{JC} of the TO-263 = 3°C/W

θ_{CS} + 0°C/W (soldered directly to board)

Preliminary Calculations

$V_{OUT\ (MIN)} = 5V - 2\% = 4.9V$

$P_D = (V_{IN\ (MAX)} - V_{OUT\ (MIN)}) \times I_{OUT} + (V_{IN\ (MAX)} \times I_{GND})$

$= [9V - 4.9V] \times 700mA + (9V \times 15mA) = 3W$

Maximum temperature rise, $\Delta T = T_{J(MAX)} - T_A$

$= 125°C - 50°C = 75°C$

Thermal resistance requirement, θ_{JA} (worst case):

$$\frac{\Delta T}{P_D} = \frac{75°C}{3.0W} = 25°C/W$$

Heat sink thermal resistance

$\theta_{SA} = \theta_{JA} - (\theta_{JC} + \theta_{CS})$

θ_{SA} = 25 – (3 + 0) = **22°C/W (max)**

Determining Heat Sink Dimensions

Figure 3-63 shows the total area of a round or square pad, centered on the device. The solid trace represents the area of a square, single sided, horizontal, solder masked, copper PC board trace heat sink, measured in square millimeters. No airflow is assumed. The dashed line shows a heat sink covered in black oil-based paint and with 1.3m/sec (250 feet per minute) airflow. This approaches a “best case” pad heat sink.

Conservative design dictates using the solid trace data, which indicates a pad size of 5000 mm^2 is needed. This is a pad 71mm by 71mm (2.8 inches per side).

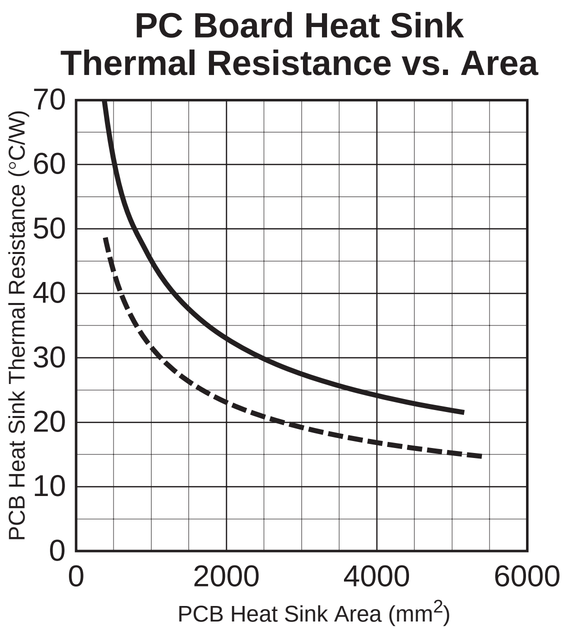


Figure 3-63. Graph to Determine PC Board Area for a Given Thermal Resistance (See text for Discussion of the Two Curves)

Example 2: SO-8 and SOT-223 Package

Given the following requirements, determine the safe heat sink pad area.

V_{OUT} = 5.0V

$V_{IN\ (MAX)}$ = 14V

$V_{IN\ (MIN)}$ = 5.6V

I_{OUT} = 150mA

Duty cycle = 100%

T_A = 50°C

Your board production facility prefers handling the dual-in-line SO-8 packages whenever possible. Is the SO-8 up to this task? Choosing the MIC2951-03BM, we get these characteristics:

$T_{J\ (MAX)}$ = 125°C

θ_{JC} of the SO-8 = 100°C/W

SO-8 Calculations:

P_D = [14V – 5V] × 150mA + (14V × 8mA) = **1.46W**

Temperature rise = 125°C – 50°C = **75°C**

Thermal resistance requirement, θ_{JA} (worst case):

$$\frac{\Delta T}{P_D} = \frac{75°C}{1.46W} = \mathbf{51.3°C/W}$$

Heat sink θ_{SA} = 51 – 100 = **–49°C/W (max)**

The negative sign flags the problem: without refrigeration, the SO-8 is not suitable for this application. Consider the MIC5201-5.0BS in a SOT-223 package. This package is smaller than the SO-8, but its three terminals are designed for much better thermal flow. Choosing the MIC5201-3.3BS, we get these characteristics:

$T_{J\ (MAX)}$ = 125°C

θ_{JC} of the SOT-223 = 15°C/W

θ_{CS} = 0°C/W (soldered directly to board)

SOT-223 Calculations:

P_D = [14V – 4.9V] × 150mA + (14V × 1.5mA)
= **1.4W**

Temperature rise = 125°C – 50°C = **75°C**

Thermal resistance requirement, θ_{JA} (worst case):

$$\frac{\Delta T}{P_D} = \frac{75°C}{1.4W} = \mathbf{54°C/W}$$

Heat sink θ_{SA} = 54 – 15 = **39°C/W (max)**

Board Area

Referring to Figure 3-63, a pad of 1400mm^2 (a square pad 1.5 inches per side) provides the required thermal characteristics.

Example 3: SOT-23-5 Package

A regulator for a cellular telephone must provide 3.6V at 50mA from a battery that could be as high as 6.25V. The maximum ambient temperature is 70°C and the maximum desired junction temperature is 100°C. The minimum-geometry thermal capability of the MIC5205 in the SOT-23-5 is 220°C/W; must we provide additional area for cooling?

P_D = [6.25 – 3.56V] × 50mA + (6.25V × 0.35mA)
= 137mW

$$\frac{\Delta T}{P_D} = \frac{30°C}{0.137W} = 219°C/W$$

Which is close enough to 220°C/W θ_{JA} for our purposes. We can use the minimum-geometry layout.

If our electrical or thermal parameters worsened, we could refer to Figure 3-63 and determine the additional copper area needed for heat sinking. Use a value of 130°C/W θ_{JC} for the MIC5205-xxBM5.

Example 4, Measurement of θ_{JA} with a MSOP-8

An MIC5206-3.6BMM (in the 8-pin MSOP package) was soldered to 1oz. double-sided copper PC board material. The board, measuring 4.6 square inches, had its top layer sliced into four quadrants, corresponding to input, output, ground, and enable (see Figure 3-64), and a temperature probe was soldered close to the regulator. The device thermal shutdown temperature was measured at zero power dissipation to give an easy-to-detect temperature reference point. The device was cooled, then the load was increased until the device reached thermal shutdown. By combining T_A, $T_{J\,(SHUTDOWN)}$, and P_D, we may accurately determine θ_{JA} as:

$$\theta_{JA} = (T_{J\,(SHUTDOWN)} - T_A) \div P_D$$

For a given board size. Next, the board was trimmed to about 2 square inches and retested. Measurements were also taken at 1 and 0.5 square inches. The results are shown in Figure 3-65.

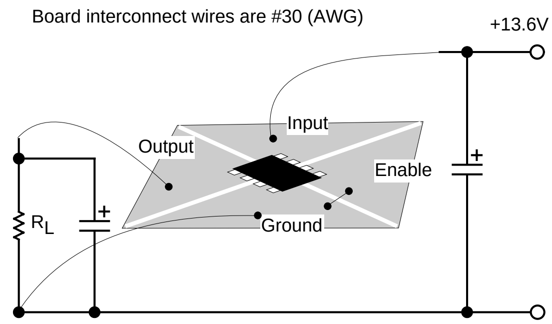


Figure 3-64. MSOP-8 Thermal Resistance Test Jig

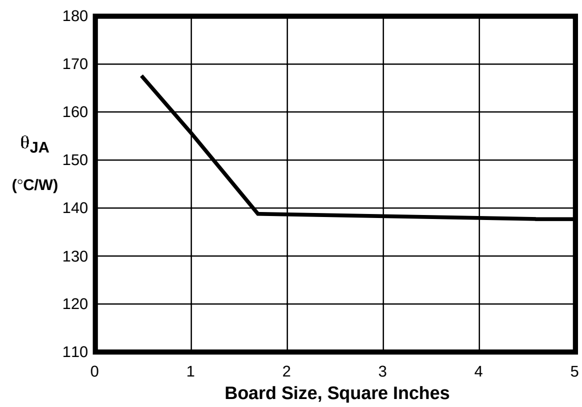


Figure 3-65. Junction to Ambient Thermal Resistance for the MSOP-8 Package

Comments

These formulas are provided as a general guide to thermal characteristics for surface mounted power components. Many estimations and generalizations were made; your system will vary. Please use this information as a rough approximation of board area required and fully evaluate the thermal properties of each board you design to confirm the validity of the assumptions.

Linear Regulator Troubleshooting Guide

Problem	Possible Cause
Output Voltage Low at Heavy Load	Regulator in dropout Excessive lead resistance between regulator and load Regulator in current limit Regulator in thermal shutdown
Output Voltage Bad at Light Load	Regulator in Dropout Minimum output load current not satisfied Input voltage too high (overvoltage shutdown) Layout problem
Regulator Oscillates	Output capacitor too small (Super βeta PNP) Output capacitor ESR too small Input capacitor bad or missing Layout problems
Regulator Does Not Start	Output polarity reversed Input voltage too high (overvoltage shutdown) Load is shorted or latched up
AC Ripple on Output	Ground loop with input filter capacitor

Solutions to each of these possible causes are presented earlier in this section. If problems persist, please contact Micrel Applications Engineering for assistance.

Section 4. Linear Regulator Solutions

Super βeta PNP™ Regulators

Micrel's easy to use Super ßeta PNP™ LDO monolithic regulators deliver highly accurate output voltages and are fully protected from fault conditions. Their maximum output currents range from 80mA to 7.5A. They are available in numerous fixed voltages, and most families offer adjustable versions.

Micrel's monolithic linear regulator family appears below, listed by increasing output current capability.

•

- MIC5203 — 80mA regulator in the tiny SOT-143 package. Fixed output voltages of 2.85, 3.0, 3.3, 3.6, 3.8, 4.0, 4.75, and 5.0V are available.
- LP2950 — 100mA fixed 3.3, 4.85, and 5.0V regulator available in the TO-92 package.
- LP2951 — 100mA fixed 5.0V and adjustable regulator available in the SO-8 package.
- MIC5200 — 100mA regulator available in SO-8 and SOT-223 packages. Fixed output voltages of 3.0, 3.3, 4.85, and 5.0V are available.
- MIC5202 — dual 100mA version of the '5200, available in the SO-8 package.
- MIC5205 — 150mA low-noise fixed and adjustable regulator supplied in the small SOT-23-5 package.
- MIC5206 — 150mA low-noise regulator supplied in the small SOT-23-5 or MSOP-8 packages.
- MIC5207 — 180mA low-noise regulator supplied in the small SOT-23-5 or TO-92 packages.
- MIC2950 — 150mA fixed 3.3, 4.85, and 5.0V regulator available in the TO-92 package.
- MIC2951 — 150mA fixed 5.0V and adjustable regulator available in the SO-8 package.
- MIC5201 — 200mA regulator available in SO-8 and SOT-223 packages. Fixed output voltages of 3.0, 3.3, 4.85, and 5V, plus an adjustable version are available.
- MIC2920A — family of 400mA regulators in TO-220, TO-263-3, SOT-223, and SO-8 packages. Fixed output voltages of 3.3V, 4.85V, 5V, and 12V plus three adjustable versions are available.
- MIC2937A — family of 750mA regulators in TO-220 and TO-263 packages. Fixed output voltages of 3.3V, 5V, and 12V, plus two adjustable versions are available.
- MIC2940A — 1250mA regulators in TO-220 and TO-263 packages with fixed output voltages of 3.3V, 5V, and 12V. The MIC2941A is an adjustable version.
- MIC29150 — family of 1.5A regulators in TO-220 and TO-263 packages. Fixed output voltages of 3.3V, 5V, and 12V, plus two adjustable versions are available.
- MIC29300 — family of 3A regulators in TO-220 and TO-263 packages. Fixed output voltages of 3.3V, 5V, and 12V, plus two adjustable versions are available.
- MIC29310 — low-cost 3A regulator with 3.3 and 5V fixed outputs in a TO-220 package. The MIC29312 is an adjustable version.
- MIC29500 — family of 5A regulators in TO-220, and TO-263 packages. Fixed output voltages of 3.3V and 5V, plus two adjustable versions are available.
- MIC29510 — low-cost 5A regulator with 3.3 and 5V fixed outputs in a TO-220 package. The MIC29512 is an adjustable version.
- MIC29710 — low-cost 7.5A regulator with 3.3 and 5V fixed outputs in a TO-220 package. The MIC29712 is an adjustable version.
- MIC29750 — 7.5A regulator in a TO-247 power package with 3.3 and 5V fixed outputs. The MIC29752 is an adjustable version.

Micrel's medium and high-current regulators (400mA and higher output current capability) have a part numbering code that denotes the additional features offered. The basic family number, ending in "A" or "0" denotes the easy-to-use three-pin fixed voltage regulator.

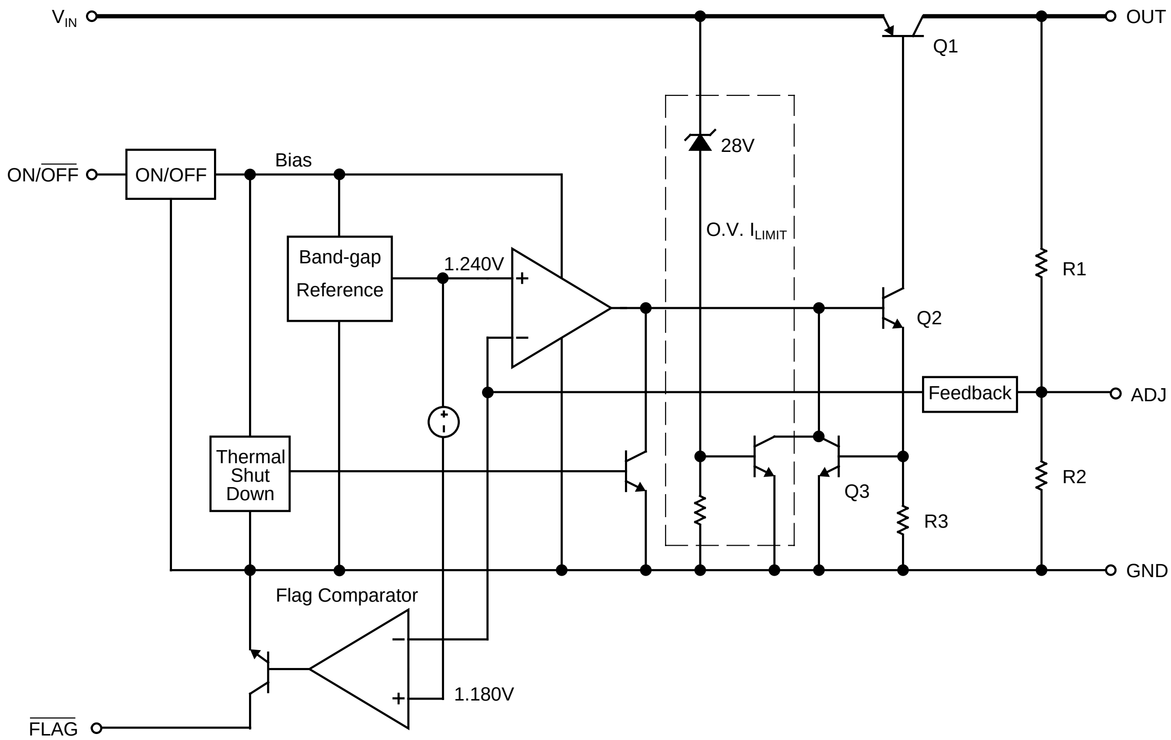


Figure 4-1. Super ßeta PNP™ Regulator Simplified Schematic Diagram

- Part numbers ending in "1" are five-pin fixed devices with a digital control pin for turning the regulator ON or OFF and an Error Flag output that signals when the output is not in regulation.
- Part numbers ending in "2" are adjustable parts with ON/OFF control.
- Devices ending with "3" are adjustables with an Error Flag.

Super βeta PNP Circuitry

The simplified schematic diagram of Micrel's medium and high current monolithic LDOs appears as Figure 4-1. The high current path from input to output through the pass transistor is in bold. The bandgap reference and all other circuitry is powered via the Enable Circuit, which allows for "zero" current draw when disabled. The reference voltage is compared to the sampled output voltage fed back by R1 and R2. If this voltage is less than the bandgap reference, the op amp output increases. This increases the current through driver transistor Q2, which pulls down on the base of Q1, turning it on harder. If Q1's base current rises excessively, the voltage drop across R3 enables Q3, which in turn limits the current through Q2. Die temperature is monitored, and if it becomes excessive, the thermal shutdown circuit activates, clamping the base of Q2 and shutting down Q1. The flag circuit looks at the output voltage sample and compares it to a reference set 5% lower. If the sample is even lower, the flag comparator saturates the open collector flag transistor, signaling the fault condition.

Dropout Voltage

The Super βeta PNP family of low-dropout regulators offers typical dropout voltages of only 300mV across the output current range. This low dropout is achieved by using large and efficient multicelled PNP output transistors, and operating them in their high-beta range well below their capacity. Dropout voltage in the Super βeta PNP regulators is determined by the saturation voltage of the PNP pass element. As in all bipolar transistors, the saturation voltage is proportional to the current through the transistor. At light loads, the dropout voltage is only a few tens of millivolts. At moderate output currents, the dropout rises to 200 to 300mV. At the full rated output, the typical dropout voltage is approximately 300mV for most of the families. Lower cost versions have somewhat higher dropout at full load, generally in the 400 to

500mV range. The data sheet for each device graphs typical dropout voltage versus output current.

Ground Current

Micrel's Super βeta PNP process allows these high current devices to maintain very high transistor beta—on the order of 100 at their full rated current. This contrasts with competitive PNP devices that suffer with betas in the 10 to 30 range. This impacts regulator designs by reducing wasteful ground current. Micrel's beta of 100 translates into typical full load ground currents of only 1% of your output. The data sheet for each device graphs typical ground current versus output current.

When linear regulators approach dropout, generally due to insufficient input voltage, base drive to the pass transistor increases to fully saturate the transistor. With some older PNP regulators, the ground current would skyrocket as dropout approached. Micrel's Super βeta PNP regulators employ saturation detection circuitry which limits base drive when dropout-induced saturation occurs, limiting ground current.

Fully Protected

Micrel regulators are survivors. Built-in protection features like current limiting, overtemperature shutdown, and reversed-input polarity protection allow LDO survival under otherwise catastrophic situations. Other protection features are optionally available, such as overvoltage shutdown and a digital error flag.

Current Limiting

Current limiting is the first line of defense for a regulator. It operates nearly instantaneously in the event of a fault, and keeps the internal transistor, its wire bonds, and external circuit board traces from fusing in the event of a short circuit or extremely heavy output load. The current limit operates by linearly clamping the output current in case of a fault. For example, if a MIC29150 with a 2A current limit encounters a shorted load, it will pass up to 2A of current into that load. The resulting high power dissipation (2A multiplied by the entire input voltage) causes the regulator's die temperature to rise, triggering the second line of defense, overtemperature shutdown.

Overtemperature Shutdown

As the output fault causes internal dissipation and die temperature rise, the regulator approaches its operating limits. At a predetermined high temperature, the regulator shuts off its pass element, bringing output current and power dissipation to zero. The hot die begins cooling. When its temperature drops below an acceptable temperature threshold, it automatically re-enables itself. If the load problem has been addressed, normal operation resumes. If the short persists, the LDO will begin sourcing current, will heat up, and eventually will turn off again. This sequence will repeat until the load is corrected or input power is removed. Although operation at the verge of thermal shutdown is not recommended, Micrel has tested LDOs for several million ON/OFF thermal cycles without undue die stress. In fact, during reliability testing, regulators are burned-in at the thermal shutdown-cycle limit.

Reversed Input Polarity

Protection from reversed input polarity is important for a number of reasons. Consumer products using LDOs with this feature survive batteries inserted improperly or the use of the wrong AC adapter. Automotive electronics must survive improper jump starting. All types of systems should last through initial production testing with an incorrectly inserted (backward) regulator. By using reversed input protected regulators, both the regulator and its load are protected against reverse polarity, which limits reverse current flow.

This feature may be simulated as an ideal diode, *with zero forward voltage drop*, in series with the output. Actually, a small current flows from the input pin to ground through the voltage divider network, but this may generally be neglected. Measured data from Super ßeta PNP regulators with a 100Ω resistor from output to ground follows:

Input Voltage (V)	Load Current (mA)
0	0
–5	0
–10	0
–15	–2.0
–20	–6.9
–25	–7.8
–30	–14

Although the devices were tested to –30V for this table without any failure, the reverse-polarity specification ranges only to –20V.

Overvoltage Shutdown

Most Micrel LDOs feature overvoltage shutdown. If the input voltage rises above a certain predetermined level, generally between 35V and 40V, the control circuitry disables the output pass transistor. This feature allows the regulator to reliably survive high voltage (60V or so—see the device data sheet for the exact limit) spikes on the input regardless of output load conditions. The automotive industry calls this feature "Load-Dump Protection"[1] and it is crucial to reliability in automotive electronics.

Many of Micrel's regulator families offer a version with a digital error flag output. The error flag monitors the output voltage and pulls its open collector (or drain) output low if the voltage is too low. The definition of "too low" ranges from about –5% to –8% below nominal output, depending upon the device type. The flag comparator is unaffected by low input voltage or a too-light or too-heavy load (although a too-heavy load generally will cause the output voltage to drop, triggering the flag).

Variety of Packages

From the tiny SOT-143 to the large TO-247 (also known as the TO-3P), Micrel Super ßeta PNP regulators span orders of magnitude in both size and output current.

Why Choose Five Terminal Regulators?

What do the extra pins of the five pin linear regulators provide? After all, three terminal regulators give Input, Output, and Ground; what else is necessary? Five terminal devices allow the system designer to monitor power quality to the load and digitally switch the supply ON and OFF. Power quality is indicated by a flag output. When the output voltage is within a few percent of its desired value, the flag is high, indicating the output is good. If the output drops, because of either low input voltage to the regulator or an overcurrent condition, the flag drops to signal a fault condition. A controller can monitor this output and make decisions regarding the system's readiness. For example, at initial power-up, the flag will instantaneously read high (if pulled up to an external supply), but as soon as the input supply to the regulator reaches about 2V, the flag pulls low. It stays low until the regulator output nears its desired value. With the MIC29150 family of low-dropout linear regulators, the flag rises when the output voltage reaches about 97% of the desired value. In a 3.3V system, the flag indicates "output good" with V_{OUT} = 3.2V.

NOTE 1: A "load dump" fault occurs in an automobile when the battery cable breaks loose and the unfiltered alternator output powers the vehicle.

Logic-compatible power control allows "sleep" mode operation and results in better energy efficiency. The ENABLE input of the MIC29150 family is TTL and 5V or 3.3V CMOS compatible. When this input is pulled above approximately 1.4V, the regulator is activated. A special feature of this regulator family is *zero power consumption* when inactive. Whenever the logic control input is low, all internal circuitry is biased OFF. (A tiny leakage current, measured in nanoamperes, may flow).

Three terminal regulators are used whenever ON/OFF control is not necessary and no processing power is available to respond to the flag output information. Three terminal regulators need only a single output filter capacitor minimizing design effort. Micrel three-terminal regulators all are fixed-output voltage devices with the same pin configuration: input, ground, output.

Five terminal regulators provide all the functionality of three pin devices PLUS allow power supply quality monitoring and ON/OFF switching for "sleep" mode applications.

Compatible Pinouts

Micrel's MIC29150/29300/29500 and MIC29310/29510/29710 families of low-dropout regulators have identical pinouts throughout the line. A single board layout accommodates from 1.5A through 7.5A of maximum current, simply by replacing one LDO with another of different rating. Additionally, the three pin and five pin versions of these two families have a similarity that allows a three pin regulator to function in a socket designed for a five pin version.

Three Pin Regulator	Five Pin Regulator
—	Enable or Flag
Input	Input
Ground	Ground
Output	Output
—	Adjust or Flag

Many applications do not require the ENABLE or FLAG functions. In these cases, if a fixed voltage is suitable, a three pin LDO may be substituted in the

five pin socket by simply leaving the outer holes open. Use care when forming the leads; gently bend them 90° before compressing them. The plastic may crack if the leads are forced excessively.

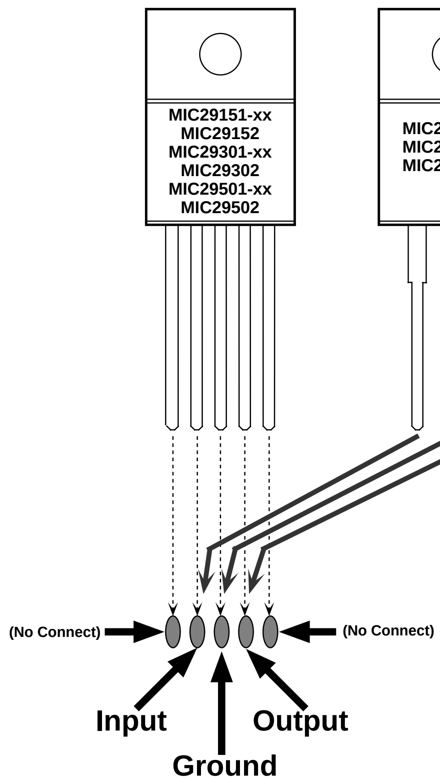


Figure 4-2. PC Board Layout for 5-Pin and 3-Pin Regulators

Stability Issues

PNP output regulators require a minimum value of output filter capacitance for stability. The data sheet for each device specifies the minimum value of output capacitor necessary.

A stability analysis of the PNP regulators shows there are two main poles, one low internal pole at about 10Hz, and an external pole provided by the output filter capacitor. An internal zero of approximately 1.5kHz cancels the internal pole, leaving the output capacitor to provide the dominant pole for stability. Gain/phase characteristics are affected by several parameters:

- Internal design (compensation and configuration)
- Load capacitor value
- Load capacitor ESR
- Load current
- Output transistor beta
- Driver stage transconductance

Stray capacitance on the feedback pins of adjustable regulators serves to decrease the phase margin. Circuits designed for minimum output noise often intentionally add capacitance across a feedback resistor, which couples back to the feedback pin. Increasing the size of the output filter capacitor in this situation recovers the phase margin required for stability.

Paralleling Bipolar Regulators

The most difficult aspect of using linear regulators is heat sinking. As output current and/or input-to-output voltage differential increases, the heat sink size rapidly increases. One method of mitigating this is to split the heat into more than one point source. In **Section 3**, *Thermal Management*, using a resistor to dissipate excess power when the input voltage is much higher than the desired output was discussed, but this technique is unusable when we need low system dropout. Another method of power sharing is to parallel the regulators. This preserves their low dropout characteristics and also allows scaling to higher output currents. As also shown in *Thermal Management*, heat sinking two devices is up to 33% more efficient than sinking one at the same overall power level.

Bipolar transistors have a negative temperature coefficient of resistance; as they get hotter, they pass more current for a given voltage. This characteristic makes paralleling bipolar transistors difficult—if the transistors are not precisely matched and at identical temperatures, one will draw more current than the others. This transistor will thereby get hotter and draw even more current. This condition, known as thermal runaway, prevents equal current sharing between devices and often results in the destruction of the hottest device.

We may parallel bipolar transistors if we monitor the current through each of the devices and somehow force them to be equal. An easy and accurate method is by using current sense resistors and op amps. Figure 4-3 shows two 7.5A MIC29712 in parallel to produce a 15A composite output. One regulator is chosen as the master. Its output is adjusted to the desired voltage in the usual manner with two resistors. A small-value sense resistor samples the output for the op amp. The resistor value is chosen to provide an output voltage large enough to swamp the input offset voltage (V_{OS}) of the op amp with medium output current. If the resistor is too small, matching will be poor; if it is too large, system dropout voltage

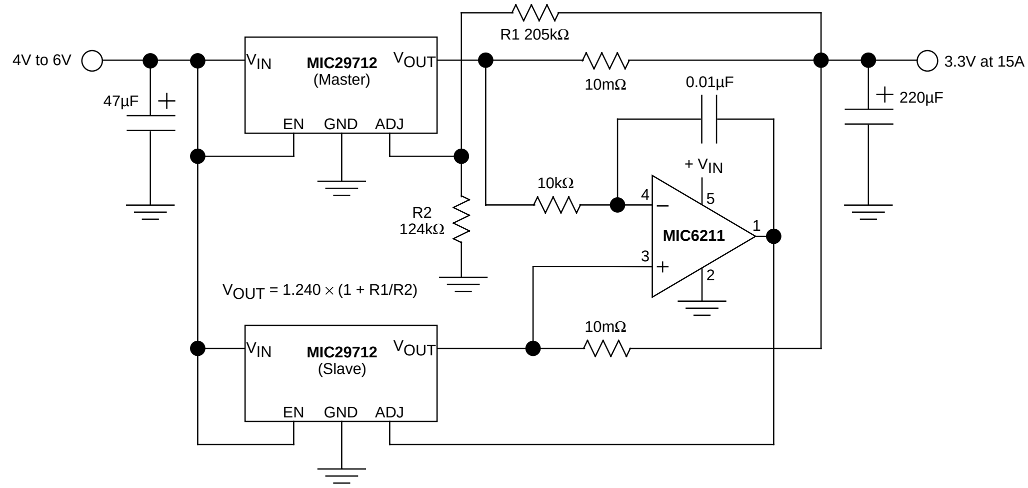


Figure 4-3. Two Super ßeta PNP Regulators in Parallel

will increase. The op amp drives the ADJ input of the slave regulator and matches its output to the master.

This technique is also applicable to three or more paralleled regulators: Figure 4-4 shows three in parallel. This may be extended to any number of devices by merely adding a sense resistor and op amp circuit to each additional slave regulator.

Although a fixed regulator can be used as a master, this is not recommended. Load regulation suffers because fixed output regulators (usually) do not have a separate SENSE input to monitor load voltage. As current through the sense resistor increases, the output voltage will drop because voltage sensing occurs on the wrong side of the current sense resistor.

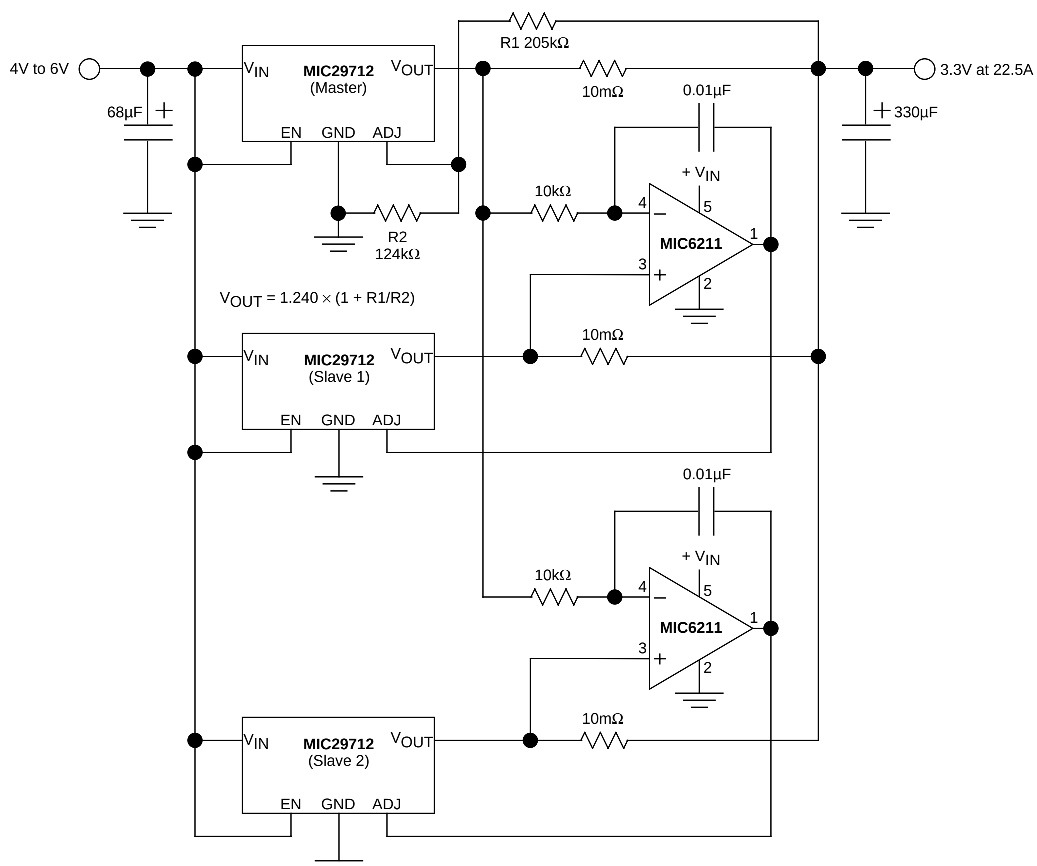


Figure 4-4. Three or More Parallel Super ßeta PNP Regulators

Micrel's Unique "Super LDO™"

The Super LDO™ is a dedicated control IC to drive an external N-channel MOSFET pass element. It allows economical management of moderate to high output currents.

The external pass element offers the designer three advantages unattainable with the monolithic approach: First, because the control circuitry is separate, the pass element's die area in a given package can be increased. This results in lower dropout voltages at higher output currents. Second, the junction-to-case thermal resistance is much less allowing higher output currents before a heat sink is required. Third, the semiconductor process for manufacturing MOSFETs is simpler and less costly than the process needed to fabricate accurate voltage references and analog comparators. High current monolithic regulators have most of their die area dedicated to the output device; why build a large, relatively simple device on an expensive process? The Super LDO combines all three advantages to produce a high performance, low cost regulating system.

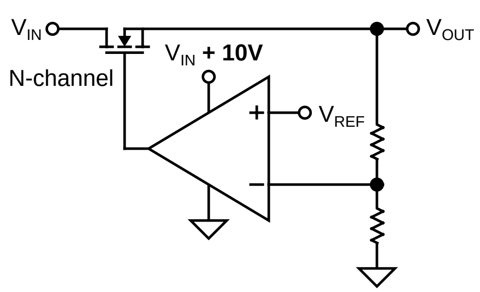


Figure 4-5. N-Channel Regulator

The most attractive device for the external pass element is the N-channel power MOSFET (see Figure 4-5). Discrete N-channel MOSFET prices continue to decrease (due to high volume usage), and the race for lower and lower ON resistance works in your favor. The N-channel MOSFET, like the P-channel MOSFET, reduces ground current. With device ON resistance now below 10mΩ, dropout voltages below 100mV are possible with output currents in excess of 10A. Even lower dropouts are possible by using two or more pass elements in parallel.

Unfortunately, full gate-to-source enhancement of the N-channel MOSFET requires an additional 10V to 15V above the required output voltage. Controlling the MOSFET's gate using a second higher voltage supply requires additional circuitry and is clumsy at best.

Micrel's Super LDO Family

Micrel's Super LDO Regulator family consists of three regulators which control an external N-channel MOSFET for low dropout at high current. Two members of the family internally generate the required higher MOSFET enhancement voltage, while the other relies on an existing external supply voltage.

All members of the Super LDO Regulator family have a 35mV current limit threshold, ±2% nominal output voltage setting, and a 3V to 36V operating voltage range. All family members also include a TTL compatible enable/shutdown input (EN) and an open collector fault output (FLAG). When shutdown (TTL low), the device draws less than 1µA. The FLAG output is low whenever the output voltage is 6% or more below its nominal value.

The MIC5156

The MIC5156 Super LDO Regulator occupies the least printed circuit board space in applications where a suitable voltage is available for MOSFET gate enhancement. To minimize external parts, the MIC5156 is available in fixed output versions of 3.3V or 5V. An adjustable version is also available which uses two external resistors to set the output voltage from 1.3V to 36V.

The MIC5157 and MIC5158

For stand-alone applications the MIC5157 and MIC5158 incorporate an internal charge-pump voltage tripler to supply the necessary gate enhancement for an external N-channel MOSFET. Both devices can fully enhance a logic-level N-channel MOSFET from a supply voltage as low as 3.0V. Three inexpensive small value capacitors are required by the charge pump.

The MIC5157 output voltage is externally selected for a fixed output voltage of 3.3V, 5V or 12V.

The MIC5158 output voltage is externally selectable for either a fixed 5V output or an adjustable output. Two external resistors are required to set the output voltage for adjustable operation.

3.3V, 10A Regulator Application

Figure 4-6 shows the MIC5157's ability to supply the additional MOSFET gate enhancement in a

low dropout 3.3V, 10A supply application. Capacitors C1 and C2 perform the voltage tripling required by the N-channel logic-level MOSFETs. Improved response to load transients is accomplished by using output capacitors with low ESR characteristics. The exact capacitance value required for a given design depends on the maximum output voltage disturbance that can be tolerated during a worse case load change. Adding low-value (0.01µF to 0.1µF) film capacitors (such as Wima MKS2 series) near the load will also improve the regulator's transient response.

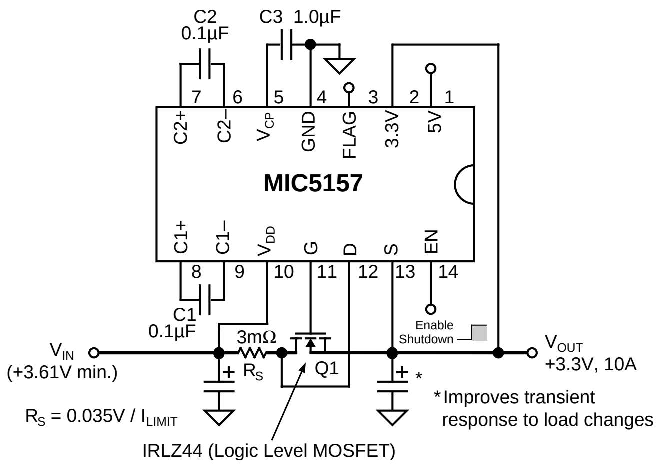


Figure 4-6. 10A Linear Regulator

Comparison With Monolithics

Similarities to Monolithics

Like Micrel's Super ßeta PNP monolithic regulators, the Super LDO is a linear regulator. It provides a regulated and filtered output voltage from a (at least) slightly higher input source; it does not require inductors; it is available in fixed as well as user-adjustable output voltages; and it protects itself and its load by implementing current limiting. There are significant differences between the Super LDO and monolithic designs, however.

Differences from Monolithics

The differences between the Super LDO and monolithic designs is depicted in Table 4-1. The external N-channel MOSFET required by the Super LDO gives it great flexibility—by simply selecting the MOSFET, the designer may choose output current capability as well as dropout voltage. You may customize your regulator for your exact needs: the dropout voltage is simply $V_{DO} = I \times R_{DS\ ON}$ and the current limit is adjustable by selecting one resistor. Also, by placing the hot pass element away from the sensitive reference and voltage comparators, better performance over the operating temperature range and much higher output currents are possible.

The Super LDO does not offer thermal shutdown protection and the pass MOSFET's tab is V_{OUT} instead of ground, unlike the Super βeta PNP versions.

Above approximately 5A, the Super LDO is generally the most economical regulation solution.

Super LDO	Monolithic LDO
"Any" output current	Output current set by die size
Adjustable current limit	Fixed Current limit
User-selectable dropout voltage	Dropout voltage set by die size
Better stability than PNP LDOs	
Reference temperature independent of hot pass element	Reference gets hot
Pass transistor tab is V_{OUT}	Tab is grounded
No thermal shutdown	Thermal shutdown
Multiple component solution	Only capacitors needed

Table 4-1. Super LDO and Monolithic Regulator Comparison

Unique Super LDO Applications

Super High-Current Regulator

Figure 4-7 shows a linear regulator offering output current to 30A with a dropout voltage of only 330mV. Current limit is set to 45A. With proper cooling and current-limit resistor changes, this circuit scales to any arbitrary output current: 50A, 100A—you name it!

Achieving the heat sinking required for the high current output mentioned above is difficult. As output current and/or input-to-output voltage differentials increase, the heat sink size rapidly increases. One technique to ease the heat sinking problem is to split the heat generators into multiple sources—by using multiple pass MOSFETs in parallel.

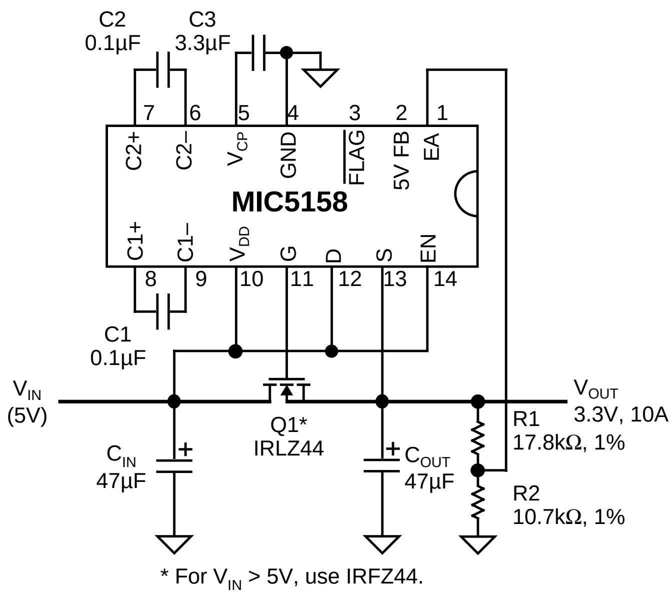


Figure 4-7. A High Current Regulator Using the MIC5158

Unlike bipolar transistors, MOSFETs have a negative temperature coefficient of resistance. This makes them easier to parallel than bipolars. The MOSFET carrying more current heats up; the heat increases the channel resistance, reducing the current flow through that FET.

Unfortunately for Super LDO applications, the MOSFET threshold voltage varies from part-to-part and over the operating temperature range. Unlike power switching applications, Super LDO linear regulator operation of the pass MOSFET is in the linear region, which is at or just above the threshold. This means device-to-device threshold voltage variation causes mismatch.

If two MOSFETs are mounted on the same heat sink, it is possible to directly parallel them in less demanding applications where the maximum output current is within the rating of a single device and total power dissipation is close to that possible with a single unit.

A better solution, usable with two or more MOSFETs in parallel, is to use ballast resistors in series with the source lead (output). Size the ballast resistors to drop a voltage equal to or a bit larger than the worst-case gate-to-source threshold voltage variation. As current flow through one MOSFET and ballast resistor increases, the ballast resistor voltage drop reduces MOSFET V_{GS}, increasing its resistance. This reduces current flow through that MOSFET. Figure 4-8 shows an example of this technique.

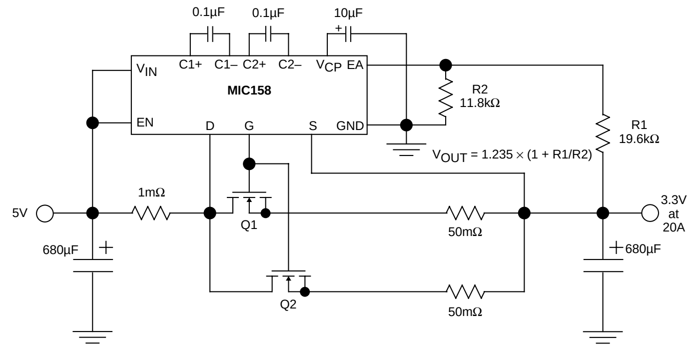


Figure 4-8. Ballast Resistors Promote Current Sharing With Parallel MOSFETs

Lower dropout voltage and even better matching is possible using op amps to force sharing. A low current drain op amp may be powered by the V_{CP} pin of the MIC5157 or MIC5158, as shown in Figure 4-9.

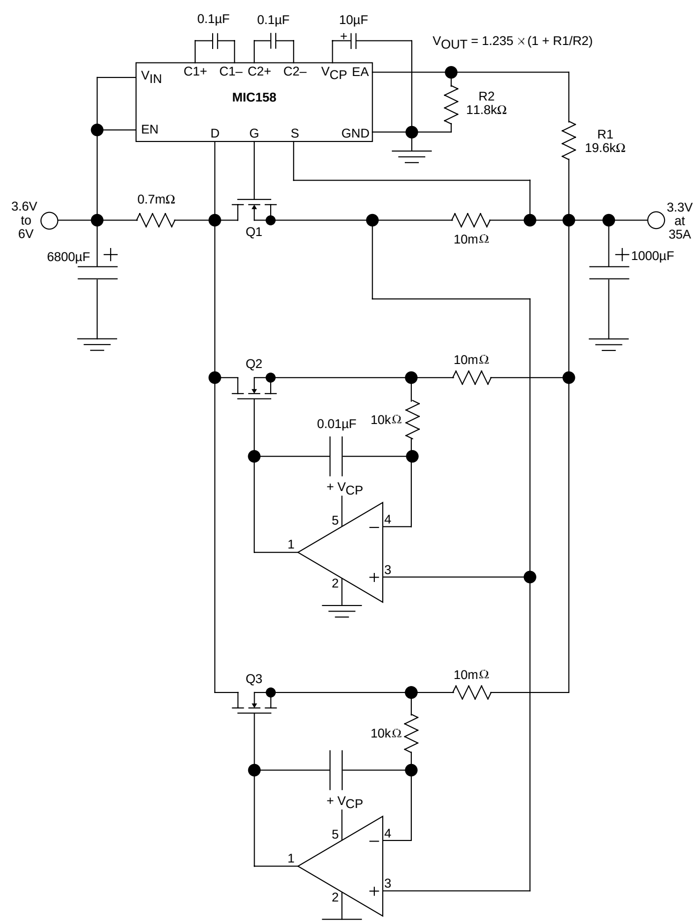


Figure 4-9. Parallel MOSFETs for High Current and/or High Power Dissipation Regulators

Selecting the Current Limit Threshold

By choosing one resistor value, the current limit threshold of the Super LDO is set. The resistor is chosen to drop 35mV at the desired output current limit value. While discrete resistors may be used, a more economical solution is often a length of copper wire or PC board trace used as the current sense resistor. The wire diameter or the width of the copper trace must be suitable for the current density flowing through it, and its length must provide the required resistance.

Sense Resistor Power Dissipation

The power dissipation of sense resistors used in Super LDO regulator circuits is small and generally does not require the power dissipation capability found in most low-value resistors.

Kelvin Sensing

A Kelvin, or four-lead, connection is a measurement connection that avoids the error caused by voltage drop in the high-current path leads.

Referring to Figure 4-10, sense leads are attached directly across the resistance element—intentionally excluding the power path leads. Because the sense conductors carry negligible current (sense inputs are typically high impedance voltage measurement inputs), there is no voltage drop to skew the $E = I \times R$ measurement.

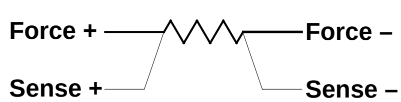


Figure 4-10. A Kelvin-sense Resistor

Manufacturers of Kelvin-sensed resistors are listed in the References section.

Alternative Current Sense Resistors

A low-value resistor can be made from a length of copper magnet wire or from a printed circuit board trace. Tables 4-2, 4-3, and 4-4 are provided for wire and printed circuit traces.

Copper has a positive temperature coefficient of resistivity of +0.39%/°C. This can be significant when higher-accuracy current limiting is required.

A Kelvin connection between the sense element and the Super LDO Regulator Controller improves the accuracy of the current limit set-point.

Table 4-2. Copper Wire Resistance

AWG Wire Size	Resistance at 20°C $10^{-6}\Omega$ / cm	$10^{-6}\Omega$ / in
10	32.70	83.06
11	41.37	105.1
12	52.09	132.3
13	65.64	166.7
14	82.80	210.3
15	104.3	264.9
16	131.8	334.8
17	165.8	421.1
18	209.5	532.1
19	263.9	670.3
20	332.3	844.0
21	418.9	1064.0
22	531.4	1349.8
23	666.0	1691.6
24	842.1	2138.9
25	1062.0	2697.5
26	1345.0	3416.3
27	1687.6	4286.5
28	2142.7	5442.5
29	2664.3	6767.3
30	3402.2	8641.6
31	4294.6	10908.3
32	5314.9	13499.8
33	6748.6	17141.4
34	8572.8	21774.9
35	10849	27556.5
36	13608	34564.3
37	16801	42674.5
38	21266	54015.6
39	27775	70548.5
40	35400	89916.0
41	43405	110248.7
42	54429	138249.7
43	70308	178582.3
44	85072	216082.9

Overcurrent Sense Resistors from PC Board Traces

Building the resistor from printed-circuit board (PCB) copper is attractive; arbitrary values can be provided inexpensively. The ever-shrinking world of electronic assemblies requires minimizing the physical size of this resistor which presents a power-dissipation issue. Making the resistor too small could cause excessive heat rise, leading to PCB trace damage or destruction (i.e., a fuse rather than a controlled resistor).

Table 4-3 Printed Circuit Copper Resistance

Conductor Thickness	Conductor Width (inches)	Resistance $m\Omega$ / in
$0.5oz/ft^2$ (18µm)	0.025	39.3
	0.050	19.7
	0.100	9.83
	0.200	4.91
	0.500	1.97
$1\ oz/ft^2$ (35µm)	0.025	19.7
	0.050	9.83
	0.100	4.91
	0.200	2.46
	0.500	0.98
$2oz/ft^2$ (70µm)	0.025	9.83
	0.050	4.91
	0.100	2.46
	0.200	1.23
	0.500	0.49
$3oz/ft^2$ (106µm)	0.025	6.5
	0.050	3.25
	0.100	1.63
	0.200	0.81
	0.500	0.325

Resistor Design Method

Three design equations provide a resistor that occupies the minimum area. This method considers current density as it relates to heat dissipation in a surface layer resistor.

(4-1) $$\rho_S(T) = \frac{\rho\left[1+\alpha\left(T_A + T_{RISE} - 20\right)\right]}{h}$$

where:

$\rho_S(T)$ = sheet resistance at elevated temp. (Ω/□)
ρ = 0.0172 = copper resistivity at 20°C (Ω • µm)
α = 0.00393 = temperature coefficient of ρ (per °C)
T_A = ambient temperature (°C)
T_{RISE} = allowed temperature rise (°C)
h = copper trace height (µm, see Table 4-4)

(4-2) $$w = \frac{1000 I_{MAX}}{\sqrt{\frac{T_{RISE} \div \theta_{SA}}{\rho_S(T)}}}$$

where:

w = minimum copper resistor trace width (mils)
I_{MAX} = maximum current for allowed T_{RISE} (A)
T_{RISE} = allowed temperature rise (°C)
θ_{SA} = resistor thermal resistance (°C × in^2/W)
$\rho_S(T)$ = sheet resistance at elevated temp. (Ω/□)
Note: $\theta_{SA} \approx 55$ °C • in^2/W

(4-3) $$l = \frac{wR}{\rho_S(T)}$$

where:

l = resistor length (mils)
w = resistor width (mils)
R = desired resistance (Ω)
$\rho_S(T)$ = sheet resistance at elevated temp. (Ω/□).

PCB Weight (oz/ft^2)	Copper Trace Height (mils)	Copper Trace Height (µm)
1/2	0.7	17.8
1	1.4	35.6
2	2.8	71.1
3	4.2	106.7

Table 4-4. Copper Trace Heights

Design Example

Figure 4-11 is a circuit designed to produce a 3.3V, 10A output from a 5V input. Meeting the design goal of occupying minimal PC board space required minimizing sense resistor area. This resistor is shown as R_S.

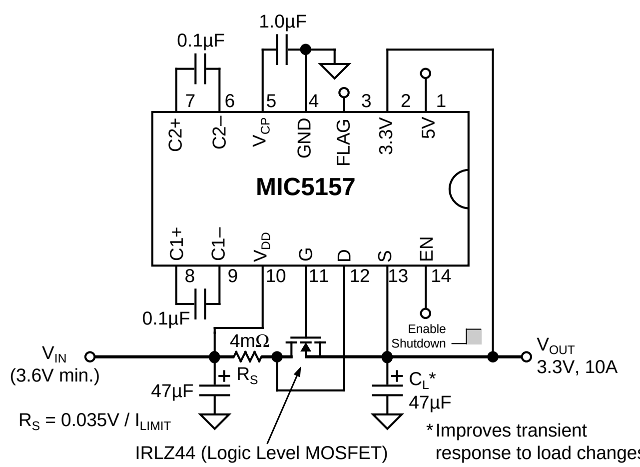


Figure 4-11. Regulator Circuit Diagram

The 4mΩ current-sensing resistor (R_S) of Figure 4-11 is designed as follows: (1) based on copper trace height and an allowed temperature rise for the resistor, calculate the sheet resistance using Equation 4-1; (2) based on the maximum current the resistor will have to sustain, calculate its minimum trace width using Equation 4-2; and (3) based on the desired resistance, calculate the required trace length using Equation 4-3.

Calculate Sheet Resistance

This design uses 1 oz/ft^2 weight PCB material, which has a copper thickness (trace height) of 35.6µm. See Table 4-4. Allowing the resistor to produce a 75°C temperature rise will place it at 100°C (worst case) when operating in a 25°C ambient environment:

$$\rho_S(T) = 635 \times 10^{-6}\ \Omega = 0.635\ \text{m}\Omega/\square.$$

Calculate Minimum Trace Width

The design example provides an output current of 5A. Because of resistor tolerance and the current-limit trip-point specification of the MIC5158 (0.028 to 0.042V), a trip-point of 8.75A is chosen, allowing for as much as 10A of current during the sustained limiting condition:

$$w = 215.8 \text{ mils} \approx 216 \text{ mils}.$$

Calculate Required Trace Length

The length of a 4mΩ resistor is determined via Equation 4-3 as follows:

$$l = 1360.6 \text{ mils} \approx 1361 \text{ mils}.$$

Resistor Layout

To avoid errors caused by voltage drops in the power leads, the resistor should include Kelvin sensing leads. Figure 4-12 illustrates a layout incorporating Kelvin sensing leads.

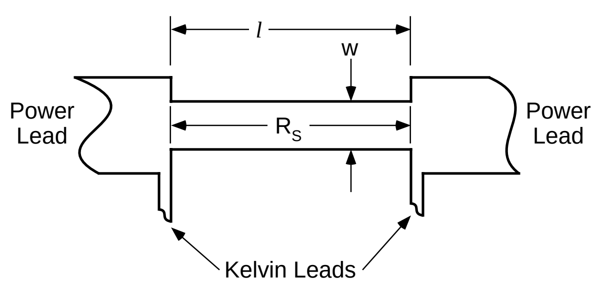


Figure 4-12. Typical Kelvin Resistor Layout

Thermal Considerations

The previous equations produce a resistance of the desired value at *elevated temperature*. It is important to consider resistance at temperature because copper has a high temperature coefficient. This design method is appropriate for current-sensing resistors because their accuracy should be optimized for the current they are intended to sense.

Resistor Dimensions Spreadsheet

A spreadsheet is available to ease the calculation process. Its source code, in Lotus 1-2-3 format, is available via e-mail from Micrel. Send a message to `apps@micrel.com` requesting “SENSERES.WK1”

Design Aids

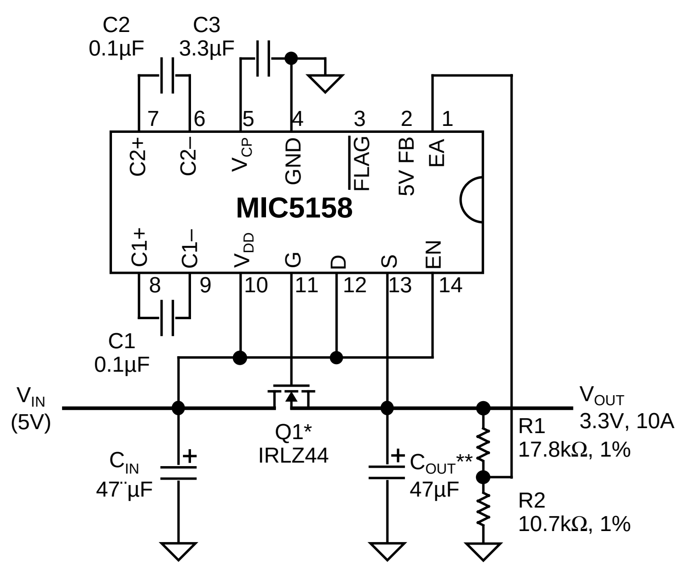
Table 4-4 provides an input needed for Equation 4-1 (trace height), and Figure 3-63 [from Section 3, *Thermal Management*] indicates that 1 in^2 (645 mm^2) of solder-masked copper in still air has a thermal resistance of 55°C/W. Different situations; e.g., internal layers or plated copper, will have different thermal resistances. Other references include MIL-STD-275E: *Printed Wiring for Electronic Equipment.*

Highly Accurate Current Limiting

Improving upon the accuracy of the current limit mechanism is possible. Refer to Section 3 for a description of using the Super LDO as a highly accurate adjustable current source.

Protecting the Super LDO from Long-Term Short Circuits

Foldback current limiting is a useful feature for regulators like the Super LDO that do not have overtemperature shutdown.



* For V_{IN} > 5V, use IRFZ44.
** Improves transient response to load changes.

Figure 4-13. Simple 10A, 5V-to-3.3V, Voltage Regulator

A momentary short can increase power dissipation in a MOSFET voltage regulator pass device to a

catastrophic level. In the circuit of Figure 4-13, normal Q1 power dissipation is $I_{OUT} \times V_{DS}$, or

$$(5 - 3.3)V \times 10A = 17W.$$

Given the 0.028Ω $R_{DS(ON)}$ of the IRLZ44, if the output of the power supply is shorted, power dissipation becomes $(V_{IN}/R_{DS(ON)})^2 \times R_{DS(ON)}$, or an unworkable 892W. Conservative heat sink design will not help matters!

The Micrel MIC5156/5157/5158 Super LDO™ Regulator Controllers offer two features that can be used to save the pass device. The first feature is a current limit capability (not implemented in Figure 4-13). Output current can be limited at a user-defined value, but the function is not the classic foldback scheme. While fixed-value current limiting can reduce shorted-output power dissipation to a manageable level, the additional dissipation imposed by the short can still threaten the pass device. Power dissipation of a current-limited supply is the full supply voltage multiplied by the current limit of the regulator system: 5V × (>) 10A > 50W. At higher input supply voltages and/or higher current limit levels, power dissipation rises rapidly—a 30V supply limited to 10A has a short-circuit dissipation of 300W. When considerable voltage is being dropped by the pass device the short-circuit power dissipation becomes dramatically high.

The second feature offered by the MIC5156/5157/5158 is an error flag. This is an open-collector output which generates a signal if the output voltage is approximately 6% or more below the intended value. This flag output is asserted logic low in the event of a shorted output, and may be used to control the enable-input pin of the regulator, disabling it upon detection of a low output voltage condition.

An Example

Figure 4-14 implements both the current-limit capability and a control scheme for dealing with shorted outputs. The 2.3mΩ resistor R_S provides for current limiting at about 15A. Since a shorted output may be momentary, the circuitry built around U1 automatically restarts the regulator when a short is removed. Existence of a shorted output is continually monitored; the system will protect the pass device for an indefinite time. When a short exists the regulator is enabled for a very brief interval and disabled for a much longer interval. Power dissipation is reduced by this drop in duty cycle, which may be empirically designed.

Circuit Description

Schmitt-trigger NAND-gate A is used to control a gated oscillator (gate B). Resistors R5 and R6, diode D3, and capacitor C5 provide oscillator timing. With the values shown the enable time is about 110ms approximately every 2.25ms. This provides a safe 1:20 ON/OFF ratio (5% duty cycle) for reducing power dissipated by the pass device. Diode D2 keeps C5 discharged until gate A enables the oscillator. This assures that oscillation will begin with a full-width short enable pulse. Different enable and/or disable times may be appropriate for some applications. Enable time is approximately k1 × R5 × C5; disable time is approximately k2 × R6 × C5. Constants k1 and k2 are determined primarily by the two threshold voltages (V_T+ and V_T–) of Schmitt-trigger gate B. Values for k1 and k2 (empirically derived from a breadboard) are 0.33 and 0.23, respectively. Component tolerances were ignored.

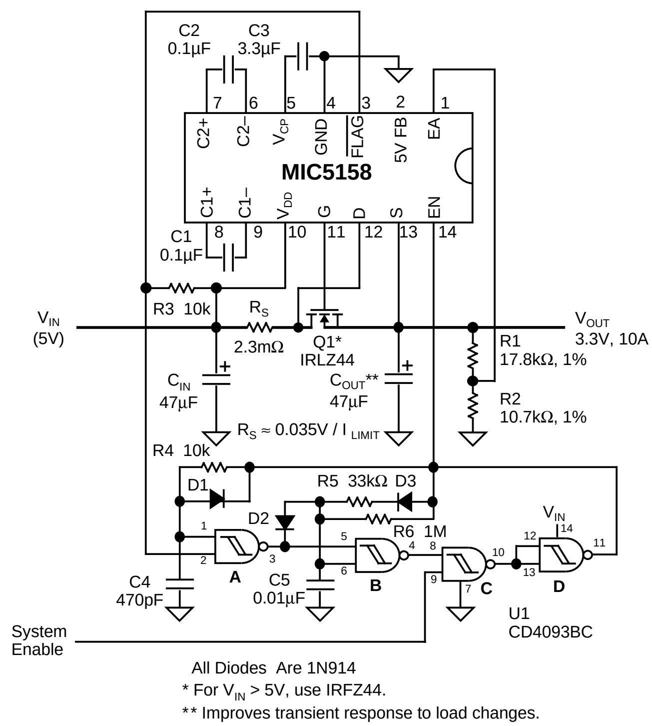


Figure 4-14. Short-Circuit Protected 10A Regulator

Getting Started

The protection circuitry provides a system enable input. Use of this input is optional; it should be tied to V_{IN} if not required. Since the output of gate B is logic high when the oscillator is disabled, a logic-high system enable input enables the MIC5158, which immediately produces a brief logic-low flag output because initially, the output voltage is too low. Since

the power supply output may or may not be shorted it is desirable to wait and see. The required wait-delay timing is implemented by resistor R4, capacitor C4, and diode D1. The leading-edge of the regulator enable signal is delayed (before application to gate A) for about 4ms, to attempt to span the width of the logic-low flag that is generated during a normal (non-shorted) regulator start-up.

Providing enough delay time to span the time of the flag may not always be practical, especially when starting with high-capacitance loads. If the logic-low flag is longer than the delayed enable input to gate A, the oscillator will cycle through its ON/OFF duty cycle and the circuit will again attempt a normal start-up. This will result in a slowing of the regulator turn-on, but this is not usually objectionable because it reduces turn-on surge currents.

After start-up, the logic-high inputs to gate A hold the oscillator off, and the system remains enabled as long as no error flag is generated. If the flag is generated due to a short, the MIC5158 remains enabled only for the time of the oscillator enable pulse and is then immediately disabled for the duration of the oscillator cycle. As long as the short exists, the oscillator runs and the system monitors the flag to detect removal of the short. Meanwhile the MOSFET stays alive, and the system again starts when the short is removed.

Section 5. Omitted

Data Sheet Reference Section Omitted for This Online Version

http://www.micrel.com

Section 6. Package Information

See Table of Contents

Packaging for Automatic Handling

Tape & Reel

Surface mount and TO-92 devices are available in tape and reel packaging. Surface mount components are retained in an embossed carrier tape by a cover tape. TO-92 device leads are secured to a backing tape by a cover tape. The tape is spooled on standard size reels.

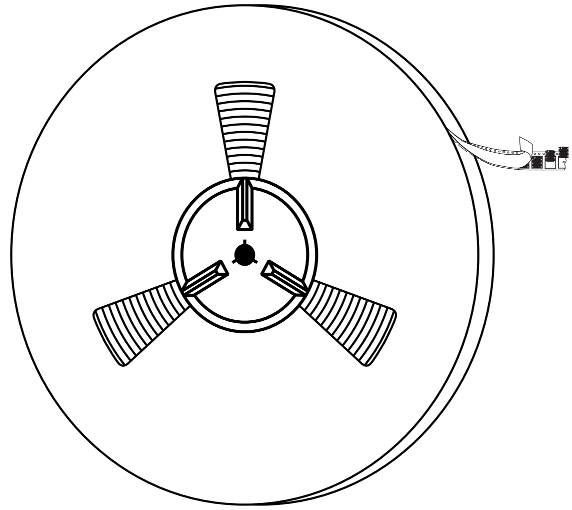
Ammo Pack

TO-92 devices are also available in an "ammo pack." TO-92 devices are secured to a backing tape by a cover tape and are fanfolded into a box. Ammo packs contain the same quantity, feed direction, and component orientation as a reel.

To order, specify the complete part number with the suffix "AP" (*example*†*: MICxxxxx***Z** AP).

Pricing

Contact the factory for price adder and availability.



Typical 13" Reel for Surface Mount Components

Tape & Reel Standards

Embossed tape and reel packaging conforms to:

- *8mm & 12mm Taping of Surface Mount Components for Automatic Handling*, EIA-481-1*
- *16mm and 24mm Embossed Carrier Taping of Surface Mount Components for Automatic Handling*, EIA-481-2*
- *32mm, 44mm and 56mm Embossed Carrier Taping of Surface Mount Components for Automatic Handling*, EIA-481-3*

Packages Available in Tape & Reel

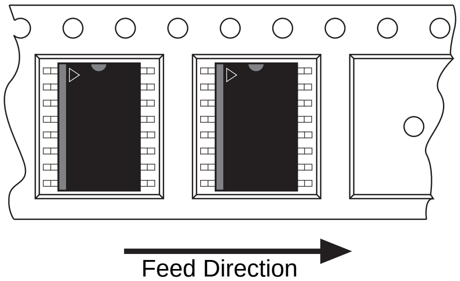
Part Number†	Package Description	Quantity / Reel	Reel Diameter	Carrier Tape Width	Carrier Tape Pitch
*MICxxxxx***M** T&R	8-lead SOIC	2,500	13"	12mm	8mm
	14-lead SOIC	2,500	13"	16mm	8mm
	16-lead SOIC	2,500	13"	16mm	8mm
*MICxxxx***WM** T&R	16-lead wide SOIC	1,000	13"	16mm	12mm
	18-lead wide SOIC	1,000	13"	16mm	12mm
	20-lead wide SOIC	1,000	13"	24mm	12mm
	24-lead wide SOIC	1,000	13"	24mm	12mm
*MICxxxx***SM** T&R	28-lead SSOP	1,000	13"	16mm	12mm
*MICxxxxx***V** T&R	20-lead PLCC	1,000	13"	16mm	12mm
	28-lead PLCC	500	13"	24mm	16mm
	44-lead PLCC	500	13"	32mm	24mm
*MICxxxxx***M4** T&R	SOT-143	3,000	7"	8mm	4mm
*MICxxxxx***M3** T&R	SOT-23	3,000	7"	8mm	4mm
*MICxxxxx***M5** T&R	SOT-23-5	3,000	7"	8mm	4mm
*MICxxxxx***S** T&R	SOT-223	2,500	13"	16mm	12mm
*MICxxxxx***U** T&R	3-lead TO-263	750	13"	24mm	16mm
	5-lead TO-263	750	13"	24mm	16mm
*MICxxxxx***Z** T&R	TO-92	2,000	14¼"‡	—	1/2"

* Standards are available from: Electronic Industries Associations, EIA Standards Sales Department, tel: (202) 457-4966

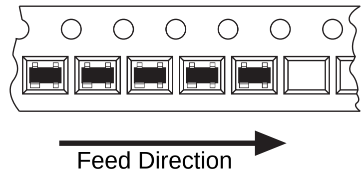
† xxxxx = base part number + temperature designation. Example: MIC<u>5201B</u>M T&R

‡ Cardboard reel

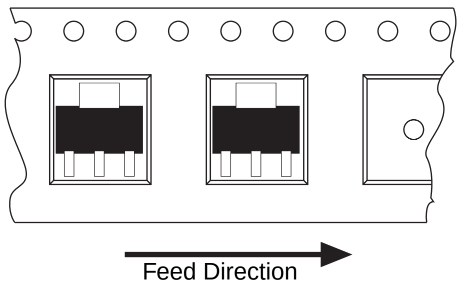
Package Orientation



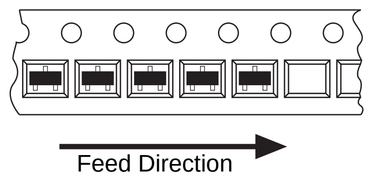
Typical SOIC Package Orientation
12mm, 16mm, 24mm Carrier Tape



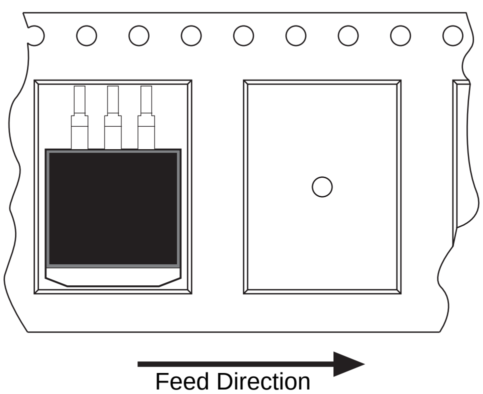
SOT-143 Package Orientation
8mm Carrier Tape



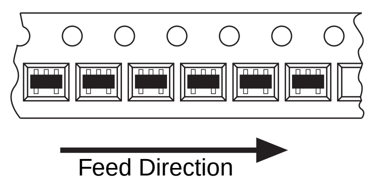
SOT-223 Package Orientation
16mm Carrier Tape



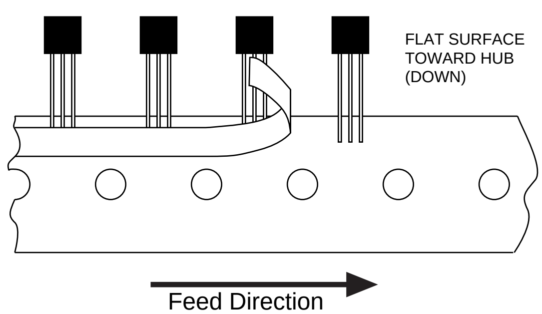
SOT-23 Package Orientation
8mm Carrier Tape



Typical TO-263 Package Orientation
24mm Carrier Tape

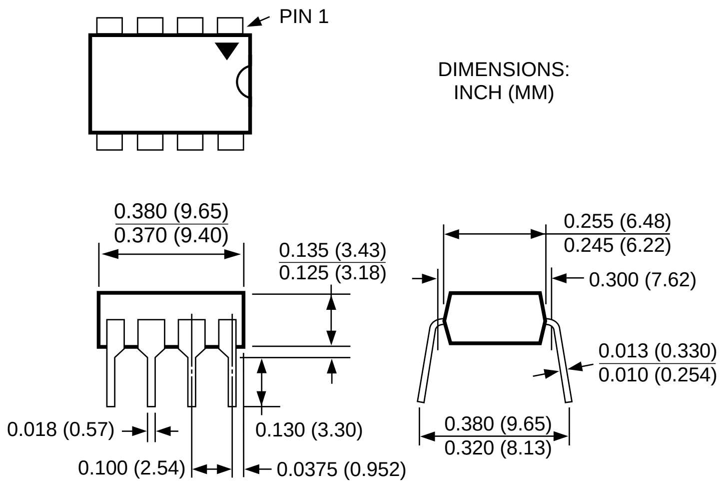


SOT-23-5 Package Orientation
8mm Carrier Tape

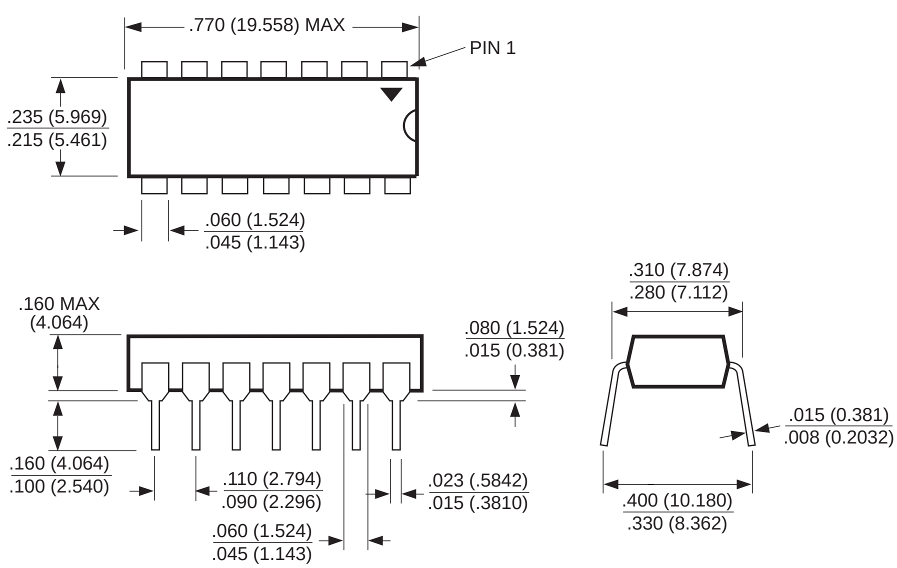


Typical TO-92 Package Orientation

Linear Regulator Packages

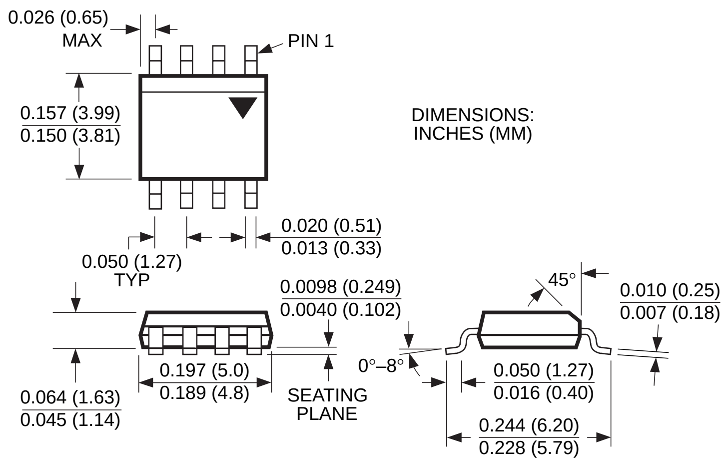


8-Pin Plastic DIP (N)

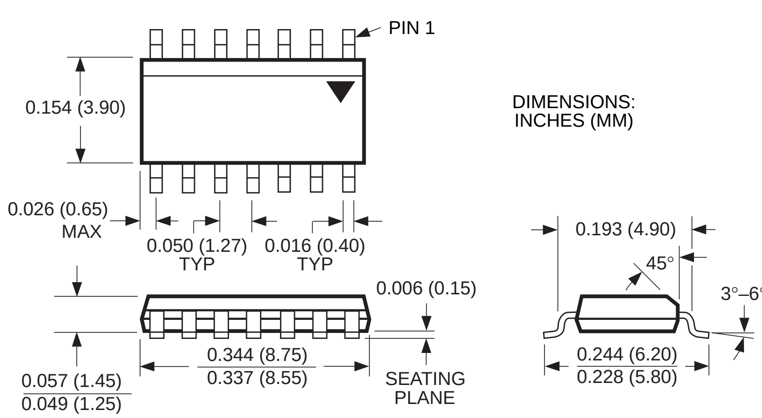


14-Pin Plastic DIP (N)

Note: Pin 1 is denoted by one or more of the following: a notch, a printed triangle, or a mold mark.

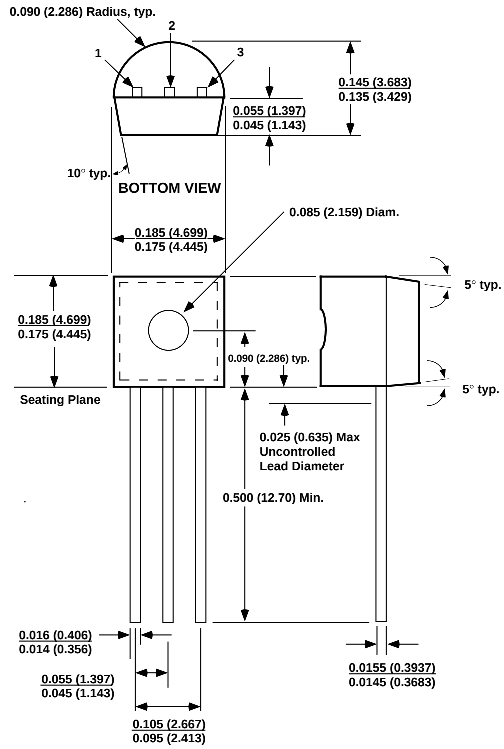


8-Pin SOIC (M)

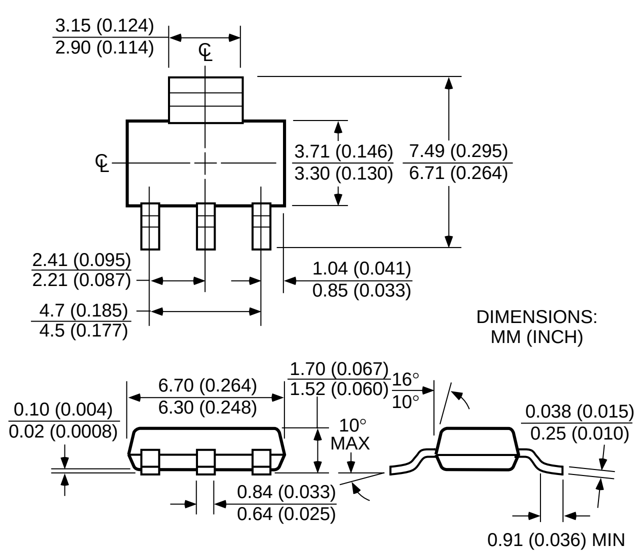


14-Pin SOIC (M)

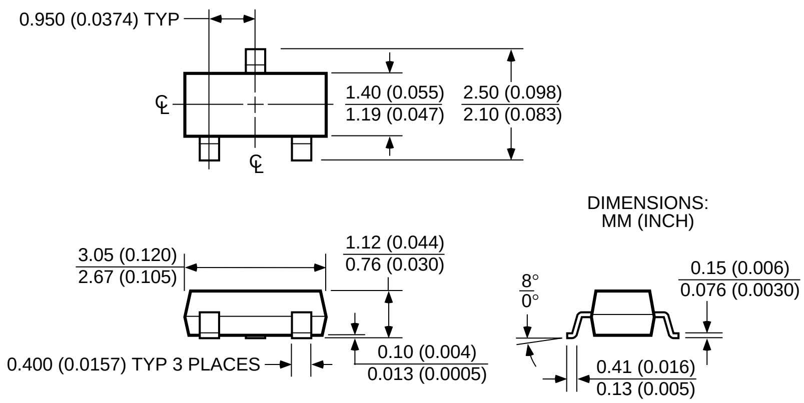
Note: Pin 1 is denoted by one or more of the following: a notch, a printed triangle, or a mold mark.



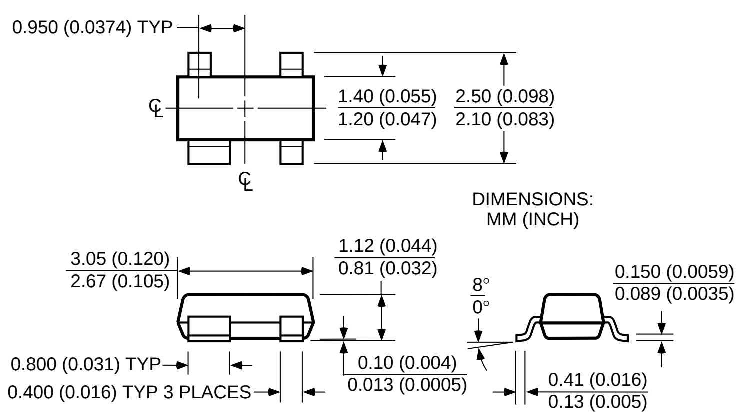
TO-92 (Z)



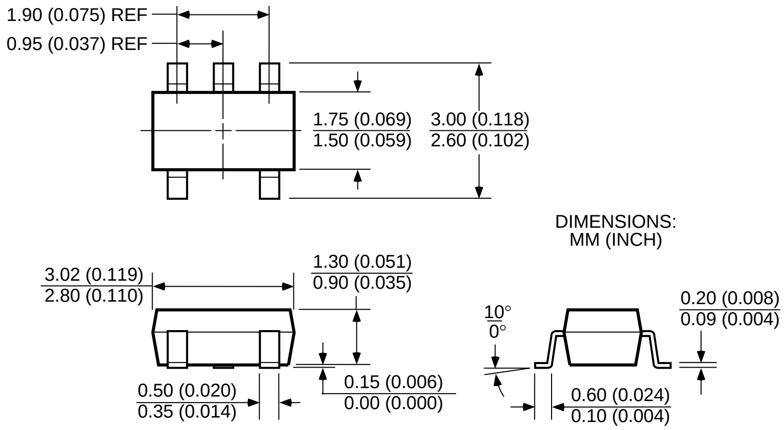
SOT-223 (S)



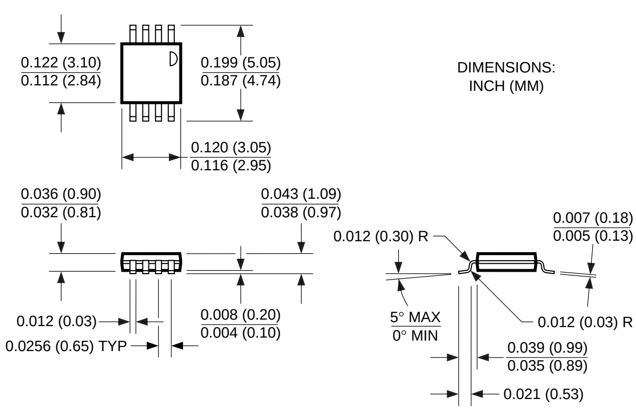
SOT-23 (M3)



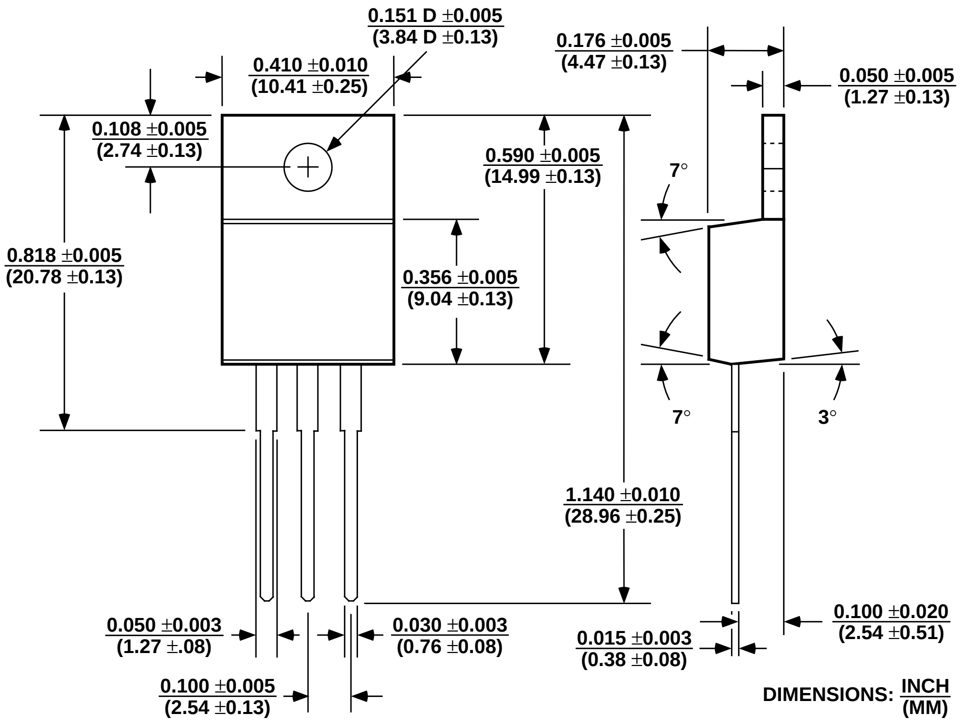
SOT-143 (M4)



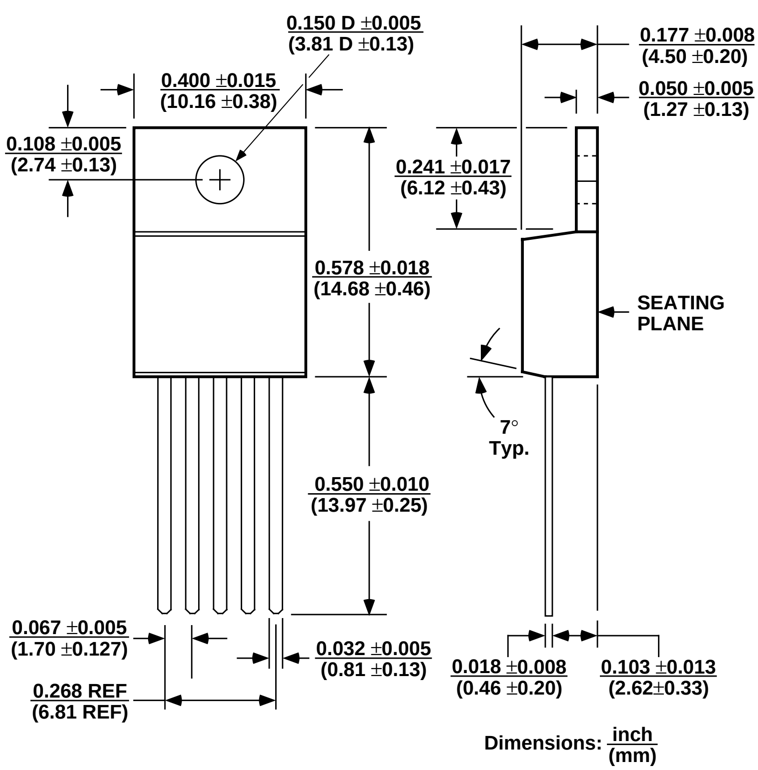
SOT-23-5 (M5)



MSOP-8 [MM8™] (MM)



3-Lead TO-220 (T)



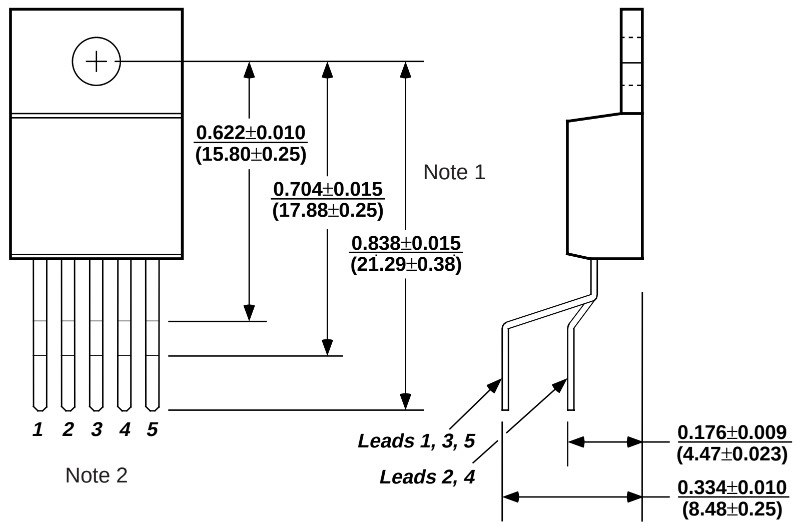
5-Lead TO-220 (T)

TO-220 Lead Bend Options *Contact Factory for Availability*

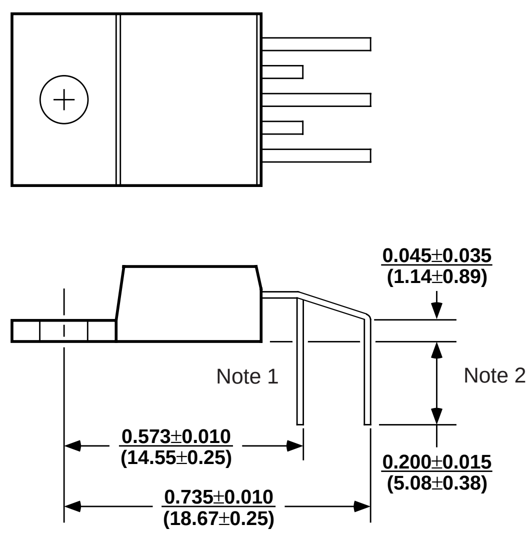
Part Number	Package	Lead Form
MICxxxxyT	5-lead TO-220	none (straight)
MICxxxxyT-LB03	5-lead TO-220	vertical, staggered leads, 0.704" seating
MICxxxxyT-LB02	5-lead TO-220	horizontal, staggered leads

MICxxxx = base part number, y = temperature range, T = TO-220

* Leads not trimmed after bending.



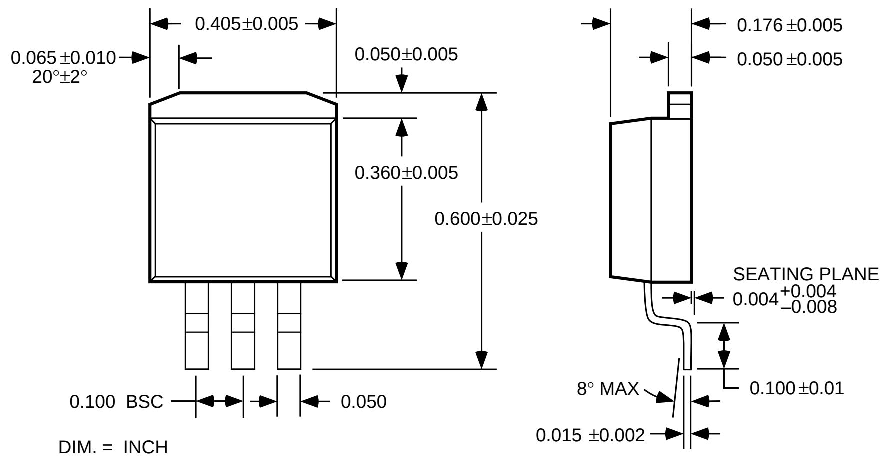
5-Lead TO-220 Vertical Lead Bend Option (-LB03)



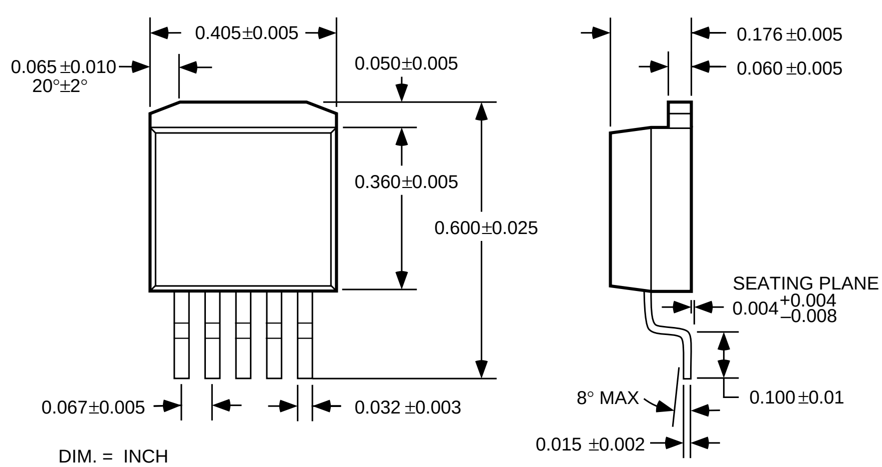
5-Lead TO-220 Horizontal Lead Bend Option (-LB02)

Note 1. Lead protrusion through printed circuit board subject to change.

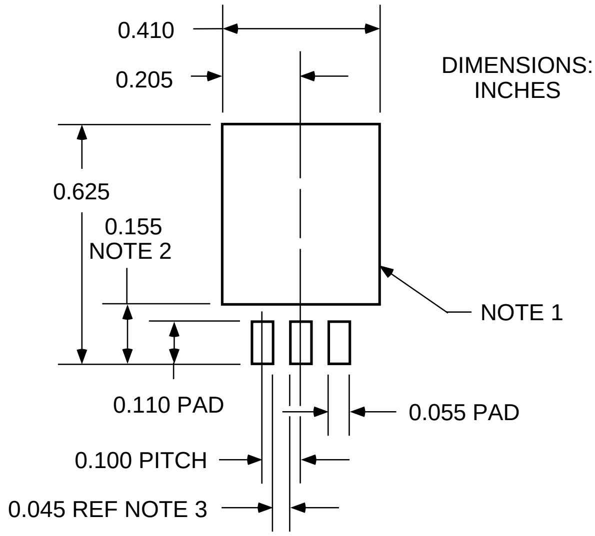
Note 2. Lead ends may be curved or square.



3-Lead TO-263 (U)

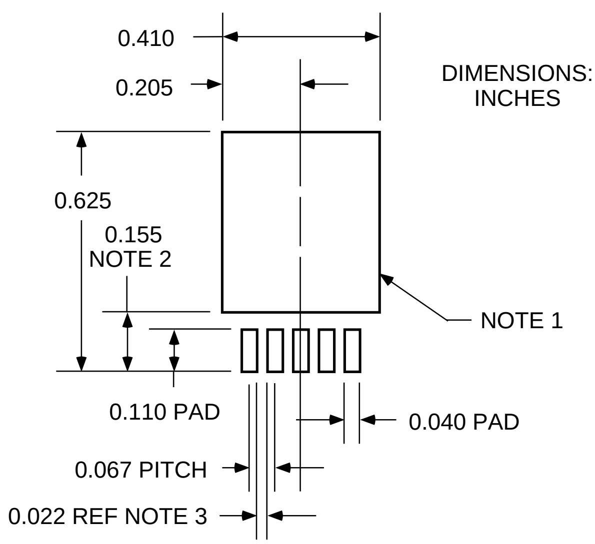


5-Lead TO-263 (U)



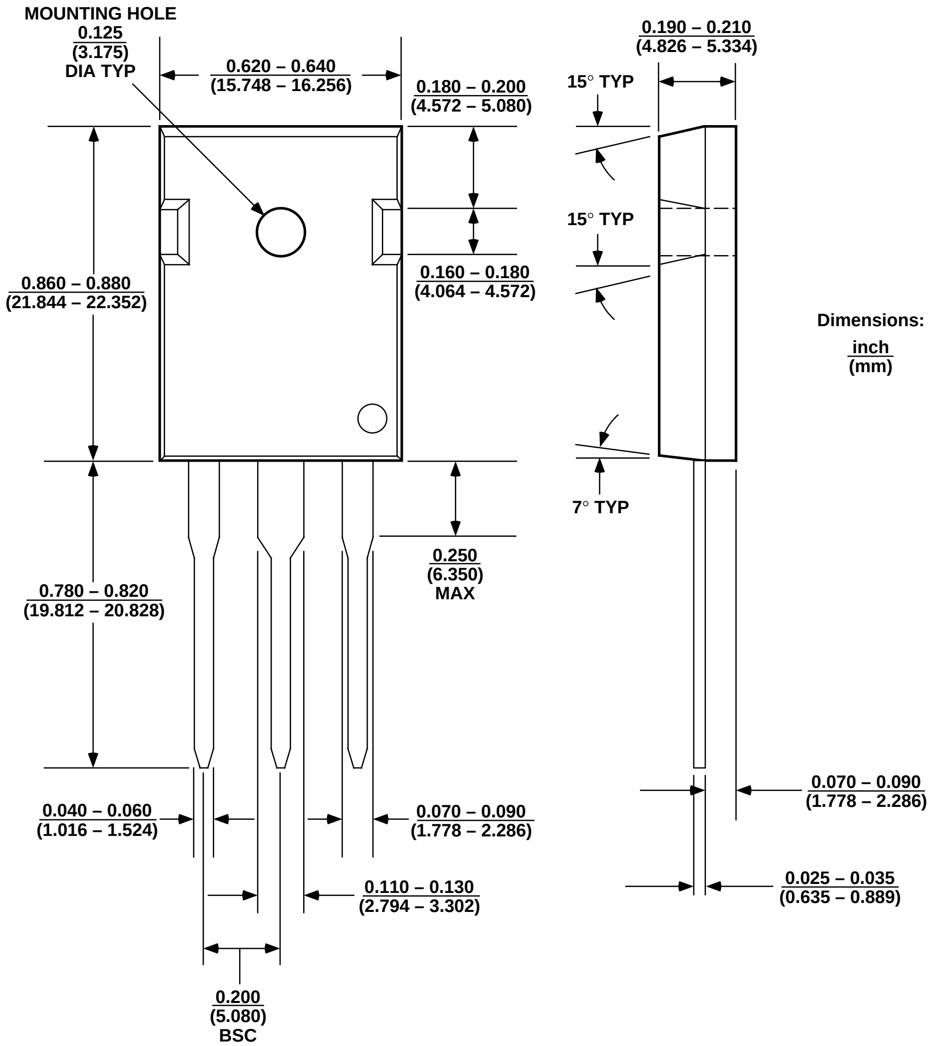
NOTE 1: PAD AREA MAY VARY WITH HEAT SINK REQUIREMENTS
NOTE 2: MAINTAIN THIS DIMENSION
NOTE 3: AIR GAP (REFERENCE ONLY)

Typical 3-Lead TO-263 PCB Layout

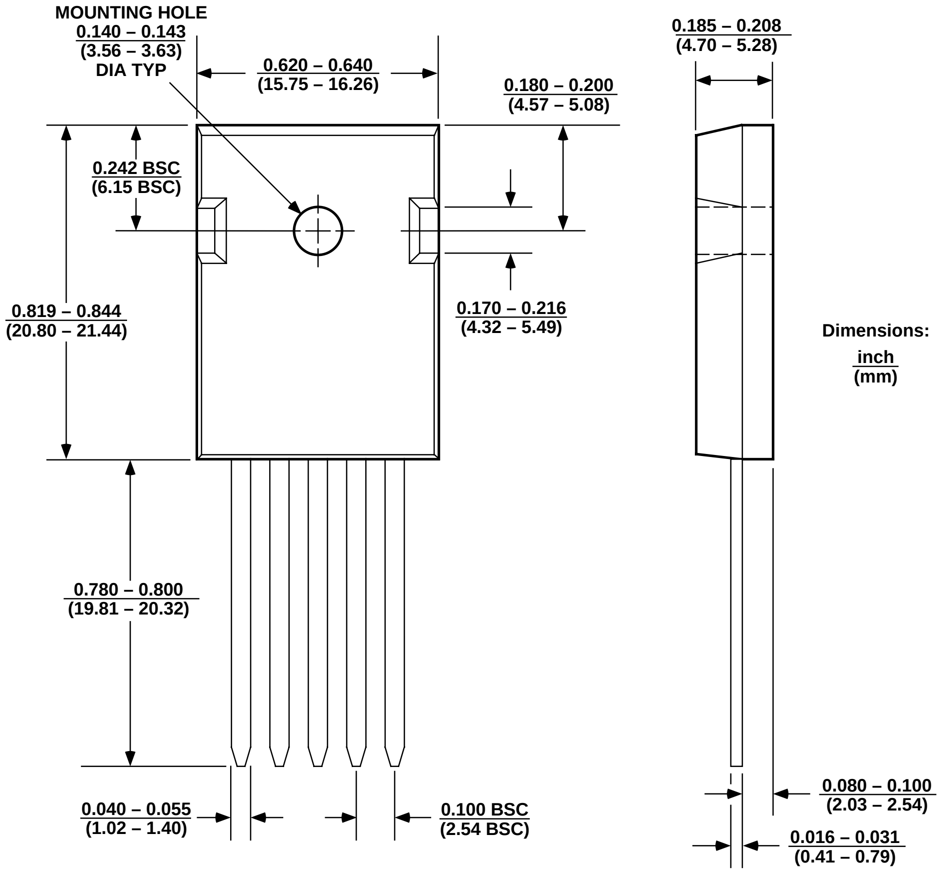


NOTE 1: PAD AREA MAY VARY WITH HEAT SINK REQUIREMENTS
NOTE 2: MAINTAIN THIS DIMENSION
NOTE 3: AIR GAP (REFERENCE ONLY)

Typical 5-Lead TO-263 PCB Layout



3-Lead TO-247 (WT)



5-Lead TO-247 (WT)

Section 7. Appendices

List of Appendices

Appendix A. Table of Standard 1% Resistor Values 90
Appendix B. Table of Standard ±5% and ±10% Resistor Values 91
Appendix C. LDO SINK for the HP 48 Calculator 92

Appendix A. Table of Standard 1% Resistor Values

100	215	464
102	221	475
105	226	487
107	232	499
110	237	511
113	243	523
115	249	536
118	255	549
121	261	562
124	267	576
127	274	590
130	280	604
133	287	619
137	294	634
140	301	649
143	309	665
147	316	681
150	324	698
154	332	715
158	340	732
162	348	750
165	357	768
169	365	787
174	374	806
178	383	825
182	392	845
187	402	866
191	412	887
196	422	909
200	432	931
205	442	953
210	453	976

This table shows three significant digits for standard ±1% resistor values. These significant digits are multiplied by powers of 10 to determine resistor values. For example, standard resistor values are 0.100Ω, 1.00Ω, 1.00kΩ, 1.00MΩ, 100MΩ, etc.

Appendix B. Table of Standard ±5% and ±10% Resistor Values

(±10% values in **bold**)

10
11
12
13
15
16
18
20
22
24
27
30
33
36
39
43
47
51
56
62
68
75
82
91

This table shows two significant digits for the standard ±5% and ±10% resistor values. These significant digits are multiplied by powers of 10 to determine resistor values. For example, standard resistor values are 0.1Ω, 1.0Ω, 1.0kΩ, 1.0MΩ, 10MΩ, etc.

Appendix C. LDO SINK for the HP 48 Calculator

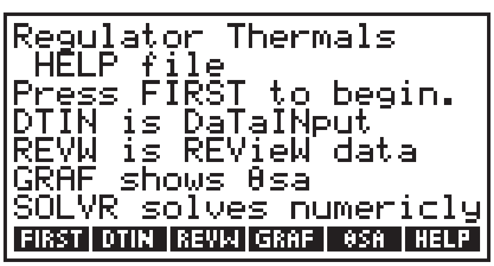
The following program, written for the HP 48 calculator, will calculate all power dissipation and heat sink related parameters and ease your design optimization process. It will also graph the resulting heat sink characteristics versus input voltage. The program listing follows the user information. It was written on a HP 48S and runs on both the “S” and the 48G(X) version of the calculator. If you would like to receive the program electronically, send e-mail to Micrel at `apps@micrel.com` and request program “LDO SINK for the HP48”. It will be sent via return e-mail.

Using LDO SINK

After loading the program, change to the directory containing it. In the example shown, it is loaded into `{HOME MICREL LDO SINK}`.

The first screen you will see looks like this:

Pressing the white `HELP` function key displays a screen of on-line help.



Pressing either `FIRST` or `DTIN` will start the program and prompt you for the most commonly changed data. `REVW` brings up a list of data already entered. `GRAF` draws the heat sink θSA versus input voltage. `SOLVR` begins the built-in solve routine that allows you to solve for any variable numerically.

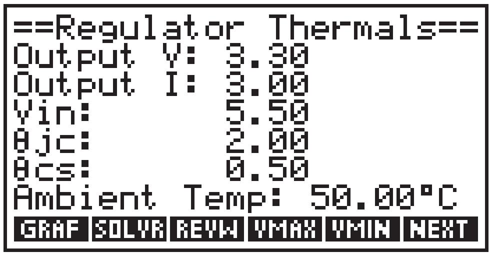
Let’s run the program. Press `FIRST` to begin. Your screen shows:

After a brief pause, the output voltage prompt appears:

Enter a new number and press ← `CONT` to continue. If the data previously entered is still correct, you may simply press ← `CONT` to retain it. Proceed through the list, entering data as prompted and pressing ← `CONT` to continue. You will be prompted for

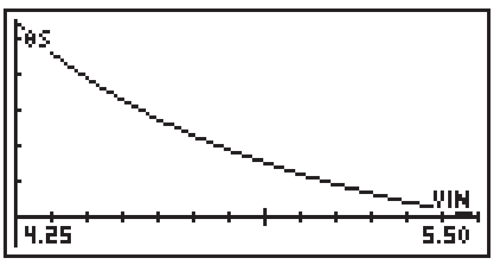
- `Vout` the desired regulator output voltage
- `Iout` regulator output current
- `Vmax` the maximum input voltage
- `Vmin` the lowest input voltage (used only by the graphing routine
- `θjc` thermal resistance, junction to case (from the device data sheet)
- `θcs` thermal resistance from the case to the heat sink

After these data are entered, the Review screen appears and confirms your entries.



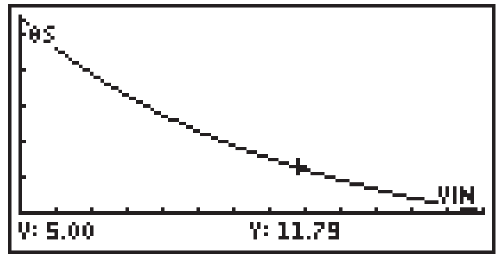
Ambient temperature was not on the list of prompted data. If you wish to change it, press `ON` (`CANCEL`) followed by the white `NEXT` key. Enter the ambient temperature followed by the white `TA` key. Press the white `NEXT` key twice to get to the calculation menu. Another variable used but not prompted for is `TJM`, the maximum junction temperature for the regulator.

You may now press `GRAF` to calculate and view the θ`sa` versus `Vin` graph, or `SOLVR` to start the numerical solve routine. If we press `GRAF`, the following is displayed:

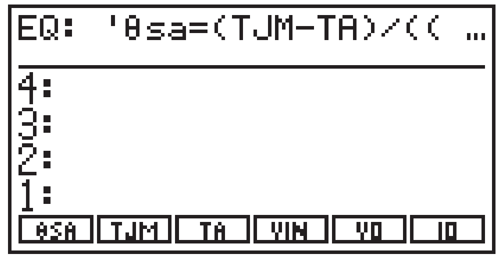


This shows the thermal resistance of the heat sink as the input voltage varies from a low of 4.25V to a high of 5.50V. Pressing `ON/CANCEL` at this time returns you to the stack display, with θ`sa` at the maximum input voltage displayed.

NOTE: the x-axis is shown beneath the HP 48 graph menu. Press the minus (–) key to toggle between the menu and axis display. Pressing `TRACE` followed by `(X,Y)` puts the HP 48 in trace mode and displays the coordinate values of the plot. Press the cursor keys to move around the plot and show voltage (V) versus θ`sa` and displays the coordinate values of the plot. Press the cursor keys to move around the plot and show voltage (V) versus θ`sa` (y-axis). Here the cursor has been moved to a `Vin` of 5.00V and shows a required maximum θ`sa` of 11.79 C/W.



Pressing `ON/CANCEL` returns you to the calculation menu. If you hit the white `SOLVR` key, the HP 48 Solve application is started and you may solve for any of the variables numerically.



Enter a value and press its white function key to modify variables. Use the HP 48 `NXT` key to access θ`jc` and θ`cs`. Solve for a variable by pressing the ← key followed by the variable's white function key. Press → `VIEW` (HP 48G) or ← `REVIEW` (HP 48S) to review all variable values.

Program Listing

For those without the HP 48 compatible serial cable or e-mail access, here is the program listing for LDO SINK. "SINK" is installed as a directory. It is 1948.5 bytes long and has a checksum of # 35166d.

```
%%HP: T(1)A(D)F(.);
DIR
  FIRST
    « DTIN
    »
  DTIN
    « CLLCD
"Regulator Thermals
Enter data, then press
← CONT"
1 DISP 3 WAIT CLEAR
VO "Vout=" VO + "?"
+ PROMPT 'VO' STO
CLEAR IO "Iout=" IO
+ "?" + PROMPT 'IO'
```

```
STO CLEAR VMAX
"Vmax=" VMAX + "?"
+ PROMPT 'VMAX' STO
CLEAR VMIN "Vmin="
VMIN + "?" + PROMPT
'VMIN' STO CLEAR
θJC "θjc=" θJC +
"?" + PROMPT 'θJC'
STO CLEAR θCS
"θcs=" θCS + "?" +
PROMPT 'θCS' STO
REVW
    »
  REVW
    « CLLCD
"==Regulator Thermals=="
1 DISP "Output V: "
VO + 2 DISP
"Output I: " IO + 3
DISP "Vin:      "
VMAX VMAX 'VIN' STO
+ 4 DISP
"Ambient Temp: " TA
+ "°C" + 7 DISP
"θjc:      " θJC +
5 DISP "θcs:      "
θCS + 6 DISP NEX1
TMENU 3 FREEZE
    »
  GRAF
    « CLLCD
"Regulator Thermals
   Graphing θsa vs Vin"
2 FIX 1 DISP '(TJM-
TA)/((1.02*VIN-VO)*
IO)-θJC-θCS' STEQ
FUNCTION 'VIN'
INDEP VMIN VMAX
XRNG VMIN VMAX
'VIN' STO EQ EVAL
R+C AXES { "Vin"
"θS" } AXES AUTO
ERASE DRAW DRAX
LABEL VMAX 'VIN'
STO EQ EVAL 1 TRNC
"θsa(min)" →TAG
PICTURE
    »
  θsa 1.19549150037
  HELP
    « CLLCD
"Regulator Thermals
 HELP file
Press FIRST to begin.
DTIN is DaTaINput
REVW is REVieW data
GRAF shows θsa
SOLVR solves numericly"
1 DISP 3 FREEZE
    »
  NEX1 { GRAF {
"SOLVR"
    « HS STEQ 30
MENU
    » } REVW VMAX
VMIN { "NEXT"
    « NEX2 TMENU
    » } }
  NEX2 { VO IO VIN
TA TJM { "NEXT"
    « NEX3 TMENU
    » } }
  NEX3 { θJC θCS ""
"" HELP { "NEXT"
    « NEX1 TMENU
    » } }
```

Variables

```
  θJC 2
  VMAX 5.5
  VMIN 4.25
  HS 'θsa=(TJM-TA)/
((1.02*VIN-VO)*IO)-
θJC-θCS'
  PPAR {
(4.25,6.47110814478)
(5.5,22.6889168766)
VIN 0 {
(4.25,8.5864745011)
"Vin" "θS" }
FUNCTION Y }
  EQ 'θsa=(TJM-TA)/
((1.02*VIN-VO)*IO)-
θJC-θCS'
  θCS .5
  IO 6
  VO 3.3
  VIN 5.5
  TJM 125
  TA 75
END
```

Section 8. Low-Dropout Voltage Regulator Glossary

Dropout (Voltage)

The minimum value of input-to-output voltage differential required by the regulator. Usually defined as the minimum additional voltage needed before the regulator's output voltage dips below its normal in-regulation value, and regulation ceases. For example, if an output of 5V is desired, and the regulator has a dropout voltage (V_{DO}) of 0.3V, then at least 5.3V is required on the regulator input.

Enable

Digital input allowing ON/OFF control of the regulator. Also called "control or "shutdown" (see Shutdown, below). Enable denotes positive logic—a high level enables the regulator.

Error Flag

A digital indicator that signals an error condition. Micrel LDOs have optional error flags that indicate the output is not in-regulation because of overcurrent faults, low input voltage faults, or excessively high input voltage faults.

Forced Convection

Heat flow away from a source, such as a regulator or heat sink, aided by forced air flow (usually provided by a fan). See Natural Convection.

Ground Current

The portion of regulator supply current that flows to ground instead of to the load. This is wasted current and should be minimized. Ground current is composed of quiescent current and base current. (See quiescent current, below). Base current is reduced by using Micrel's proprietary Super βeta PNP™ process, giving Micrel LDOs the best performance in the industry.

Heat Sink

A conductor of heat attached to a regulator package to increase its power handling ability.

LDO

Low DropOut. Jargon for a linear, low drop out voltage regulator.

Line Transient

The change in regulator output caused by a sudden change in input voltage.

Linear Regulator

A regulator that uses linear control blocks and pass elements, as opposed to a switching regulator. Linear regulators are simple to use, require no magnetic components, and produce extremely clean, well regulated output. Their efficiency varies greatly with input voltage. Linear regulators have approximately the same *output current* as *input current.*

Load Dump

An automotive industry term for a large positive voltage spike that is created when the alternator's load is suddenly disconnected due to a system fault. The automotive industry considers an electronic component "load dump protected" if it can survive a +60V transient for at least 100msec.

Load Transient The change in output voltage caused by a sudden change in load current.

Natural Convection Heat flow away from a hot source, such as a regulator or heat sink, unaided by a fan. See Forced Convection.

Overtemperature Shutdown A protection feature of Micrel regulators that disables the output when the regulator temperature rises above a safe threshold.

Overvoltage Shutdown A protection feature of some Micrel regulators that disables the output when the input voltage rises above a certain threshold.

Post Regulator A method of reducing output ripple by following a switching regulator with a linear regulator.

Quiescent Current Current used by the regulator for housekeeping. Quiescent current does not contribute to the load and should be minimized. In a PNP LDO, ground current equals quiescent when the output current is 0mA.

Reversed-Battery Protection A regulator with reversed battery protection will not be destroyed if the input supply polarity is backwards. A related feature allows Micrel LDOs to effectively act as an “ideal” diode, protecting the load from this backward polarity condition, or allowing the outputs of different output-voltage regulators to be “ORed” without damage.

Shutdown Digital input allowing ON/OFF control of the regulator. Also called “control” or “enable”. Shutdown denotes negative logic—a logic low enables the regulator.

Super ßeta PNP™ Micrel's trademarked name for a power semiconductor process combining good high voltage operation with high transistor beta (current gain). Compared to standard power PNP transistor betas of only 8 to 10, Super ßeta PNP-processed transistors feature nominal betas of 50 to 100. LDO efficiency depends on high beta: efficiency at high load current is proportional to the PNP pass transistor beta. High beta means low ground current which improves efficiency; this allows high output with less wasted power than other monolithic linear regulators, either standard or low-dropout.

Super LDO The MIC5156, MIC5157, and/or MIC5158. Linear regulator controllers that drive external N-channel power MOSFETs. Output current and dropout voltage are dependant upon the MOSFET employed. Using the Super LDO with large MOSFETs allow extremely low dropout voltage and very high output currents.

Switching Regulator Also known as SMPS (Switch Mode Power Supply). Voltage regulator topology that uses ON/OFF switching to efficiently regulate voltage. Magnetics (inductors and/or transformers) are generally used. Ideal switching regulators have nearly the same *output power* as *input power*, resulting in very high efficiency. Switching regulators usually have inferior output characteristics, such as noise and voltage regulation, compared to linear regulators.

Section 9. References

Thermal Information

Micrel Databook, Micrel Inc., San Jose, CA. Tel: + 1 (408) 944-0800

MIL-STD-275E: *Printed Wiring for Electronic Equipment*. (31 December 1984)

Innovative Thermal Management Solutions, Wakefield Engineering, 60 Audubon Road, Wakefield, MA 01880. Tel: + 1 (617) 245-5900

Spoor, Jack: *Heat Sink Applications Handbook*, 1974, Aham, Inc.

Technical Reports and Engineering Information Releases, Thermalloy Inc., Dallas Texas. Tel: + 1 (214) 243-4321

Thermal Management, AAVID™ Engineering, Inc., Laconia, NH. Tel: + 1 (603) 528-3400

Thermal Management Solutions, Thermalloy Inc., Dallas Texas. Tel: + 1 (214) 243-4321

4-Lead Resistor Manufacturers

Dale Electronics, Columbus, NE. Tel: + 1 (402)563-6506

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Suite 450C-199
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USA 75019

MICREL SEMICONDUCTOR ASIA LTD.

4F. Jinsol Building
826-14, Yeoksam-dong
Kangnam-ku Tel: + 82 (2) 3466-3000
Seoul 135-080 Fax: + 82 (2) 3466-2999
Korea

MICREL SEMICONDUCTOR, TAIWAN

12F-10, No. 237
Sec. 2, Fu-Hsing South Rd. Tel: + 886 (2) 2705-4976
Taipei, Taiwan, R.O.C. Fax: + 886 (2) 3466-2999

MICREL EUROPE TECHNICAL CENTER

Clere House
21 Old Newtown Road Tel: + 44 (1635) 524455
Newbury Fax: + 44 (1635) 524466
United Kingdom RG 147DP

U.S. Sales Representatives

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S & S Technologies
Suite 121
4545 South Wendler Dr. — Tel: (602) 438-7424
Tempe, AZ 85282 — Fax: (602) 414-1125

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CSR Electronics, Inc.
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3555 Koger Blvd. — Tel: (678) 380-5080
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HAWAII

contact factory — Tel: (408) 944-0800

IDAHO (NORTHERN)

ECS/SPS Electronics
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Mercer Island, WA 98040 — Fax: (206) 232-1095

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ILLINOIS (SOUTHERN)

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Suite 123
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Bloomfield, CT 06002 Fax: (860) 242-3949

Nu Horizons Electronics Corp.
Building I
Corporate Place, Hwy. 128
107 Audubon Rd. Tel: (203) 265-0162
Wakefield, MA 01880 Fax: (203) 791-3801

FLORIDA

Bell Industries
Suite 400
650 South North Lake Blvd. Tel: (407) 339-0078
Altamonte Springs, FL 32701 Fax: (407) 339-0139

EBV Electronics
Suite 130
600 South North Lake Blvd. Tel: (407) 767-6974
Altamonte Springs, FL 32701 Fax: (407) 767-9667

Suite 525
17757 U.S. Hwy. 19 North Tel: (813) 536-8800
Clearwater, FL 33764 Fax: (813) 536-8810

Suite 204
500 Fairway Dr. Tel: (954) 418-0065
Deerfield Beach, FL 33442 Fax: (954) 418-9080

FAI
Suite 307
237 South Westmonte Dr. Tel: (407) 685-7900
Altamonte Springs, FL 32701 Tel: (800) 333-9719
Fax: (407) 865-5969

Suite 200 Tel: (954) 626-4043
1400 East Newport Center Dr. Tel: (800) 305-8181
Deerfield Beach, FL 33442 Fax: (954) 426-9477

Suite 108
2200 Tall Pines Dr. Tel: (813) 530-1665
Largo, FL 34641 Fax: (813) 538-9598

Future Electronics
Suite 307 Tel: (407) 865-7900
237 South Westmonte Dr. Tel: (800) 950-0168
Altamonte Springs, FL 32714 Fax: (407) 865-7660

Suite 200 Tel: (954) 426-4043
1400 East Newport Center Dr. Tel: (800) 305-2343
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Ft. Lauderdale, FL 33309 Fax: (954) 486-9929

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Tampa, FL 33609 Fax: (813) 286-2572

Nu Horizons Electronics Corp.
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Altamonte Springs, FL 32701 Fax: (407) 831-8862

3421 Northwest 55th St. Tel: (954) 735-2555
Ft. Lauderdale, FL 33309 Fax: (954) 735-2880

GEORGIA

Bell Industries
Suite 115
3000 Northwoods Pkwy. Tel: (770) 446-9777
Norcross, GA 30071 Fax: (770) 446-1186

EBV Electronics
Suite 2700
6855 Jimmy Carter Blvd. Tel: (770) 441-7878
Norcross, GA 30071 Fax: (770) 441-1001

FAI
Suite 130
3150 Holcomb Bridge Rd.
Norcross, GA 30071 Tel: (404) 441-7676

Future Electronics
Suite 130
3150 Holcomb Bridge Rd. Tel: (404) 441-7676
Norcross, GA 30071 Fax: (404) 441-7580

Newark Electronics
520 Guthridge Ct. Tel: (770) 448-1300
Norcross, GA 30092 Fax: (770) 448-7843

Nu Horizons Electronics Corp.
Suite 155
100 Pinnacle Way Tel: (770) 416-8666
Norcross, GA 30071 Fax: (770) 416-9060

IDAHO

Future Electronics
12301 West Explorer Dr.
Boise, ID 83713 Tel: (208) 376-8080

ILLINOIS

Active Electronics
1776 West Golf Rd.
Mount Prospect, IL 60056 Tel: (847) 640-7713

Bell Industries
175 West Central Rd. Tel: (847) 202-6400
Schaumburg, IL 60195 Fax: (847) 202-5849

EBV Electronics
Suite 4610
3660 North Lake Shore Dr. Tel: (773) 883-5593
Chicago, IL 60613 Fax: (773) 975-2110

FAI
Suite 115 Tel: (847) 843-0034
3100 West Higgins Rd. Tel: (800) 283-1899
Hoffman Estates, IL 60195 Fax: (847) 843-1163

Future Electronics
Suite 200 Tel: (847) 882-1255
3150 West Higgins Rd. Tel: (800) 490-9290
Hoffman Estates, IL 60195 Fax: (847) 490-9290

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4801 North Ravenswood Tel: (773) 784-5100
Chicago, IL 60640 Fax: (773) 907-5217

Suite A320
1919 South Highland Ave. Tel: (630) 317-1000
Lombard, IL 60148 Fax: (630) 424-8048

110 South Alpine Rd. Tel: (815) 229-0225
Rockford, IL 61108 Fax: (815) 229-2587

1012 North St. Tel: (217) 787-9972
Springfield, IL 62704 Fax: (217) 787-7740

INDIANA

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Fort Wayne, IN 46825 Fax: (219) 490-2100

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5605 Fortune Cir. South Tel: (317) 842-4244
Indianapolis, IN 46241 Fax: (317) 570-1344

6982 Hillsdale Ct. Tel: (317) 842-4244
Indianapolis, IN 46250 Fax: (317) 570-1344

FAI
Suite 170
8425 Woodfield Crossing Tel: (317) 469-0441
Indianapolis, IN 46240 Fax: (317) 469-0446

Future Electronics
Suite 170
8425 Woodfield Crossing Tel: (317) 469-0447
Indianapolis, IN 46240 Fax: (317) 469-0448

Newark Electronics
4410 Executive Blvd. Tel: (219) 484-0766
Fort Wayne, IN 46808 Fax: (219) 482-4751

50 East 91st St. Tel: (317) 844-0047
Indianapolis, IN 46240 Fax: (317) 844-0165

IOWA

Newark Electronics
2550 Middle Rd. Tel: (319) 359-3711
Bettendorf, IA 52722 Fax: (319) 359-5638

KANSAS

Bell Industries
Suite 313
6400 Glenwood Tel: (913) 236-8800
Overland Park, KS 66202 Fax: (913) 384-6825

FAI
Suite 210
10977 Granada Ln. Tel: (913) 338-4400
Overland Park, KS 66211 Fax: (913) 338-3412

Future Electronics
Suite 210
10977 Granada Ln. Tel: (913) 498-1531
Overland Park, KS 66211 Fax: (913) 498-1786

Newark Electronics
6811 West 63rd St. Tel: (913) 677-0727
Overland Park, KS 66202 Fax: (913) 677-2725

KENTUCKY

Newark Electronics
1313 Lyndon Ln. Tel: (502) 423-0280
Louisville, KY 40222 Fax: (502) 425-3741

LOUISIANA

Newark Electronics
3525 North Causeway Blvd. Tel: (504) 838-9771
Metairie, LA 70002 Fax: (504) 833-9461

MARYLAND

Bell Industries
6460 Dobbin Rd. Tel: (410) 730-6119
Columbia, MD 21045 Fax: (410) 730-8940

EBV Electronics
Suite 118
10010 Junction Dr. Tel: (301) 617-0200
Annapolis Junction, MD 20701 Fax: (301) 617-0202

FAI
Suite 101
6716 Alexander Bell Dr. Tel: (410) 312-0833
Columbia, MD 21046 Fax: (410) 312-0877

Future Electronics
International Tower, 2nd Floor
857 Elkridge Landing Rd. Tel: (410) 314-1111
Linthicum Heights, MD 21090 Fax: (410) 314-1110

Newark Electronics
7272 Park Circle Dr. Tel: (410) 712-6922
Hanover, MD 21076 Fax: (410) 712-6932

Nu Horizons Electronics Corp.
Suite 160 Tel: (410) 995-6330
8965 Guilford Rd. Tel: (301) 621-8244
Columbia, MD 21046 Fax: (410) 995-6332

MASSACHUSETTS

Active Electronics
11 Cummings Park
Woburn, MA 01801 Tel: (781) 932-0050

Bell Industries
Suite G-01
100 Burtt Rd. Tel: (978) 623-3200
Andover, MA 01810 Fax: (978) 474-8902

187 Ballardvale St. Tel: (978) 657-5900
Wilmington, MA 01887 Fax: (978) 658-7989

EBV Electronics
131 Middlesex Turnpike Tel: (617) 229-0047
Burlington, MA 01803 Fax: (617) 229-0031

FAI
41 Main St. Tel: (978) 779-3111
Bolton, MA 01740 Fax: (978) 779-3199

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41 Main St. Tel: (978) 779-3000
Bolton, MA 01740 Fax: (978) 779-3050

Newark Electronics
59 Composite Way Tel: (978) 551-4300
Lowell, MA 01851 Fax: (978) 551-4329

65 Boston Post Rd. West Tel: (508) 229-2200
Marlborough, MA 01752 Fax: (508) 229-2222

Nu Horizons Electronics Corp.
19 Corporate Pl., Bldg. 1
107 Audubon Rd. Tel: (781) 246-4442
Wakefield, MA 01880 Fax: (781) 246-4462

MICHIGAN

Future Electronics
Suite 280
4595 Broadmoor, SE Tel: (616) 698-6800
Grand Rapids, MI 49512 Fax: (616) 698-6821

Suite 106
35200 Schoolcraft Rd. Tel: (313) 261-5270
Livonia, MI 48150 Fax: (313) 261-8175

Newark Electronics
900 East Paris Ave., SE Tel: (616) 954-6700
Grand Rapids, MI 49546 Fax: (616) 954-6713

4600 Fashion Square Blvd. Tel: (517) 799-0480
Saginaw, MI 48604 Fax: (517) 799-7722

550 Stephenson Hwy. Tel: (248) 583-2899
Troy, MI 48083 Fax: (248) 583-1092

MINNESOTA

Bell Industries
Suite 232
9555 James Ave. South Tel: (612) 888-7747
Bloomington, MN 55431 Fax: (612) 888-7757

FAI
Suite 198
10025 Valley View Rd. Tel: (612) 974-0909
Eden Prairie, MN 55344 Fax: (612) 944-2520

Future Electronics
Suite 196
10025 Valley View Rd. Tel: (612) 944-2200
Eden Prairie, MN 55344 Fax: (612) 944-2520

Newark Electronics
2021 Hennipin Ave. Tel: (612) 331-6350
Minneapolis, MN 55413 Fax: (612) 331-1504

Nu Horizons Electronics Corp.
10907 Valley View Rd. Tel: (612) 942-9030
Eden Prairie, MN 55344 Fax: (612) 942-9144

MISSISSIPPI

Newark Electronics
795 Woodlands Pkwy. Tel: (601) 956-3834
Ridgeland, MS 39157 Fax: (601) 957-1240

MISSOURI

FAI
Suite 220
12125 Woodcrest Executive Dr. Tel: (314) 542-9922
St. Louis, MO 63141 Fax: (314) 542-9655

Future Electronics
Suite 220
12125 Woodcrest Executive Dr. Tel: (314) 469-6805
St. Louis, MO 63141 Fax: (314) 469-7226

Newark Electronics
2258 Schuetz Rd. Tel: (314) 991-0400
St. Louis, MO 63146 Fax: (314) 991-6945

NEBRASKA

Newark Electronics
11128 John Galt Blvd. Tel: (402) 592-2423
Omaha, NE 68137 Fax: (402) 592-0508

NEW JERSEY

Active Electronics
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1871 Route 70
Cherryhill, NJ 08034 Tel: (609) 424-7070

Bell Industries
Suite F202-203
271 Route 46 West Tel: (973) 227-6060
Fairfield, NJ 07004 Fax: (973) 227-2626

Suite 110
158 Gaither Dr. Tel: (609) 439-8860
Mt. Laurel, NJ 08054 Fax: (609) 439-9009

EBV Electronics
Suite A104
530 Fellowship Rd. Tel: (609) 235-7474
Mt. Laurel, NJ 08054 Fax: (609) 235-4992

FAI
Suite 130
12 East Stow Rd. Tel: (609) 988-1500
Marlton, NJ 08053 Fax: (609) 988-9231

Future Electronics
Suite 200
12 East Stow Rd. Tel: (609) 596-4080
Marlton, NJ 08053 Fax: (609) 596-4266

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Parsippany, NJ 07054 Fax: (973) 299-1377

Newark Electronics
197 Hwy. 18 South Tel: (732) 937-6600
East Brunswick, NJ 08816 Fax: (732) 937-6667

Nu Horizons Electronics Corp.
Suite 200
18000 Horizon Way Tel: (609) 231-0900
Mt. Laurel, NJ 08054 Fax: (609) 231-9510

39 U.S. Route 46 Tel: (973) 882-8300
Pine Brook, NJ 07058 Fax: (973) 882-8398

NEW MEXICO

Newark Electronics
8205 Spain, NE Tel: (505) 828) 1878
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NEW YORK

Active Electronics
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1 Corporate Pl.
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Suite 150
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Suite 200
200 Salina Meadows Pkwy. Tel: (315) 451-2371
Syracuse, NY 13212 Fax: (315) 451-7258

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3 Marcus Blvd. Tel: (518) 489-1963
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5500 Main St. Tel: (716) 631-2311
Williamsville, NY 14221 Fax: (716) 631-4049

Nu Horizons Electronics Corp.
70 Maxess Rd. Tel: (516) 396-5000
Melville, NY 11747 Fax: (516) 396-5050

333 Metro Park Tel: (716) 292-0777
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NORTH CAROLINA

Bell Industries
Suite 800
3100 Smoketree Ct. Tel: (919) 874-0011
Raleigh, NC 27604 Fax: (919) 874-0013

EBV Electronics
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8000 Regency Pkwy. Tel: (919) 468-3580
Cary, NC 27511 Fax: (919) 462-0891

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Charlotte, NC 28262 Fax: (704) 547-9650

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Smith Towers
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Nu Horizons Electronics Corp.
Suite 125
2920 Highwood Blvd. Tel: (919) 954-0500
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OHIO

Bell Industries
8149 Washington Church Road Tel: (937) 428-7300
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FAI
Suite 203
1430 Oak Ct. Tel: (513) 427-6090
Beavercreek, OH 45430 Fax: (216) 449-8987

Future Electronics
Suite 203
1430 Oak Ct. Tel (513) 426-0090
Beavercreek, OH 45430 Fax: (513) 426-8490

6009 East Landerhaven Dr. Tel: (440) 449-6996
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Columbus, OH 43220 Fax: (614) 326-0231

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Toledo, OH 43614 Fax: (419) 866-9204

Nu Horizons Electronics Corp.
2208 Enterprise E. Pkwy. Tel: (216) 963-9933
Twinsburg, OH 44087 Fax: (216) 963-9944

OKLAHOMA

Newark Electronics
3524 Northwest 56th St. Tel: (405) 943-3700
Oklahoma City, OK 73112 Fax: (405) 943-6403

OREGON

Bell Industries
Suite 100
8705 Southwest Nimbus Ave. Tel: (503) 644-3444
Beaverton, OR 97008 Fax: (503) 520-1948

EBV Electronics
Suite 360
8196 Southwest Hall Blvd. Tel: (503) 574-2255
Beaverton, OR 97008 Fax: (503) 574-2266

Future Electronics
Suite 800
7204 Southwest Durham Rd. Tel: (503) 645-9454
Portland, OR 97224 Fax: (503) 645-1559

Newark Electronics
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Portland, OR 97225 Fax: (503) 297-1925

PENNSYLVANIA

Bell Industries
Suite 110
158 Gaither Dr. Tel: (215) 557-6450
Mt. Laurel, NJ 08054 Fax: (609) 231-9510

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Suite A104
520 Fellowship Rd. Tel: (609) 235-7474
Mt. Laurel, NJ 08054 Fax: (609) 235-4992

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Suite 200
12 East Stow Rd. Tel: (609) 596-4080
Marlton, NJ 08053 Fax: (609) 596-4266

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Allentown, PA 18104 Fax: (610) 432-3390

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Fort Washington, PA 19034 Fax: (215) 654-1460

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Suite 200
18000 Horizon Way Tel: (215) 557-6450
Mt. Laurel, NJ 08054 Fax: (609) 231-9510

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Newark Electronics
150 Executive Center Dr. Tel: (864) 288-9610
Greenville, SC 29615 Fax: (864) 297-3558

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TEXAS

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11824 Jollyville Rd. Tel: (512) 331-9961
Austin, TX 78759 Fax: (512) 331-1070

Suite 170
14110 North Dallas Pkwy. Tel: (972) 458-0047
Dallas, TX 75240 Fax: (972) 404-0267

Suite 310
12000 Richmond Ave. Tel: (281) 870-8101
Houston, TX 77082 Fax: (281) 870-8122

EBV Electronics
Suite 215
11500 Metric Blvd. Tel: (512) 491-9340
Austin, TX 78758 Fax: (512) 491-9345

Suite 320
1778 Plano Rd. Tel: (972) 783-8322
Richardson, TX 75081 Fax: (972) 783-8774

FAI
Northpoint Center Bldg. II
Suite 320
6850 Austin Center Blvd. Tel: (512) 346-6426
Austin, TX 78731 Fax: (512) 346-6781

Suite 126 Tel: (972) 231-7195
800 East Campbell Tel: (800) 272-0694
Richardson, TX 75081 Fax: (972) 231-2508

Suite 137E
6800 Park Ten Blvd. Tel: (210) 738-3330
San Antonio, TX 78213 Fax: (210) 738-0511

Future Electronics
Northpoint Center Bldg. II
Suite 320
6850 Austin Center Blvd. Tel: (512) 502-0991
Austin, TX 78731 Fax: (512) 502-0740

Suite 970 Tel: (713) 952-7088
10333 Richmond Ave. Tel: (203) 250-0083
Houston, TX 77042 Fax: (713) 952-7098

Suite 130 Tel: (972) 437-2437
800 East Campbell Tel: (203) 250-0083
Richardson, TX 75081 Fax: (972) 669-2347

Newark Electronics
3737 Executive Center Dr. Tel: (512) 338-0287
Austin, TX 78731 Fax: (512) 345-2702

12880 Hillcrest Rd. Tel: (972) 458-2528
Dallas, TX 75230 Fax: (972) 458-2530

Suite 292
7500 Viscount Tel: (915) 772-6367
El Paso, TX 79925 Fax: (915) 772-3192

8203 Willow Pl. South Tel: (281) 894-9334
Houston, TX 77070 Fax: (281) 894-7919

Nu Horizons Electronics Corp.
Suite 100 Tel: (512) 873-9300
2404 Rutland Dr. Tel: (888) 747-NUHO
Austin, TX 78758 Fax: (512) 873-9800

Suite 200 Tel: (972) 488-2255
1313 Valwood Pkwy. Tel: (800) 200-1586
Carrollton, TX 75006 Fax: (972) 488-2265

UTAH

Bell Industries
Suite 110
310 East 4500 South Tel: (801) 261-2999
Murray, UT 84107 Fax: (801) 261-0880

EBV Electronics
Suite 131
825 East 4800 South Tel: (801) 261-1088
Murray, UT 84107 Fax: (801) 261-1442

FAI
Suite 301
3450 South Highland Dr. Tel: (801) 467-9696
Salt Lake City, UT 84106 Fax: (801) 467-9755

Future Electronics
Suite 301
3450 South Highland Dr. Tel: (801) 467-4448
Salt Lake City, UT 84106 Fax: (801) 467-3604

Newark Electronics
4424 South 700 East Tel: (801) 261-5660
Salt Lake City, UT 84107 Fax: (801) 261-5675

VIRGINIA

FAI
Suite 202
660 Hunters Pl. Tel: (804) 984-5022
Charlottesville, VA 22911 Fax: (804) 984-5422

Newark Electronics
131 Elden St. Tel: (703) 707-9010
Herndon, VA 22070 Fax: (703) 707-9203

1504 Santa Rosa Rd. Tel: (804) 282-5671
Richmond, VA 23229 Fax: (804) 282-3109

WASHINGTON

Active Electronics
13107 Northup Way 20th St., NE
Bellevue, WA 98005 Tel: (206) 881-8191

Bell Industries
Suite 102
19119 North Creek Pkwy. Tel: (425) 486-2124
Bothell, WA 98011 Fax: (425) 487-1927

FAI
North Creek Corporate Center
Suite 118
19102 North Creek Pkwy. Tel: (206) 485-6616
Bothell, WA 98011 Fax: (206) 483-6109

Future Electronics
North Creek Corporate Center
Suite 118
19102 North Creek Pkwy. Tel: (206) 489-3400
Bothell, WA 98011 Fax: (206) 489-3411

Newark Electronics
12015 115th Ave., NE Tel: (425) 814-6230
Kirkland, WA 98034 Fax: (425) 814-9190

West 222 Mission Ave. Tel: (509) 327-1935
Spokane, WA 99201 Fax: (509) 328-8658

WISCONSIN

Bell Industries
W 226 N 900 Eastmound Dr. Tel: (414) 547-8879
Waukesha, WI 53186 Fax: (414) 547-6547

FAI
Suite 170
250 North Patrick Blvd. Tel: (414) 793-9778
Brookfield, WI 53045 Fax: (414) 792-9779

Future Electronics
Suite 170
250 North Patrick Blvd. Tel: (414) 879-0244
Brookfield, WI 53045 Fax: (414) 879-0250

Newark Electronics
6400 Enterprise Ln. Tel: (608) 278-0177
Madison, WI 53719 Fax: (608) 278-0166

2525 North Mayfair Rd. Tel: (414) 453-9100
Wauwatosa, WI 53226 Fax: (414) 453-2238

International Sales Representatives and Distributors

Micrel Semiconductor sales indicated by [Micrel].
Synergy Semiconductor sales indicated by [Synergy].

NORTH AMERICA—DIE DISTRIBUTION ONLY

Chip Supply, Inc. [Micrel]
7725 Orange Blossom Trail   Tel: + 1 (407) 298-7100
Orlando, FL   Fax: + 1 (407) 290-0164
USA 32810-2696

EUROPE—DIE DISTRIBUTION ONLY

Chip Supply, Inc. [Micrel]
5 Queen Street   Tel: + 44 (1616) 336627
Oldham OL1 1RD   Fax: + 44 (1616) 260380
United Kingdom

Eltek Semiconductor, Ltd. [Micrel]
Nelson Road Industrial Estate
Dartmouth   Tel: + 44 (1803) 834455
Devon TQ6 9LA   Fax: + 44 (1803) 833011
United Kingdom

INTERNATIONAL—PACKAGED DEVICES

AUSTRALIA

Future Electronics [Synergy]
2nd Floor
1013 Whitehorse Rd.   Tel: (613) 98997944
Box Hill, Victoria 3128   Fax: (613) 98909632

KC Electronics [Synergy] *(Rep.)*
152 Highbury Road   Tel: (613) 92453253
Burwood, Victoria 3125   Fax: (613) 92453288

BELGIUM

Alcom Electronics Belgium BV [Synergy] *(Stocking Rep.)*
Singel 3   Tel: + 32 (3) 458 30 33
2550 Kontich   Fax: + 32 (3) 458 31 26

Nijkerk Elektronika B.V. [Micrel]
Drentestraat 7   Tel: + 31 (20) 504 14 35
1083 HK Amsterdam   Fax: + 31 (20) 642 39 48
Netherlands

BRAZIL

Aplicacoes Electronicas Artimar Ltda. [Micrel]
8º Andar
Rua Marques de Itu 70   Tel: + 55 (11) 231-0277
01223-000 São Paulo - SP   Fax: + 55 (11) 255-0511

CANADA—ALBERTA

Microwe Electronics Corporation [Micrel-Synergy] *(Rep.)*
Suite 28
2333 18th Avenue NE   Tel: (403) 250-7577
Calgary, AB T2E 8T6   Fax: (403) 250-7867

Active Electronics [Micrel-Synergy]
Unit 1
2015 32nd Ave., NE   Tel: (403) 291-5626
Calgary, AB T2E 6Z3   Fax: (403) 291-5444

Future Active Industrial [Micrel-Synergy]
Unit 1
2015 32nd Ave., NE   Tel: (403) 291-5333
Calgary, AB T2E 6Z3   Fax: (403) 291-5444

6029 103rd St.   Tel: (403) 438-5888
Edmonton, AB T6H 2H3   Fax: (403) 436-1874

Future Electronics [Micrel-Synergy]
3833 - 29th St., NE   Tel: (403) 250-5550
Calgary, AB T1Y 6B5   Fax: (403) 291-7054

6029 103rd St.   Tel: (403) 438-2858
Edmonton, AB T6H 2H3   Fax: (403) 434-0812

CANADA—BRITISH COLUMBIA

Microwe Electronics Corporation [Micrel-Synergy] *(Rep.)*
8394-208th St.   Tel: (604) 882-4667
Langley, BC V2Y 2B4   Fax: (604) 882-4668

Bell Industries [Micrel]
Suite B201
4185 Still Creek Dr.   Tel: (604) 291-0044
Burnaby, BC V5C 6G9   Fax: (604) 291-9939

Future Active Industrial [Micrel-Synergy]
200-3689 East 1st. Avenue   Tel: (604) 654-1050
Vancouver, BC V5M 1C2   Fax: (604) 294-3170

Future Electronics [Micrel-Synergy]
1695 Boundary Road
Vancouver, BC V5K 4X7   Tel: (604) 294-1166

CANADA—MANITOBA

Future Active Industrial [Micrel-Synergy]
504-1780 Wellington Ave.   Tel: (204) 786-3075
Winnipeg, MB R3H 1B2   Fax: (204) 783-8133

Future Electronics [Micrel-Synergy]
504-1780 Wellington Ave.   Tel: (204) 944-1446
Winnipeg, MB R3H 1B2   Fax: (204) 783-8133

CANADA—ONTARIO

Kaltron Technologies Ltd. [Micrel-Synergy] *(Rep.)*
P.O. Box 1214
261 Williams St.   Tel: (613) 256-5278
Almonte, ON K0A 1A0   Fax: (613) 256-4757

147 Lloydalex Cres. RR#3   Tel: (613) 860-0627
Carp., ON K0A 1L0   Fax: (905) 831-3475

200-5925 Airport Rd.   Tel: (905) 405-6276
Mississauga, ON L4V 1W1   Fax: (905) 405-6274

Active Electronics [Micrel-Synergy]
Unit 2
1350 Matheson Blvd.   Tel: (905) 238-8825
Mississauga, ON L4W 4M1   Fax: (905) 238-2817

1023 Merivale Road   Tel: (613) 728-7900
Ottawa, ON K1Z 6A6   Fax: (613) 728-3586

Bell Industries [Micrel]
2783 Thamesgate Dr.   Tel: (905) 678-0958
Mississauga, ON L4T 1G5   Fax: (905) 678-1213

Future Active Industrial [Micrel-Synergy]
Suite 205/210
5935 Airport Rd.   Tel: (613) 820-8244
Mississauga, ON L4V 1W5   Fax: (613) 820-8046

Future Electronics [Micrel-Synergy]
Suite 210
1101 Price of Wales Dr.   Tel: (613) 820-8313
Ottawa, ON K2C 3W7   Fax: (613) 820-3271

Newark Electronics [Micrel]
569 Consortium Ct.   Tel: (519) 685-4280
London, ON N6E 2S8   Fax: (519) 685-7104

6200 Dixie Rd.   Tel: (905) 670-2888
Mississauga, ON L5T 2E1   Fax: (905) 670-1019

CANADA—QUEBEC

Kaltron Technologies Ltd. [Micrel-Synergy] *(Rep.)*
224 Forest Rd.   Tel: (514) 630-7238
Beaconsfield, PQ H9W 2N2

Active Electronics [Micrel-Synergy]
Suite 190
1990 Boul. Charest Ouest   Tel: (418) 682-5775
Ste. Foy, PQ G1N 4K8   Fax: (418) 682-6282

Bell Industries [Micrel]
Suite 209
6600 Trans Canada Hwy.   Tel: (514) 426-5900
Pointe Claire, PQ H9R 4S2   Fax: (514) 526-5836

Future Active Industrial [Micrel-Synergy]
5651 Ferrier St.   Tel: (514) 731-7444
Montreal, PQ H4P 1N1   Fax: (514) 731-0129

6080 Metropolitan Blvd.   Tel: (514) 256-7538
Montreal, PQ H1S 1A9   Fax: (514) 256-4890

Future Electronics [Micrel-Synergy]
Suite 100
1000 Ave. St. Jean Baptiste   Tel: (418) 877-6666
Quebec, PQ G2E 5G5   Fax: (418) 877-6671

237 Hymus Blvd.   Tel: (514) 694-7710
Pointe Claire, PQ H9R 5C7   Fax: (514) 695-3707

Newark Electronics [Micrel]
4480 Cote De Liesse   Tel: (514) 738-4488
Mt. Royal, PQ H4N 2R1   Fax: (514) 738-4606

CHINA

Cytech Technology, Ltd. [Synergy] *(Rep.)*
Room 302
New High Tech Building
No. 19 Zhong Guan Cun Road
Haidian District   Tel: + 86 (10) 62546450
Beijing 100080   Tel/Fax: + 86 (10) 62546451

Room 306
Tian Ge Wu Cheng Building
Mo Zi Giao   Tel: + 86 (28) 5532883
Yi Huan Road South Section 2   ext. 3306
Chengdu 610041   Tel/Fax: + 86 (28) 5548808

Room 3-5
Ke Chuang Building
50 Yu Zhou Road
Goa Xin Ji Shu Kaifa Qu
Shi Qiao Pu   Tel: + 86 (23) 68608938
Chongqing 400039   Tel/Fax: + 86 (23) 68619097

Room 03, 19/F
Donghuan Tower
No. 474 Donghuan Road   Tel: + 86 (20) 87627220
Guangzhou 510075   Fax: + 86 (20) 87627227

Room 205
No. 29D Yudao Street   Tel: + 86 (25) 4890188
Nanjing 210016   Tel/Fax: + 86 (25) 4892089

Room 804
1583 Zhong Shan Road West Tel: + 86 (21) 64388082
Shanghai 200233   Tel/Fax: + 86 (21) 64644953

Unit K, 13/F
Hangdu Bldg.
No. 1006 Huafu Road   Tel: + 86 (75) 53780519
Shenzhen 518041   Tel/Fax: + 86 (75) 53780516

Galaxy Far East Corp. [Micrel]
Room 0514
New Caohejing Tower
509 Caobao Road   Tel: + 86 (21) 64956485
Shanghai   Fax: + 86 (21) 64852237

+ *country code* **(***city code***)** *telephone number*

Lestina International Ltd. [Micrel]
Room 302
New High Tech Building
No. 19 Zhong Guan Cun Road
Haidian District Tel: + 86 (10) 62546450
Beijing 100080 Tel/Fax: + 86 (10) 62546451

Room 306
Tian Ge Wu Cheng Building
Mo Zi Giao Tel: + 86 (28) 5532883
Yi Huan Road South Section 2 ext. 3306
Chengdu 610041 Tel/Fax: + 86 (28) 5548808

Room 3-3
Ke Chuang Building
50 Yu Zhou Road
Goa Xin Ji Shu Kaifa Qu
Shi Qiao Pu Tel: + 86 (23) 68619099
Chongqing 400039 Tel/Fax: + 86 (23) 68608938

Room 03, 19/F Tel: + 86 (20) 87627232
Donghuan Tower Tel: + 86 (20) 87627220
No. 474 Donghuan Road Tel: + 86 (20) 87627222
Guangzhou 510075 Fax: + 86 (20) 87627227

Room 205
No. 29D Yudao Street Tel: + 86 (25) 4890188
Nanjing 210016 Tel/Fax: + 86 (25) 4892089

Room 804
1583 Zhong Shan Road West Tel: + 86 (21) 64388082
Shanghai 200233 Tel/Fax: + 86 (21) 64644953

Unit K, 13/F
Hangdu Building
No. 1006 Huafu Road Tel: + 86 (755) 3790519
Shenzhen 518041 Tel/Fax: + 86 (755) 3790516

DENMARK

Future Electronics a/s [Micrel-Synergy]
Lille Ostergade 5.3 Tel: + 45 96 10 09 75
7500 Holstebro Fax: + 45 96 10 09 62

Micronor a/s [Synergy] *(Stocking Rep.)*
Trovets 1 Tel: + 45 86 81 65 22
8600 Silkeborg Fax: + 45 86 81 28 27

FINLAND

Integrated Electronics Oy Ab [Micrel]
Laurinmäenkuja 3 A Tel: + 358 (9) 2535 4400
00440 Helsinki Fax: + 358 (9) 2535 4450

P.O. Box 31
00441 Helsinki

Memec Finland Oy [Synergy] *(Stocking Rep.)*
Kauppakaare 1 Tel: + 358 (9) 836 2600
00700 Helsinki Fax: + 358 (9) 836 26027

FRANCE

Future Electronics [Micrel-Synergy]
Parc Technopolis
Bat. theta 2 LP854 Les Ulis
3, avenue du Canada Tel: + 33 (1) 69.82.11.11
91940 Courtaboeuf cedex Fax: + 33 (1) 69.82.11.00

LSX S.A.R.L. [Micrel] *(Rep.)*
30, rue du Morvan SILIC 525 Tel: + 33 (1) 46.87.83.36
94633 Rungis cedex Fax: + 33 (1) 45.60.07.84

Newtek Quest [Synergy] *(Stocking Rep.)*
2A Rue de Bordage Tel: + 33 (2) 99.83.04.40
35510 Cesson Sevigne Fax: + 33 (2) 99.83.04.44

Newtek SA [Synergy] *(Stocking Rep.)*
8 Rue de le Estoril
SILIC 583 Tel: + 33 (1) 46.87.22.00
94663 Rungis Fax: + 33 (1) 46.87.80.49

Sonepar Electronique [Micrel]
6-8, rue Ambroise Croizat Tel: + 33 (1) 64.47.29.29
91127 Palaiseau cedex Fax: + 33 (1) 64.47.00.84

GERMANY

ActiveComp GmbH [Micrel] *(Rep.)*
Schubertstraße 35 Tel: + 49 (70) 43 93 29 10
75438 Knittlingen Fax: + 49 (70) 4 33 34 92

dacom Electronic Vertriebs GmbH [Micrel]
Freisinger Straße 13 Tel: + 49 (89) 9 96 54 90
85737 Ismaning Fax: + 49 (89) 96 49 89

Future Electronics Deutschland GmbH [Micrel-Synergy]
München Straße 18 Tel: + 49 (89) 95 72 70
85774 Unterföhring Fax: + 49 (89) 95 72 71 73

Retronic GmbH [Synergy] *(Stocking Rep.)*
Willhoop 1 Tel: + 49 (89) 40 58 97 44
22453 Hamburg Fax: + 49 (89) 40 58 97 44

HONG KONG

Comex Technology [Synergy] *(Rep.)*
Room 405, Park Tower
15 Austin Road
Tsimshatsui Tel: + 852 27350325
Kowloon Fax: + 852 27307538

Cytech Technology [Synergy] *(Rep.)*
Room 1803, 18th Floor
Hom Kwok Jordan Center
7 Hillwood Road
Tsimshatsui Tel: + 852 23782212
Kowloon Fax: + 852 23757700

Lestina International Ltd. [Micrel]
14th Floor, Park Tower
15 Austin Road Tel: + 852 27351736
Tsimshatsui Fax: + 852 27305260
Kowloon Fax: + 852 27307538

INDIA

Hynetic International [Synergy] *(Rep.)*
No. 50, 2nd Cross
Gavipuram Extension Tel: + 91 (80) 620852
Bangalore - 560019 Fax: + 91 (80) 624073

Samura Electronics Pvt. Ltd. [Micrel]
Room No. 507 W
Navketan Commercial Complex Tel:+ 91 (40) 7806541
62, S. D. Road Tel: + 91 (40) 7806542
Secunderabad - 500003 Fax: + 91 (40) 7806542

IRELAND

Future Electronics [Micrel-Synergy]
Post Office Lane
Abbey Street Tel: + 353 (65) 41330
Ennis, County Clare Fax: + 353 (65) 40654

Solid State Supplies Ltd. [Micrel] *(Stocking Rep.)*
2 Wesley Place Tel: + 353 (67) 34455
Nenagh Fax: + 353 (67) 34329
County Tipperary

ISRAEL

El-Gev Electronics, Ltd. [Micrel-Synergy]
11, Ha-avoda Street Tel: + 972 (3) 9027202
48017 Rosh Ha-aydin Fax: + 972 (3) 9027203

POB 248
48101 Rosh Ha-aydin

ITALY

Aertronica S.r.l. [Synergy] *(Stocking Rep.)*
Viale Cesare Battisti, 38 Tel: + 39 (39) 2302240
20052 Manza (MI) Fax: + 39 (39) 2302226

Carlo Gavazzi Cefra S.p.A. [Micrel]
Via G. De Castro, 4 Tel: + 39 (02) 48012355
20144 Milano Fax: + 39 (02) 48008167

Future Electronics S.r.l. [Micrel]
Via Fosse Ardeantine 4 Tel: + 39 (02) 66012763
20092 Cinisello Balsamo (MI)Fax: + 39 (02) 66012843

Pinnacle Special Technologies, S.r.l. [Micrel]
(Stocking Rep.)
Via Brembo 21 Tel: + 39 (02) 56810413
20139 Milan Fax: + 39 (02) 56810349

JAPAN

Hakuto Co. Ltd. [Synergy] *(Rep.)*
Nagoya-Seni Bldg.
9-27, Nishiki, 2-chome
Naka-ku
Nagoya Tel: + 81 (52) 204-8910
Aichi 460 Fax: + 81 (52) 204-8935

292-4, Asouda-machi
Matsuyama Tel: + 81 (89) 931-8910
Ehime 790 Fax: + 81 (89) 945-6218

Felix Iwai Bldg.
2-3, Hakataekiminami, 3-chome
Hakata-ku Tel: + 81 (92) 431-5330
Fukoka 812 Fax: + 81 (89) 431-5265

3-18, Miyanomae, 2-chome, Itami
Hoygo 664 Tel: + 81 (72) 784-8910
Fax: + 81 (72) 784-7860

56, Takehanatakenokaido-cho
Yamashina-ku Tel: + 81 (75) 593-8910
Kyoto 607 Fax: + 81 (75) 593-8990

Kamisugikokune Bldg.
4-10, Kamisugi, 1-chome,
Aoba-ku Tel: + 81 (22) 224-8910
Sendai, Miyagi 980 Fax: + 81 (22) 224-0645

Micro Summit K.K. [Micrel] *(Stocking Rep.)*
Premier K1 Bldg.
1 Kanda Mikura-cho
Chiyoda-ku Tel: + 81 (3) 3258-5531
Tokyo 101 Fax: + 81 (3) 3258-0433

Nippon Imex Corporation [Micrel]
No. 6 Sanjo Bldg., 5F
1-46-9 Matsubara
Setagaya-ku Tel: + 81 (3) 3321-8000
Tokyo 156 Fax: + 81 (3) 3325-0021

KOREA

GenTech Corporation [Micrel] *(Stocking Rep.)*
301, Daewon B/D
67-5, Yangjae-dong
Seocho-ku Tel: + 82 (2) 3463-0040
Seoul Fax: + 82 (2) 3463-4935

UTO International [Synergy] *(Rep.)*
Suite 801, Union Bldg.
837-11, Yeoksam-dong
Kangnam-ku Tel: + 82 (2) 566-3745
Seoul Fax: + 82 (2) 508-3250

MALAYSIA

JAG Components Sdn Bhd [Micrel]
Room 3B 1st Floor
Mutiara I&P
47 Green Hall Tel: + 604-2634932
10200 Penang Fax: + 604-2633376

MEXICO

Harwood Associates Mexico [Micrel] *(Rep.)*
Anguila 3627
Col. Loma Bonita Tel: + 52 (3) 634-99-27
44590 Zapopan, Jalisco Fax: + 52 (3) 634-62-56

EBV Electronics [Synergy]
Prol. Americas 1612 6to Piso Tel: + 52 (3) 678-91-20
Colonia Country Cluby Fax: + 52 (3) 678-92-43
44610 Guadalajara, Jalisco

Future Electronics Mexico S.A. de C.V. [Micrel]
5º Piso, Suite 2
Chimalhuacán 3569
Ciudad del Sol Tel: + 52 (3) 122-00-43
45050 Zapopan, Jalisco Fax: + 52 (3) 122-10-66

Mexican States of Sonora and Chihuahua

S & S Technologies [Micrel]
Suite 121
4545 South Wendler Dr. Tel: + 1 (602) 438-7424
Tempe, AZ Fax: + 1 (602) 414-1125
USA 85282

+ *country code* **(***city code***)** *telephone number*

NETHERLANDS

Alcom Electronics [Synergy] *(Stocking Rep.)*
Rivium 1 e straat 52 Tel: + 31 (10) 288 2500
2909LE Cappelle aan den Ijsell
Fax: + 31 (10) 288 2525

Nijkerk Elektronika B.V. [Micrel]
Drentestraat 7 Tel: + 31 (20) 504 14 35
1083 HK Amsterdam Fax: + 31 (20) 642 39 48

NEW ZEALAND

Avnet Pacific Pty. [Micrel]
274 Church Street Tel: + 64 (9) 636 7801
Penrose, Auckland Fax: + 64 (9) 634 4900

P.O. Box 92821
Penrose, Auckland

NORWAY

ACTE NC Norway AS [Micrel]
Vestvollveien 10 Tel: + 47 63 89 89 89
2020 Skedsmokorset Fax: + 47 63 87 59 00

Postboks 84
2020 Skedsmokorset

Bit Elektronikk AS [Synergy] *(Stocking Rep.)*
Smedsvingen 4 Tel: + 47 66 77 65 00
1364 Hvaldstad Fax: + 47 66 77 65 01

NORTHERN IRELAND

SEI Bloomer Electronics Ltd. [Synergy] *(Stocking Rep.)*
9-10 Carn Industrial Estate Tel: + 44 1762 339818
Craigavon Fax: + 44 1762 330650
County Armagh BT63 5RH

PHILIPPINES

Crystal Semiconductors, Inc. [Micrel]
Crystal Semiconductors Bldg.
Nos. 64-66 Kanlaon St.
Highway Hills Tel: + 63 (2) 531-2336
Mandaluyong City 1500 Fax: + 63 (2) 533-4990

PORTUGAL

Comdist Lda. [Synergy] *(Stocking Rep.)*
Edificio turia
Rua do Entreposto Industrial, 3-2
Andar Sala-E, Qta Grande Tel: + 351 (1) 472 5190
2720, Alfrgaide Lisbon Fax: + 351 (1) 472 5199

SINGAPORE

JAG Components (Pte.) Ltd. [Micrel]
Ruby Industrial Complex
Genting Block
80 Genting Lane, #11-06A Tel: + 65 749 56 63
Singapore 349565 Fax: + 65 749 56 62

Microtronics Associates [Synergy] *(Stocking Rep.)*
8, Lorong Bakar Batu
03-01 Kolam Ayer Industrial Park Tel: + 65 748 18 35
Singapore 348743 Fax: + 65 743 30 65

SOUTH AFRICA

Integrated Circuit Technologies [Micrel]
(Stocking Rep.)
66 Third St. Tel: + 27 (11) 444 3386
Marlboro, Sandton Fax: + 27 (11) 444 3389
Johannesburg

MB Silicon Systems (Pty.) Ltd. [Micrel]
P.O. Box 2292 Tel: + 27 (11) 728 4757
Houghton 2041 Fax: + 27 (11) 728 4979
Johannesburg

SPAIN

Comelta Distribution S.L. [Synergy] *(Stocking Rep.)*
Ctra de Fuencarral Km 15,700
Edifico Europa I a pl-1 Tel: + 34 (1) 657 2770
28108 Alcobendas, Madrid Fax: + 34 (1) 662 4220

Avgnda Parc Technologic 4 Tel: + 34 (3) 582 1991
08200, Cerdanyola del valles Fax: + 34 (3) 582 1992
Barcelona

Unitronics Componentes, S.A. [Micrel]
Pza. Espana, 18. PL9 Tel: + 34 91 304 3043
28008 Madrid Fax: + 34 91 327 2472

SWEDEN

Memec Scandinavia AB [Synergy] *(Stocking Rep.)*
Sehistedtsgaten 6 Tel: + 46 (8) 459 7900
11528 Stockholm Fax: + 46 (8) 459 7999

Pelcon Electronics AB [Micrel]
Girovägen 13 Tel: + 46 (8) 795 98 70
175 62 Jarfalla Fax: + 46 (8) 760 76 85

Quartum Electronics AB [Micrel] *(Rep.)*
Girovägen 13 Tel: + 46 (8) 621 03 35
175 62 Jarfalla Fax: + 46 (8) 621 02 99

SWITZERLAND

Computer Controls AG [Synergy] *(Stocking Rep.)*
P.O. Box C14 Tel: + 41 (1) 308 66 66
8057 Zurich Fax: + 41 (1) 308 66 55

Electronitel SA [Micrel] *(Stocking Rep.)*
Ch. du Grand-Clos 1
B.P. 142 Tel: + 41 (26) 401 00 60
1752 Villars-sur-Glâne 1 Fax: + 41 (26) 401 00 70

TAIWAN, R.O.C.

Galaxy Far East Corp. [Micrel]
1F, No. 15 Alley 20 Lane.544
Sec. 1, Kuang Fu Road Tel: + 886 (3) 578-6766
Hsinchu Fax: + 886 (3) 577-4795

7F-A3, 29 Hai-Pien Road Tel: + 886 (7) 338-0559
Kaohsiung Fax: + 886 (7) 338-1343

8F-6, No. 390, Section 1
Fu Hsing South Road Tel: + 886 (2) 2705-7266
Taipei Fax: + 886 (2) 2708-7901

Prohubs International Corp. [Synergy] *(Rep.)*
20F-4, 79, Section 1
Hsin Tai Wu Road Tel: + 886 (2) 2698-9801
Hs-Chih, Taipei Hsien Fax: + 886 (2) 2698-9802

THAILAND

JAG Components Thailand Co. Ltd. [Micrel]
48/157 Moo 1
Ramkhamhaeng Road
Sapansoong Tel: + 662-7294245/6
Buengkum BangKok 10240 Fax: + 662-7293030

UNITED KINGDOM

Focus Electronics Distribution Ltd. [Synergy]
(Stocking Rep.)
Suite 1
Sovereign House
82 West Street Tel: + 44 1702 542301
Rochford Essex SS4 1AS Fax: + 44 1702 542302

Future Electronics Ltd. [Micrel-Synergy]
Future House
Poyle Road
Colnbrook Tel: + 44 (1753) 763000
Berkshire SL3 0EZ Fax: + 44 (1753) 689100

Silicon Concepts Ltd. [Micrel] *(Stocking Rep.)*
PEC Lynchborough Road
Passfield, Lipphook Tel: + 44 (1428) 751617
Hampshire GU30 7SB Fax: + 44 (1428) 751603

Solid State Supplies Ltd. [Micrel] *(Stocking Rep.)*
Unit 2, Eastlands Lane
Paddock Wood Tel: + 44 (1892) 836836
Kent TN12 6BU Fax: + 44 (1892) 837837