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Programmable Multi-Chemistry Fast-Charge Management IC

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FEATURES

- Safe Management of Fast Charge for NiCd, NiMH, or Li-Ion Battery Packs
- High-Frequency Switching Controller for Efficient and Simple Charger Design
- Pre-Charge Qualification for Detecting Shorted, Damaged, or Overheated Cells
- Fast-Charge Termination by Peak Voltage (PVD) for Nickel chemistries, Minimum Current for Li-Ion chemistries, Maximum Temperature, and Maximum Charge Time
- Selectable Top-Off Mode for Achieving Maximum Capacity in NiMH Batteries
- Programmable Trickle-Charge Mode for Reviving Deeply Discharged Batteries and for Postcharge Maintenance
- Built-in Battery Removal and Insertion Detection
- Sleep Mode for Low Power Consumption

APPLICATIONS

- Multi-Chemistry Charger
- Nickel Charger
- High-Power, Multi-Cell Charger

GENERAL DESCRIPTION

The bq2000 is a programmable, monolithic IC for fast-charge management of nickel cadmium (NiCd), nickel metal-hydride (NiMH), or lithium-ion (Li-Ion) batteries in single- or multi-chemistry applications. The bq2000 chooses the proper battery chemistry (either nickel or lithium) and proceeds with the optimal charging and termination algorithms. This process eliminates undesirable, undercharged, or overcharged conditions, and allows accurate and safe termination of fast charge.

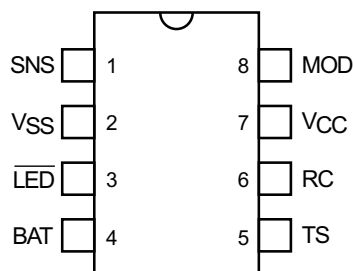
Depending on the chemistry, the bq2000 provides a number of charge termination criteria:

- Peak voltage, PVD (for NiCd and NiMH)
- Minimum charge current (for Li-Ion)
- Maximum temperature
- Maximum charge time

For safety, the bq2000 inhibits fast charge until the battery voltage and temperature are within user-defined limits. If the battery voltage is below the low-voltage threshold, the bq2000 uses trickle-charge to condition the battery. For NiMH batteries, the bq2000 provides an optional top-off charge to maximize the battery capacity.

The integrated high-speed comparator allows the bq2000 to be the basis for a complete, high-efficiency battery charger circuit for both nickel-based and lithium-based chemistries.

8-Pin DIP or Narrow SOIC or TSSOP



Pin Names

SNS	Current-sense input
V _{SS}	System ground
LED	Charge-status output
BAT	Battery-voltage input
TS	Temperature-sense input
RC	Timer-program input
V _{CC}	Supply-voltage input
MOD	Modulation-control output



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These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

PIN DESCRIPTIONS

SNS Current-sense input

Enables the bq2000 to sense the battery current via the voltage developed on this pin by an external sense-resistor connected in series with the battery pack

V_{SS} System Ground

Connect to the battery's negative terminal

$\overline{\text{LED}}$ Charge-status output

Open-drain output that indicates the charging status by turning on, turning off, or flashing an external LED, driven through a resistor.

BAT Battery-voltage input

Battery-voltage sense input. A simple resistive divider, across the battery terminals, generates this input.

TS Temperature-sense input

Input for an external battery-temperature monitoring circuit. An external resistive divider network with a negative temperature-coefficient thermistor sets the lower and upper temperature thresholds.

RC Timer-program input

Used to program the maximum fast charge-time, maximum top-off charge-time, hold-off period, trickle charge rate, and to disable or enable top-off charge. A capacitor from V_{CC} and a resistor to ground connect to this pin.

V_{CC} Supply-voltage input

Recommended bypassing is 10 μ F + 0.1 μ F to 0.22 μ F of decoupling capacitance near the pin.

MOD Modulation-control output

Push-pull output that controls the charging current to the battery. MOD switches high to enable charging current to flow and low to inhibit charging-current flow.

FUNCTIONAL DESCRIPTION

The bq2000 is a versatile, multi-chemistry battery charge control device. See [Figure 1](#) for a functional block diagram and [Figure 2](#) for a state diagram.

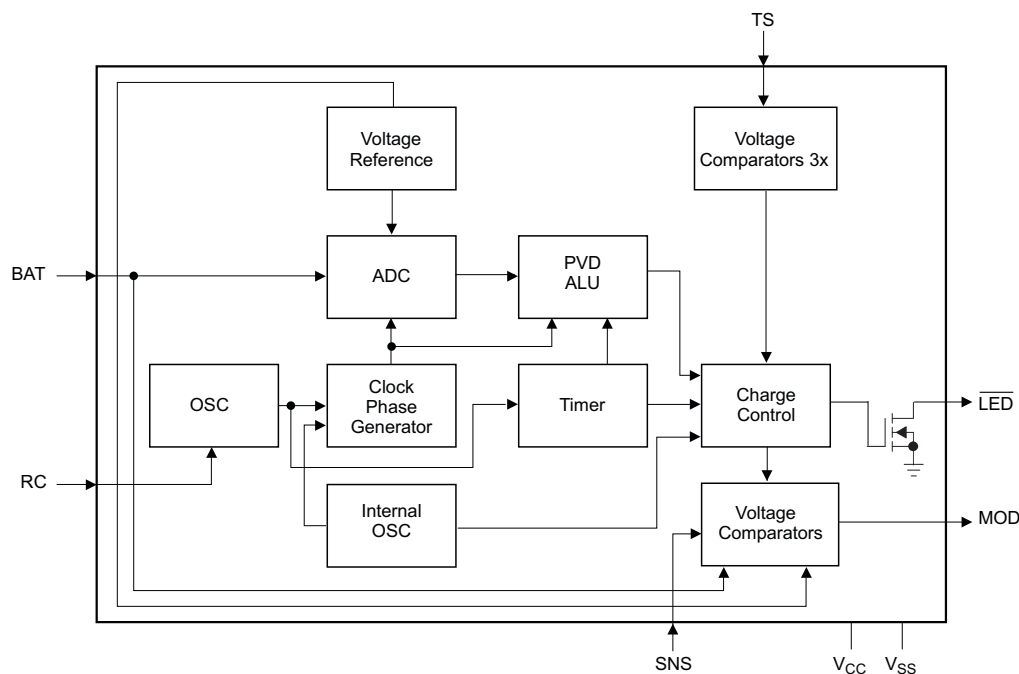
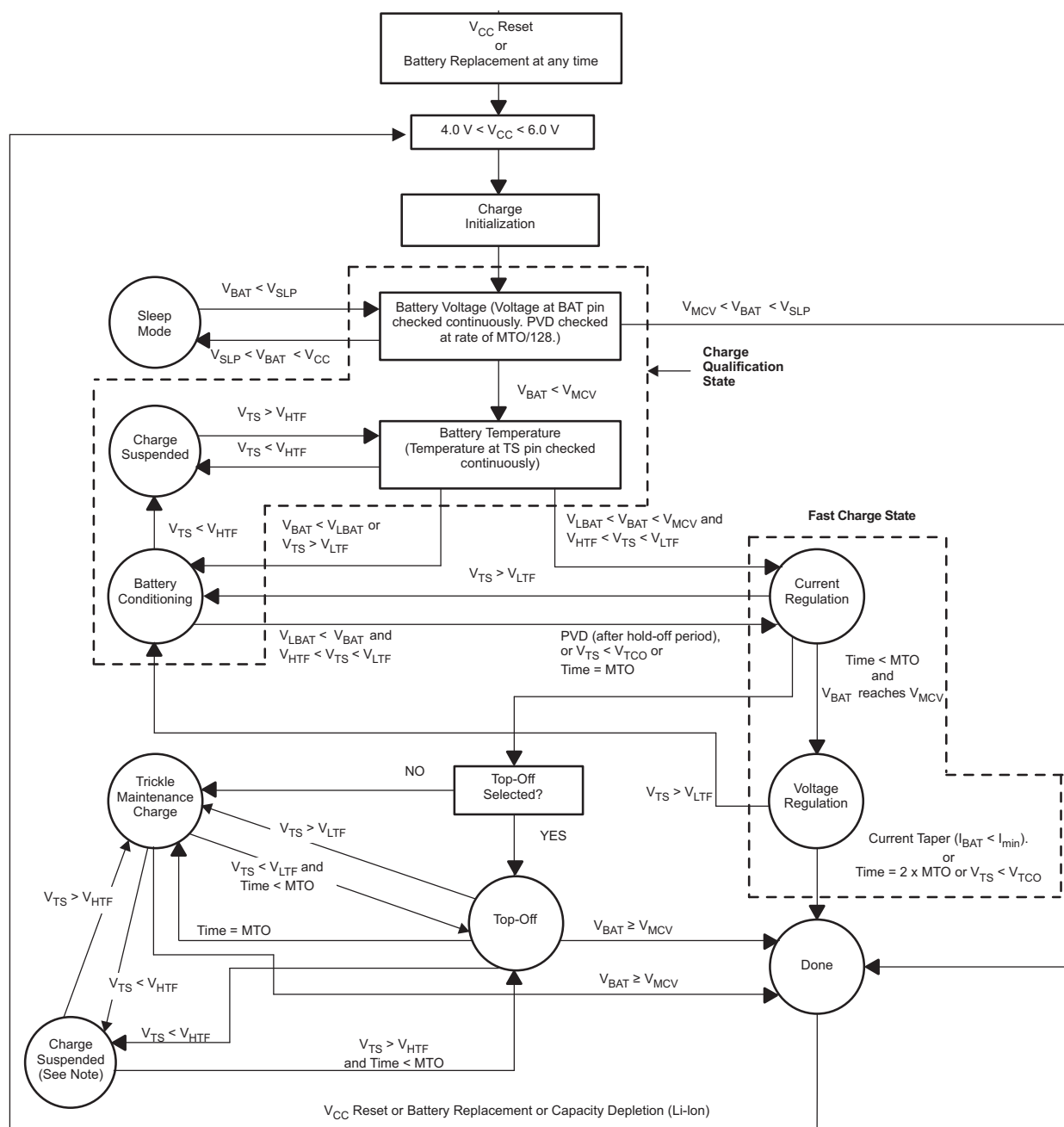


Figure 1. Functional Block Diagram



NOTE: If $V_{TS} < V_{TCO}$ at any time, may only return to Trickle Maintenance Charge state and not to Top-Off.

Figure 2. State Diagram

ABSOLUTE MAXIMUM RATINGS⁽¹⁾

		VALUE	UNIT
V _{CC}	V _{CC} relative to V _{SS}	–0.3 to 7	V
V _T	DC voltage applied on any pin, relative to V _{SS}	–0.3 to V _{CC}	V
T _{OPR}	Operating ambient temperature	–20 to 70	°C
T _{STG}	Storage temperature	–40 to 125	°C
T _{SOLDER}	Soldering temperature (10 s max.)	260	°C

- (1) Permanent device damage may occur if Absolute Maximum Ratings are exceeded. Functional operation should be limited to the Recommended DC Operating Conditions detailed in this data sheet. Exposure to conditions beyond the operational limits for extended periods of time may affect device reliability.

DC THRESHOLDS⁽¹⁾

T_A = T_{OPR}; V_{CC} = 5V ±20% (unless otherwise specified)

PARAMETER		TEST CONDITIONS	TYPICAL	TOLERANCE	UNIT
V _{TCO}	Temperature cutoff	Voltage at the TS pin	0.225 × V _{CC}	±5%	V
V _{HTF}	High-temperature fault	Voltage at the TS pin	0.25 × V _{CC}	±5%	V
V _{LTF}	Low-temperature fault	Voltage at the TS pin	0.5 × V _{CC}	±5%	V
V _{MCV}	Maximum cell voltage	Voltage at the BAT pin	2.00	±0.75%	V
V _{LBAT}	Minimum cell voltage	Voltage at the BAT pin	950	±5%	mV
PVD	BAT input change for PVD detection	Voltage at the BAT pin	3.8	±20%	mV
V _{SNSHI}	High threshold at SNS	Voltage at the SNS pin	50	±10	mV
V _{SNSLO}	Low threshold at SNS	Voltage at the SNS pin	–50	±10	mV
V _{SLP}	Sleep-mode input threshold	Voltage at the BAT pin	V _{CC} –1	±0.5	V
V _{RCH}	Recharge threshold	Voltage at the BAT pin	V _{MCV} –0.1	±0.02	V

- (1) All voltages are relative to V_{SS} except as noted.

RECOMMENDED DC OPERATING CONDITIONS

over operating free-air temperature range (unless otherwise noted)

		TEST CONDITIONS	MIN	TYP	MAX	UNIT
V _{CC}	Supply voltage		4	5	6	V
I _{CC}	Supply current	Exclusive of external loads	0.5		1	mA
I _{CCS}	Sleep current	V _{BAT} = V _{SLPM}			5	μA
V _{TS}	Thermistor input	V _{TS} < 0.5 V prohibited	0.5	V _{CC}		V
V _{OH}	Output high input	MOD, I _{OH} = 10 mA	V _{CC} –0.4			V
V _{OL}	Output low input	MOD, $\overline{\text{LED}}$, I _{OL} = 10 mA			0.2	V
I _{OZ}	High-impedance leakage current	$\overline{\text{LED}}$			5	μA
I _{snk}	Sink current	MOD, $\overline{\text{LED}}$			20	mA
R _{MTO}	Charge timer resistor		2	250		kΩ
C _{MTO}	Charge timer capacitor		0.001	1		μF

IMPEDANCE

PARAMETER		MIN	TYP	MAX	UNIT
R _{BAT}	Battery input impedance	10			MΩ
R _{TS}	TS input impedance	10			MΩ
R _{SNS}	SNS input impedance	10			MΩ

TIMING

T_A = T_{OPR}; V_{CC} = 5 V ±20% (unless otherwise noted)

PARAMETER		MIN	TYP	MAX	UNIT
d _{MTO}	MTO time-base variation	–5%		5%	
f _{TRKL}	Pulse-trickle frequency	0.9	1	1.1	Hz

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Initiation and Charge Qualification

The bq2000 initiates a charge cycle when it detects

- Application of power to V_{CC}
- Battery replacement
- Exit from sleep mode
- Capacity depletion (Li-Ion only)

Immediately following initiation, the IC enters a charge-qualification mode. The bq2000 charge qualification is based on battery voltage and temperature. If the voltage on the BAT pin is less than the internal threshold, V_{LBAT} , the bq2000 enters the battery conditioning state. This condition indicates the possibility of a defective or shorted battery pack. In an attempt to revive a fully depleted pack, the bq2000 enables the MOD pin to trickle-charge at a rate of once every 1.0s. As explained in the section "Top-Off and Pulse-Trickle Maintenance Charge," the trickle pulse-width is user-selectable and is set by the value of the resistance connected between the RC pin and V_{SS} .

During charge qualification, the $\overline{LED}$ pin blinks at a 1Hz rate, indicating the pending status of the charger.

Once battery conditioning (trickle charge) has raised the voltage on the BAT pin above V_{LBAT} , the IC enters fast charge, if the battery temperature is within the V_{LTF} to V_{HTF} range. The BQ2000 will stay in the battery conditioning state indefinitely and will not progress to fast charge until the voltage on the BAT pin is above V_{LBAT} and the temperature is within the V_{LTF} and V_{HTF} range. No timer is implemented during battery conditioning.

Battery Chemistry

The bq2000 detects the battery chemistry by monitoring the battery-voltage profile during the initial stage of the fast charge. If the voltage on the BAT pin rises to the internal V_{MCV} reference, the IC assumes a Li-Ion battery. Otherwise, the bq2000 assumes a NiCd/NiMH chemistry. While in the fast charge state, the $\overline{LED}$ pin is pulled low (the LED is on).

As shown in Figure 3, a resistor voltage-divider between the battery pack's positive terminal and V_{SS} scales the battery voltage. A low-pass filter then smooths out this voltage to present a clean signal to the BAT pin. In a mixed-chemistry design, a common voltage-divider is used as long as the maximum charge voltage of the nickel-based pack is below that of the Li-Ion pack. Otherwise, different scaling is required.

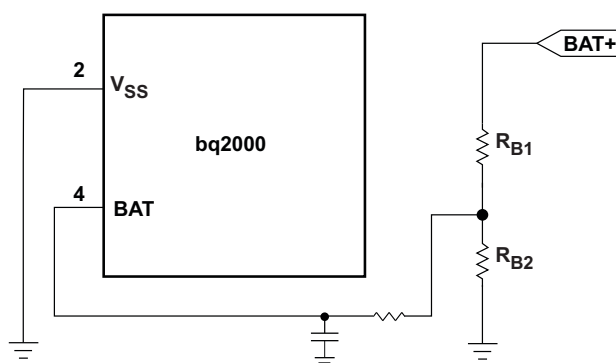


Figure 3. Battery Voltage Divider and Filter

Once the chemistry is determined, the bq2000 completes the fast charge with the appropriate charge algorithm (Table 1). The user can customize the algorithm by programming the device using an external resistor and a capacitor connected to the RC pin, as discussed in later sections.

NiCd and NiMH Batteries

Following charge qualification (which includes trickle charge, if required), the bq2000 fast-charges NiCd or NiMH batteries using a current-limited algorithm. During the fast-charge period, it monitors charge time, temperature, and voltage for adherence to the termination criteria. This monitoring is further explained in later sections. Following fast charge, the battery is topped off, if top-off is selected. The charging cycle ends with a trickle maintenance-charge that continues as long as the voltage on the BAT pin remains below V_{MCV} .

Lithium-Ion Batteries

The bq2000 uses a two-phase fast-charge algorithm for Li-Ion batteries (Figure 4). In phase one, the bq2000 regulates constant current until V_{BAT} rises to V_{MCV} . Once $V_{BAT} = V_{MCV}$, the device identifies the cell as a Li-ion, and changes the termination method from PVD to minimum current. The bq2000 then moves to phase two, regulates the battery with constant voltage of V_{MCV} , and terminates when the charging current falls below the I_{MIN} threshold or the timer expires (whichever happens first). A new charge cycle is started if the cell voltage falls below the V_{RCH} threshold.

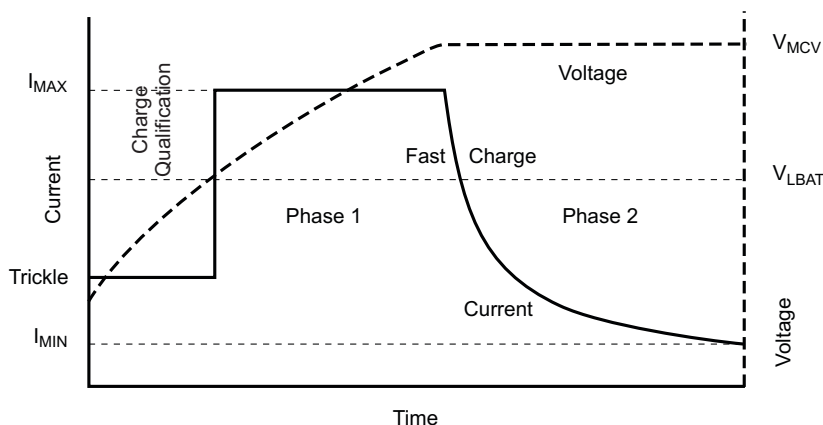


Figure 4. Lithium-Ion Charge Algorithm

During the current-regulation phase, the bq2000 monitors charge time, battery temperature, and battery voltage for adherence to the termination criteria. During the final constant-voltage stage, in addition to the charge time and temperature, it monitors the charge current as a termination criterion. There is no post-charge maintenance mode for Li-Ion batteries.

Table 1 summarizes the charging process for both Nickel and Li-Ion batteries.

Table 1. Charge Algorithm

BATTERY CHEMISTRY	CHARGE ALGORITHM
NiCd or NiMH ($V_{BAT} < V_{MCV}$ always)	1. Charge qualification 2. Trickle charge, if required 3. Fast charge (constant current) 4. Charge termination (peak voltage, maximum charge time = 1 MTO) 5. Top-off (optional) 6. Trickle charge
Li-Ion ($V_{BAT} \leq V_{MCV}$)	1. Charge qualification 2. Trickle charge, if required 3. Fast charge (constant current) 4. Fast charge (constant voltage) 5. Charge termination (minimum current, maximum charge time = 2 MTO)

FAST CHARGE TERMINATION

Initial Hold-OFF Period

The bq2000 incorporates a user programmable hold-off period to avoid premature fast charge termination that can occur with brand new cells at the very beginning of fast charge. The values of the external resistor and capacitor connected to the RC pin set the initial hold-off period. During this period, the bq2000 avoids early termination due to an initial peak in the battery voltage by disabling the peak voltage-detection (PVD) feature. This period is fixed at the programmed value of the maximum charge time (MTO) divided by 32.

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$$\text{hold-off period} = \frac{\text{MTO}}{32} \quad (1)$$

Maximum Charge Time (NiCD, NiMH, and Li-Ion)

The bq2000 sets the maximum charge-time through the RC pin. With the proper selection of external resistor and capacitor values, various time-out values may be achieved. If the timer expires while still in constant-current charging, the bq2000 assumes a Nickel chemistry and proceeds to top-off charge (if top-off is enabled) or trickle maintenance charge. Figure 5 shows a typical connection.

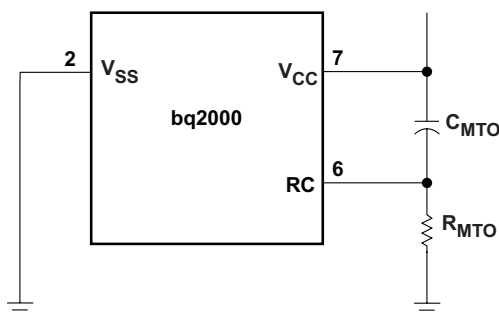


Figure 5. Typical Connection for the RC Input

The following equation shows the relationship between the R_{MTO} and C_{MTO} values and the maximum charge time (MTO) for the bq2000:

$$\text{MTO} = R_{\text{MTO}} \times C_{\text{MTO}} \times 35,988 \quad (2)$$

MTO is measured in minutes, R_{MTO} in ohms, and C_{MTO} in farads. (Note: R_{MTO} and C_{MTO} values also determine other features of the device. See Table 4 and Table 5 for details.

If, during fast charge, $V_{\text{TS}} > V_{\text{LTF}}$, then the timer is paused and the IC enters battery conditioning charge until $V_{\text{TS}} < V_{\text{LTF}}$. Since the IC is in the battery conditioning state, the LED flashes at the 1 Hz rate. Once $V_{\text{TS}} < V_{\text{LTF}}$, fast charge restarts and the timer resumes from where it left off with no change in total fast charge time.

For Li-Ion cells, when the battery reaches the constant-voltage phase of fast charge, the bq2000 adds an additional MTO of time to whatever time was left over from the constant current fast charge timer. Thus, the pack could spend longer than 1 MTO in constant-voltage fast charge, but is always limited to 1 MTO in constant-current fast charge. This feature provides the additional charge time required for Li-Ion cells.

For Nickel cells, if top-off is enabled, the timer is reset on the completion of fast charge before beginning top-off charge.

Maximum Temperature (NiCd, NiMH, Li-Ion)

A negative-coefficient thermistor, referenced to V_{SS} and placed in thermal contact with the battery, may be used as a temperature-sensing device. Figure 6 shows a typical temperature-sensing circuit.

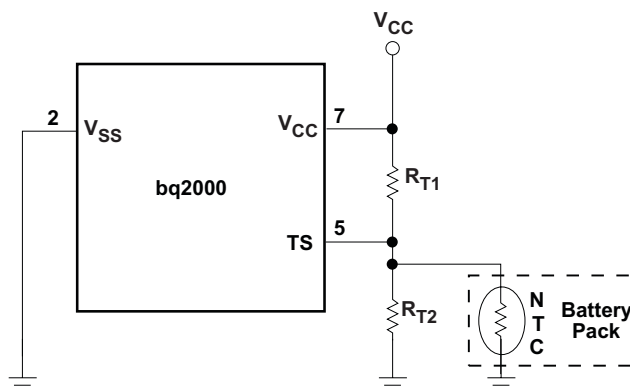


Figure 6. Temperature Monitoring Configuration

During fast charge, the bq2000 compares the battery temperature to an internal high-temperature cutoff threshold, V_{TCO} , and a low-temperature threshold, V_{LTF} . During fast charge only, the V_{HTF} fault comparator is disabled. When the voltage at the TS pin is lower than V_{TCO} , the bq2000 terminates fast charge, moves to the charge suspended state, and turns off the LED. When V_{TS} rises above V_{HTF} , the bq2000 will resume charging in the trickle maintenance charge state, per Figure 2. In fast charge (either constant current or constant voltage fast charge), when the voltage on the TS pin is higher than V_{LTF} , the charger enters the battery conditioning state, as described in the previous section. Fast charge is resumed when V_{TS} is less than V_{LTF} .

Peak Voltage (NiCd, NiMH)

The bq2000 uses a peak-voltage detection (PVD) scheme to terminate fast charge for NiCd and NiMH batteries. The bq2000 continuously monitors the voltage on the BAT pin, representing the battery voltage, to ensure that it never exceeds V_{MCV} (maximum cell voltage). In addition, it also samples, at a rate of MTO/128, the voltage on the BAT pin and triggers the peak detection feature if this value falls below the maximum sampled value by as much as 3.8mV (PVD). In preparation for sampling the BAT pin voltage, the bq2000 briefly turns off most circuits (the MOD and RC pins will both go low) in order to get the cleanest possible, noise-free measurement. While the monitoring of the BAT pin voltage is continuous, the sampling of the BAT pin voltage with the internal ADC only occurs during the constant current regulation phase of fast charge. If the cell voltage reaches V_{MCV} , the pack is assumed to be Li-Ion and the BAT pin voltage sampling is disabled, as PVD is not a termination criterion for Lithium cells. As shown in Figure 3, a resistor voltage-divider between the battery pack's positive terminal and V_{SS} scales the battery voltage measured at the BAT pin.

For Li-Ion battery packs, the resistor values R_{B1} and R_{B2} are calculated by the following equation:

$$\frac{R_{B1}}{R_{B2}} = \left(N \times \frac{V_{CELL}}{V_{MCV}} \right) - 1 \quad (3)$$

where N is the number of cells in series and V_{CELL} is the manufacturer-specified charging voltage. $R_{B1} + R_{B2}$ should be at least 200kΩ and no more than 1MΩ.

A NiCd or NiMH battery pack consisting of N series cells may benefit by the selection of the R_{B1} value to be $N-1$ times larger than the R_{B2} value. This sets the per cell regulation voltage (V_{CELL}) equal to V_{MCV} . It is critical that V_{CELL} be set high enough that the nickel pack not reach voltage regulation, thus allowing proper termination by PVD. Typical V_{CELL} for a nickel pack is between 1.7V and 2V.

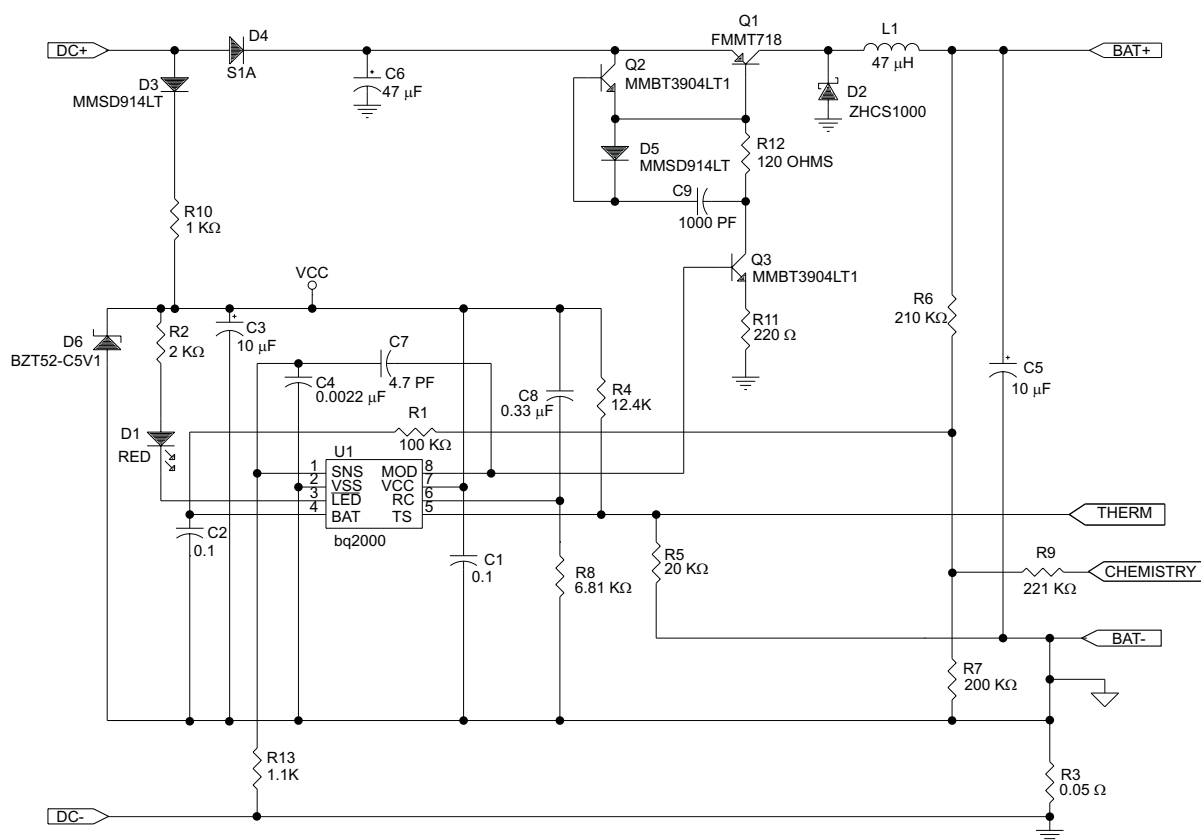
In a mixed-chemistry design, a common voltage-divider is used as long as the maximum charge voltage of the nickel-based pack is below that of the Li-Ion pack. Otherwise, different scaling is required. See Figure 7 for an example.

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- NOTES:**
1. For Li-Ion, the CHEMISTRY is left floating.
For NiCd/NiMH, the CHEMISTRY is tied to BAT-
 2. DC input voltage: 9–16V
 3. Charge current: 1A
 4. L1: 3L Global P/N PKSMD-1005-470K-1A

Figure 7. Single-Cell Li-Ion, 3-Cell NiCd/NiMH 1A Charger

Minimum Current (Li-Ion Only)

The bq2000 monitors the charging current during the voltage-regulation phase of Li-Ion batteries. Fast charge is terminated when the current is tapered off to 14% of the maximum charging current.

Once constant-current fast charge has ended, the bq2000 either measures the value of the C_{MTO} capacitor (in the case of Nickel batteries) and then proceeds to either top-off or trickle maintenance charge or simply completes the constant-voltage stage of fast charge (in the case of a Li-Ion cell).

Top-Off and Pulse-Trickle Maintenance Charge

An optional top-off charge is available for NiCd or NiMH batteries. Top-off may be desirable on batteries that have a tendency to terminate charge before reaching full capacity. To enable this option, the capacitance value of C_{MTO} connected between the RC pin and V_{CC} (Figure 5) should be greater than $0.13\mu F$, and the value of the resistor connected to this pin should be less than $250k\Omega$. To disable top-off, the capacitance value should be less than $0.07\mu F$. The tolerance of the capacitor needs to be taken into account in component selection.

Once top-off is started, the timer is reset and top-off proceeds until the timer expires, V_{MCV} is reached, or there is a temperature fault. During top-off, current is delivered to the battery in pulses that occur every second. The fixed pulse width allows an average current of 1/16 of the fast charge current to be delivered to the battery every second. The LED is always off during top-off and trickle maintenance charge.

During top-off, there are three different temperature faults that can occur. If $V_{TS} > V_{LTF}$, top-off is suspended, the timer is paused, and trickle charge is started. When V_{TS} falls below V_{LTF} , top-off is resumed. If $V_{TS} < V_{HTF}$, all charging stops, but the timer keeps counting. When $V_{TS} > V_{HTF}$, top-off is resumed, if there is still time remaining on the timer. If there is not time left, trickle maintenance charge is entered. If $V_{TS} < V_{TCO}$, all charging stops. Only trickle maintenance charge may resume after $V_{TS} > V_{HTF}$.

Following top-off, the bq2000 trickle-charges the battery by enabling the MOD pin to charge at a rate of once every 1.0 second. The trickle pulse-width is user-selectable and is set by the value of the resistor R_{MTO} , connected between the RC pin and V_{SS} . Figure 8 shows the relationship between the trickle pulse-width and the value of R_{MTO} . The typical tolerance of the pulsewidth below 150kΩ is ±10%.

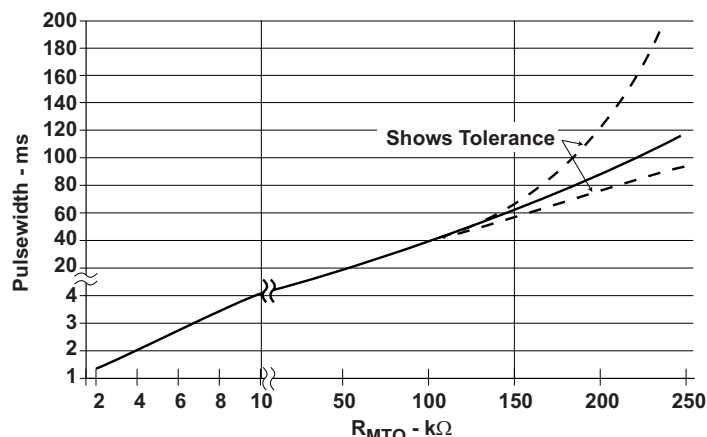


Figure 8. Relationship Between Trickle Pulse-Width and Value of R_{MTO}

Note that with an R_{MTO} value around 150 kΩ, the trickle charge pulse width is nearly identical to the top-off pulse width of 62.5 ms (1/16 of a second). With R_{MTO} values near 150 kΩ, it can be difficult to tell which state the IC is in (top-off or trickle charge). The best way to tell if the bq2000 is in top-off or trickle charge is to look at the RC pin when the temperature is between the LTF and HTF. In top-off, the RC pin will be counting and will have a sawtooth waveform on it. In trickle charge, there is no timer and the RC pin will be at a DC value.

The RC pin contains valuable information in determining what state the bq2000 is in, since it always operates in one of three modes. If the RC pin is low (around V_{SS} potential), the IC is in sleep mode. (If the RC pin is low for brief instants during fast charge, the bq2000 is sampling the BAT pin for PVD). If the RC pin is at some DC value (usually around 1-2V), then the IC has paused the timer or the timer is inactive. If the RC pin is a sawtooth waveform (similar to Figure 15), then the timer is running and the RC pin is considered "active." Lastly, the RC pin can be loaded by too large of a C or too small of an R. This will sometimes make the usual sawtooth waveform look like a triangle waveform on an oscilloscope (the rise time is lengthened), or the RC signal could have the appearance of being clipped (flat top or bottom). The timer will be unreliable under these conditions and the bq2000 should not be operated in this manner. Table 2 summarizes the different states of the RC pin.

Table 2. RC Pin Status

bq2000 CHARGE STATE	TS PIN STATE	RC PIN BEHAVIOR
Battery absent	N/A	1-2V DC level
Sleep mode	N/A	Ground (V_{SS})
Charge qualification (including battery conditioning (trickle charge) and charge suspended)	N/A	1-2V DC level
Fast charge (current and voltage regulation)	$V_{TS} < V_{LTF}$	Active
	$V_{TS} > V_{LTF}$ (in battery conditioning state)	1-2V DC level (timer is paused and will resume when $V_{TS} < V_{LTF}$)

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Table 2. RC Pin Status (continued)

bq2000 CHARGE STATE	TS PIN STATE	RC PIN BEHAVIOR
Top-off charge	$V_{TS} > V_{LTF}$ (in trickle maintenance charge state)	1-2V DC level (timer is paused and will resume when $V_{TS} < V_{LTF}$)
	$V_{LTF} > V_{TS} > V_{HTF}$	Active
	$V_{HTF} > V_{TS} > V_{TCO}$	Active (timer is still counting, even though charging is suspended)
Trickle maintenance charge (after fast charge)	N/A	1-2V DC level
Charge complete	N/A	Active

Both top-off and trickle maintenance charge are terminated and the pack never receives any more charge (until a charge initialization occurs) if the voltage on the BAT pin reaches V_{MCV} . During trickle maintenance charge, charging is suspended if $V_{TS} < V_{HTF}$. It resumes when $V_{TS} > V_{HTF}$. The bq2000 is designed to remain in trickle maintenance charge forever (excluding the two faults just mentioned) in order to keep a Nickel pack full.

Charge Current Control

The bq2000 implements a hysteretic control loop that regulates the current being delivered to the battery pack to a user programmable value that is set by the value of the R_{SNS} resistor. A second, outer control loop reduces the average current delivered to the pack in order to clamp the voltage at the BAT pin to a maximum of V_{MCV} . The bq2000 modulates the MOD pin to regulate the current and voltage of the pack. The bq2000 monitors charge current at the SNS input by sensing the voltage drop across a sense-resistor, R_{SNS} , in series with the battery pack. See Figure 9 for a typical current-sensing circuit.

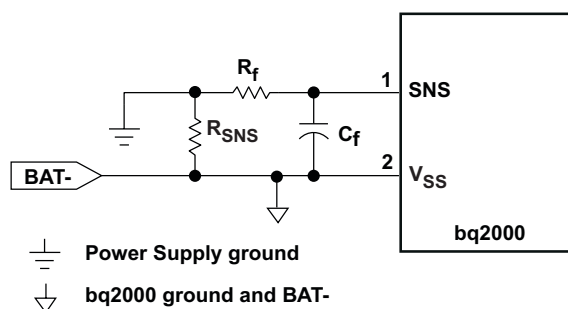


Figure 9. Current-Sensing Circuit

R_{SNS} is sized to provide the desired fast-charge current (I_{MAX}).

$$I_{MAX} = \frac{0.05}{R_{SNS}} \quad (4)$$

If the voltage at the SNS pin is greater than V_{SNSLO} or less than V_{SNSHI} , the bq2000 switches the MOD output high to pass charge current to the battery. When the SNS voltage is less than V_{SNSLO} or greater than V_{SNSHI} , the bq2000 switches the MOD output low to shut off charging current to the battery. A hysteresis capacitor (C_{HYS}) is required between the C_{MOD} pin and the SNS pin to add a healthy amount of hysteresis to the current sense signal. Typical hysteresis values are between 5 and 25 mV. The amount of hysteresis can be calculated by examining the capacitive divider formed by C_{HYS} and C_f .

$$\text{Hysteresis (V)} = V_{CC} \times \frac{C_{HYS}}{(C_{HYS} + C_f)} \quad (5)$$

Being a hysteretic controller, the switching frequency of the bq2000 is determined by the values of several of the external circuit components. The components that affect the switching frequency are: input voltage, R_{SNS} value, inductor value, hysteresis capacitor value (C_{HYS}), and the value of the filter on the current sense signal (R_f and C_f values). R_f and C_f have the most impact on the switching frequency and are also the components that are easiest to change to adjust the frequency, as they do not affect anything else in the circuit (besides, of course, the cleanliness and quality of the current sense signal being fed to the bq2000). In general, increasing the input

voltage and/or inductor value or decreasing C_{HYS} and/or the $R_f \times C_f$ filter corner frequency will increase the switching frequency. Figure 10 and Figure 11 show empirical data on the variation in switching frequency based on adjusting R_f and C_f . This data was taken with an input voltage of 12V, inductor value of 220 μ H, R_{SNS} value of 50 m Ω , and C_{HYS} value of 4.7 pF. Typical switching frequencies for the bq2000 are between 100 and 200 kHz, though it is possible to achieve switching frequencies in excess of 300kHz.

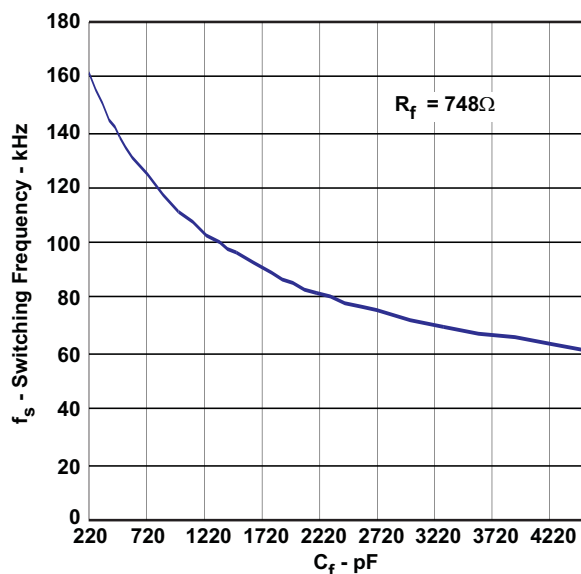


Figure 10. Switching Frequency vs Capacitance

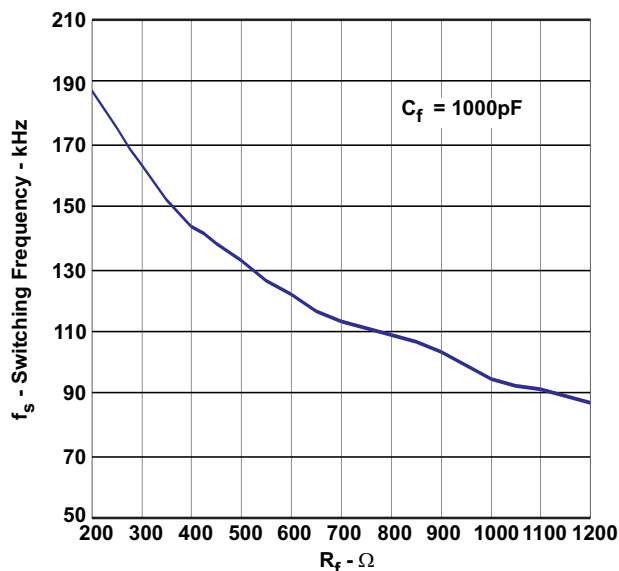


Figure 11. Switching Frequency vs Resistance

bq2000



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TEMPERATURE MONITORING

The bq2000 measures the temperature by the voltage at the TS pin. This voltage is typically generated by a negative-temperature-coefficient thermistor. The bq2000 compares this voltage against its internal threshold voltages to determine if charging is safe. These thresholds are the following:

- High-temperature cutoff voltage: $V_{TCO} = 0.225 \times V_{CC}$. This voltage corresponds to the maximum temperature (TCO) at which any charging is allowed. The bq2000 terminates charging if the voltage on the TS pin falls below V_{TCO} .
- High-temperature fault voltage: $V_{HTF} = 0.25 \times V_{CC}$. This voltage corresponds to a maximum allowed pack temperature (HTF) in all states except for fast charge. During fast charge, HTF faults are disabled to allow for a normal increase in pack temperature.
- Low-temperature fault voltage: $V_{LTF} = 0.5 \times V_{CC}$. This voltage corresponds to the minimum temperature (LTF) at which fast charging or top-off is allowed. If the voltage on the TS pin rises above V_{LTF} , the bq2000 suspends either fast charge or top-off and begins a trickle charge. When the voltage falls back below V_{LTF} , fast charge or top-off resumes from the point where suspended. If $V_{TS} > V_{LTF}$, the charger will always be in trickle charge.

Table 3 summarizes these various conditions.

Table 3. Temperature-Monitoring Conditions and Actions

TEMPERATURE	CONDITION	ACTION
$V_{TS} > V_{LTF}$	Cold battery – checked at all times	During charge qualification, no effect
		During fast charge, suspends fast charge and moves into charge qualification, pauses timer, and flashes LED
		During top-off, suspends top-off and moves into trickle maintenance charge and pauses timer
		During trickle maintenance charge, no effect
$V_{HTF} < V_{TS} < V_{LTF}$	Optimal charging range	Allows all stages of charging
$V_{TS} < V_{HTF}$	Hot battery – checked at all times, except during fast charge	During charge qualification, stops charging
		During fast charge, no effect
		During top-off, stops charging
		During trickle maintenance charge, stops charging
$V_{TS} < V_{TCO}$	Battery exceeding maximum allowable temperature – checked at all times	During charge qualification, stops charging
		During fast charge, terminates fast charge and stops charging, turns off LED
		During top-off, terminates top-off and stops charging
		During trickle maintenance charge, stops charging

Table 4. Summary of NiCd or NiMH Charging Characteristics

PARAMETER	VALUE ⁽¹⁾
Maximum cell voltage (V_{MCV})	2 V
Minimum pre-charge qualification voltage (V_{LBAT})	950 mV
High-temperature cutoff voltage (V_{TCO})	$0.225 \times V_{CC}$
High-temperature fault voltage (V_{HTF})	$0.25 \times V_{CC}$
Low-temperature fault voltage (V_{LTF})	$0.5 \times V_{CC}$
bq2000 fast-charge maximum time out (MTO)	$R_{MTO} \times C_{MTO} \times 35,988$
Fast-charge charging current (I_{MAX})	$0.05/R_{SNS}$
Hold-off period	MTO/32
Top-off charging current (optional)	$I_{MAX}/16$
Top-off period (optional)	MTO
Trickle-charge frequency	1Hz
Trickle-charge pulse-width	See Figure 8

(1) See the DC Thresholds Specification for details.

Table 5. Summary of Li-Ion Charging Characteristics

PARAMETER	VALUE ⁽¹⁾
Maximum cell voltage (V_{MCV})	2 V
Minimum pre-charge qualification voltage (V_{LBAT})	950 mV
High-temperature cutoff voltage (V_{TCO})	$0.225 \times V_{CC}$
High-temperature fault voltage (V_{HTF})	$0.25 \times V_{CC}$
Low-temperature fault voltage (V_{LTF})	$0.5 \times V_{CC}$
bq2000 fast-charge maximum time out (MTO)	$2 \times R_{MTO} \times C_{MTO} \times 35,988$ (See Maximum Charge Time section for full explanation)
Fast-charge charging current (I_{MAX})	$0.05/R_{SNS}$
Hold-off period	MTO/32
Minimum current (for fast-charge termination)	$I_{MAX}/7$
Trickle-charge frequency (before fast charge only)	1Hz
Trickle-charge pulse-width (before fast charge only)	See Figure 8

(1) See the DC Thresholds Specification for details.

Charge Status Display

The charge status is indicated by open-drain output $\overline{LED}$. Table 6 summarizes the display output of the bq2000. A temperature fault or timer expiring changes the charge state immediately (according to Figure 2) and will thus change the $\overline{LED}$ status immediately and accordingly.

Table 6. Charge Status Display

bq2000 CHARGE STATE	$\overline{LED}$ STATUS
Charge qualification (including battery conditioning and charge suspended)	1 Hz flash
Fast charge (current and voltage regulation)	Low
Top-off charge	High impedance
Trickle maintenance charge (after fast charge)	
Charge complete	
Battery absent	
Sleep mode	

Sleep Mode

The bq2000 features a sleep mode for low power consumption. This mode is enabled when the voltage at the BAT pin is above the low-power-mode threshold, V_{SLP} . During sleep mode, the bq2000 shuts down all unnecessary internal circuits, drives the $\overline{LED}$ output to high-impedance state, and drives the MOD pin low. Restoring BAT below the V_{MCV} threshold initiates the IC and starts a fast-charge cycle. Normally, the bq2000 only enters sleep mode when there is no battery connected on the output and the charger is idling with nothing to charge. In addition, V_{IN} needs to be high enough such that when V_{IN} is present on the output, V_{BAT} would be greater than V_{SLP} . In sleep mode, the output voltage will decay to V_{MCV} at which point the bq2000 turns on and pulses the MOD pin several times. With no battery connected, the output will rise to near V_{IN} at which point the bq2000 re-enters sleep mode. During sleep mode, the RC pin will be at V_{SS} potential. A typical sleep mode waveform is shown in Figure 18.

bq2000



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TYPICAL CHARACTERISTICS

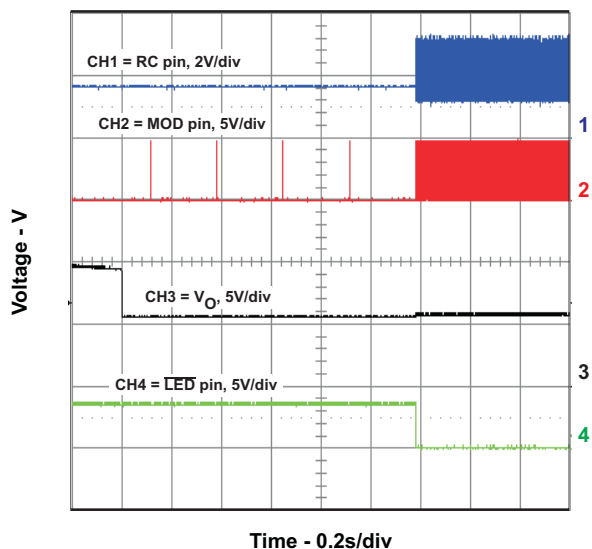


Figure 12. bq2000 Start-up on Battery Insertion

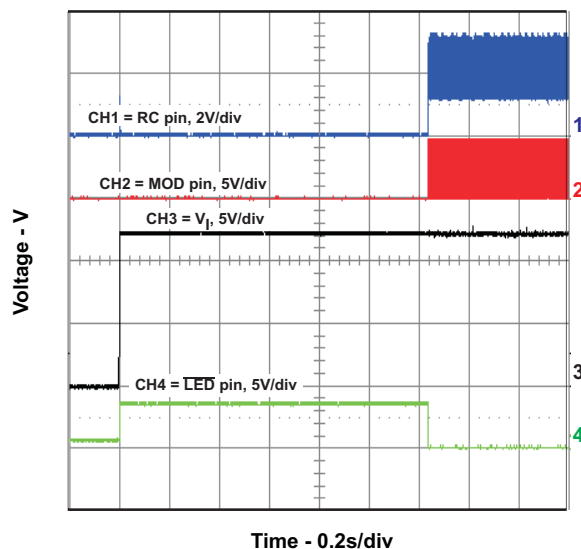


Figure 13. bq2000 Start-up on V_{in}

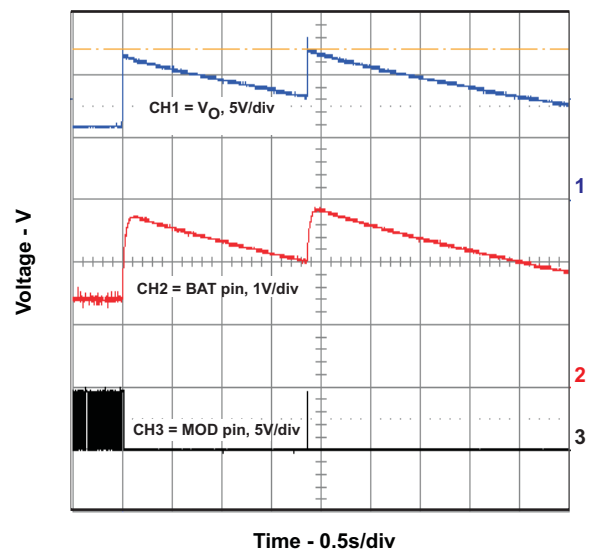


Figure 14. Battery Removal During Fast Charge

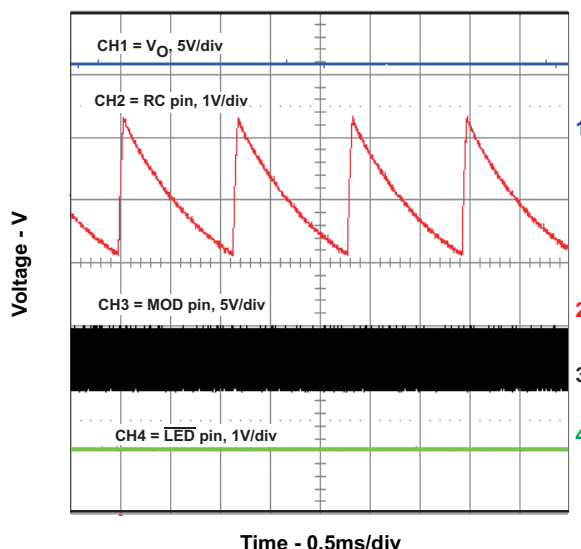


Figure 15. bq2000 in Fast Charge

TYPICAL CHARACTERISTICS (continued)

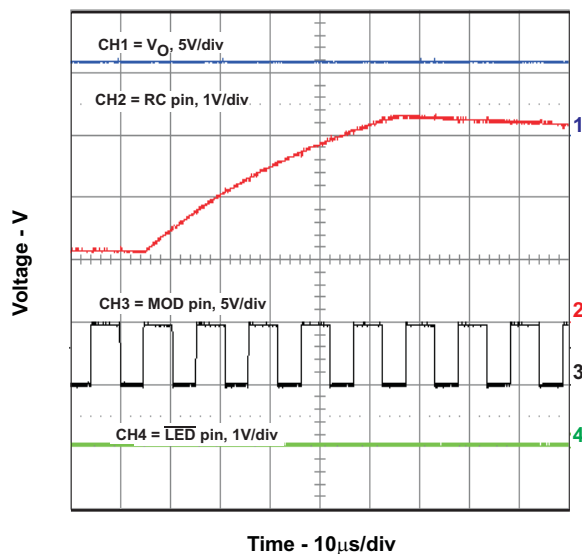


Figure 16. bq2000 in Fast Charge

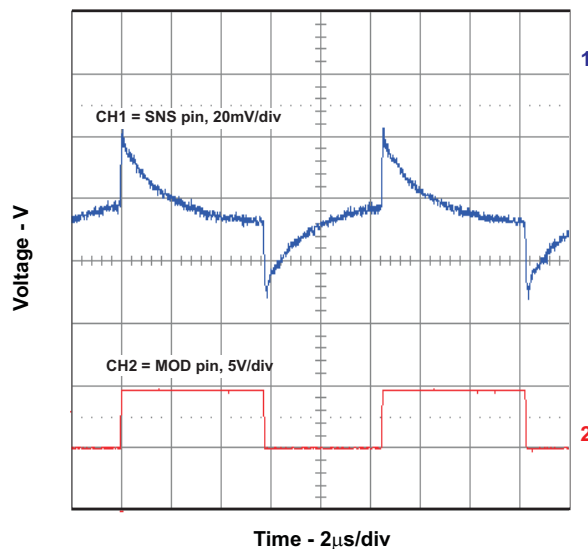


Figure 17. bq2000 Fast Charge SNS and MOD Waveforms

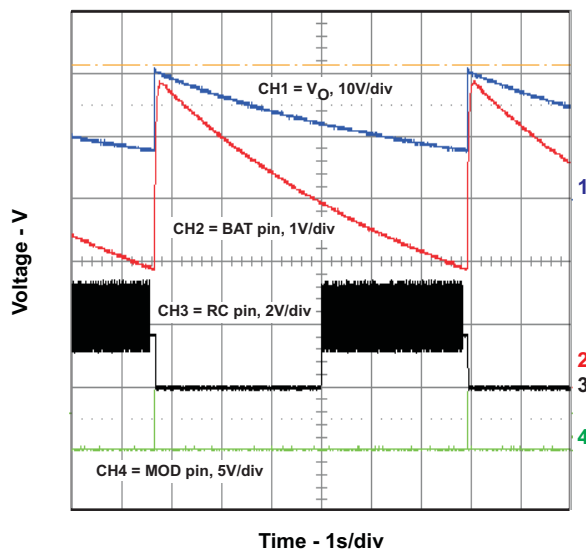


Figure 18. bq2000 in Sleep Mode

bq2000

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REVISION HISTORY

Changes from Revision September 1998 (*) to Revision 1	Page
• Changed the device status From: Preliminary To: Final	1
• Changed the DC THRESHOLDS - V_{TCO} , V_{HTF} , V_{LTF} Tolerance	5
• Changed the RECOMMENDED DC OPERATING CONDITIONS - R_{MTO} , C_{MTO} Values	5
• Added Figure 3 - Battery Voltage Divider and Filter	6
• Changed MTO equation From: $MTO = R \times C \times 71,976$	8
• Added Figure 8	11
Changes from Revision 1 (January 1999) to Revision 2	Page
• Changed Table 4 - V_{BLAT} value	14
• Changed Table 5 - V_{BLAT} value	15
Changes from Revision 2 (March 1999) to Revision 3	Page
• Added the TSSOP Package option	1
• Added Figure 2 State Diagram	4
• Changed the DC THRESHOLDS - V_{TCO} , V_{HTF} , V_{LTF} Tolerance	5
• Changed Figure 7 - Single-Cell Li-Ion, 3-Cell NiCd/NiMH 1A Charger	10
• Changed the Top-Off and Pulse-Trickle Maintenance Charge section - Updated requirement for enabling top-off	10
Changes from Revision 3 (May 1999) to Revision 4	Page
• Changed Rec DC Operating Conditions, V_{OH} - From: $MIN = V_{CC} - 0.2$ at $I_{OH} = 20mA$ To: $MIN = V_{CC} - 0.4$ at $I_{OH} = 10mA$	5
• Changed Rec DC Operating Conditions, V_{OH} - From: $I_{OH} = 20mA$ To: $I_{OH} = 10mA$	5
• Changed Figure 8 - Updated tolerance on the curve	11
Changes from Revision 4 (February 2000) to Revision 5	Page
• Changed Figure 2 State Diagram - Battery voltage detail From: (checked at all times) To: Voltage regulation checked constantly. PVD checked at rate of MTO/64.	4
• Changed Figure 2 State Diagram - Battery temperature detail From: (checked at all times) To: (checked 1,750 times per second)	4
Changes from Revision 5 (February 2001) to Revision 6	Page
• Changed the Top-Off and Pulse-Trickle Maintenance Charge section - First paragraph From: the value of the resistor connected to this pin should be less than 15k Ω To: the value of the resistor connected to this pin should be less than 250k Ω	10
Changes from Revision 6 (January 2008) to Revision D	Page
• Changed the data sheet format. The data sheet was originally from Benchmark Products. In revision D, the data sheet was converted to the TI format, and a re-write of the data sheet was implemented	1

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish	MSL Peak Temp (3)	Op Temp (°C)	Top-Side Markings (4)	Samples
BQ2000PN-B5	ACTIVE	PDIP	P	8	50	Pb-Free (RoHS)	CU NIPDAU	N / A for Pkg Type	-20 to 70	2000PN-B5	Samples
BQ2000PW	ACTIVE	TSSOP	PW	8	150	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-20 to 70	BQ200	Samples
BQ2000PWG4	ACTIVE	TSSOP	PW	8	150	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-20 to 70	BQ200	Samples
BQ2000PWR	ACTIVE	TSSOP	PW	8	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-20 to 70	BQ200	Samples
BQ2000PWRG4	ACTIVE	TSSOP	PW	8	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-20 to 70	BQ200	Samples
BQ2000SN-B5	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	-20 to 70	2000	Samples
BQ2000SN-B5G4	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	-20 to 70	2000	Samples
BQ2000SN-B5TR	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	-20 to 70	2000	Samples
BQ2000SN-B5TRG4	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	-20 to 70	2000	Samples

⁽¹⁾ The marketing status values are defined as follows:

ACTIVE: Product device recommended for new designs.

LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.

NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.

PREVIEW: Device has been announced but is not in production. Samples may or may not be available.

OBSOLETE: TI has discontinued the production of the device.

⁽²⁾ Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check <http://www.ti.com/productcontent> for the latest availability information and additional product content details.

TBD: The Pb-Free/Green conversion plan has not been defined.

Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.

Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.

Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)



⁽³⁾ MSL, Peak Temp. -- The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

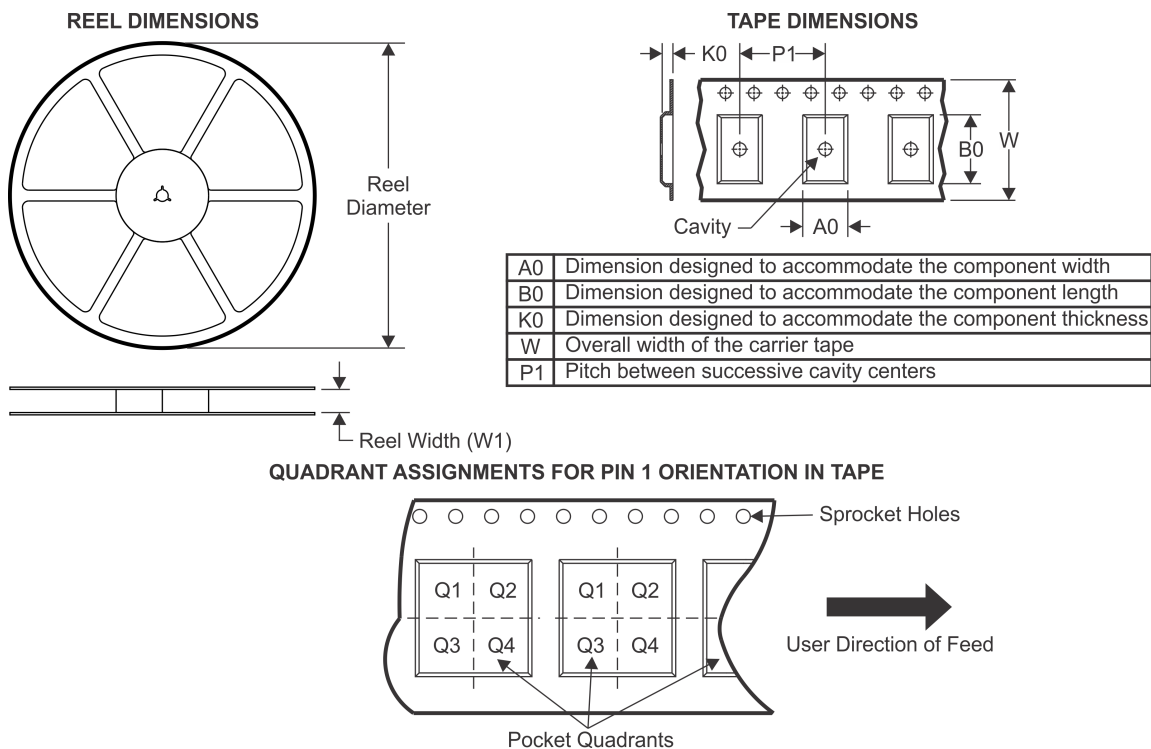
⁽⁴⁾ Multiple Top-Side Markings will be inside parentheses. Only one Top-Side Marking contained in parentheses and separated by a "-" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Top-Side Marking for that device.

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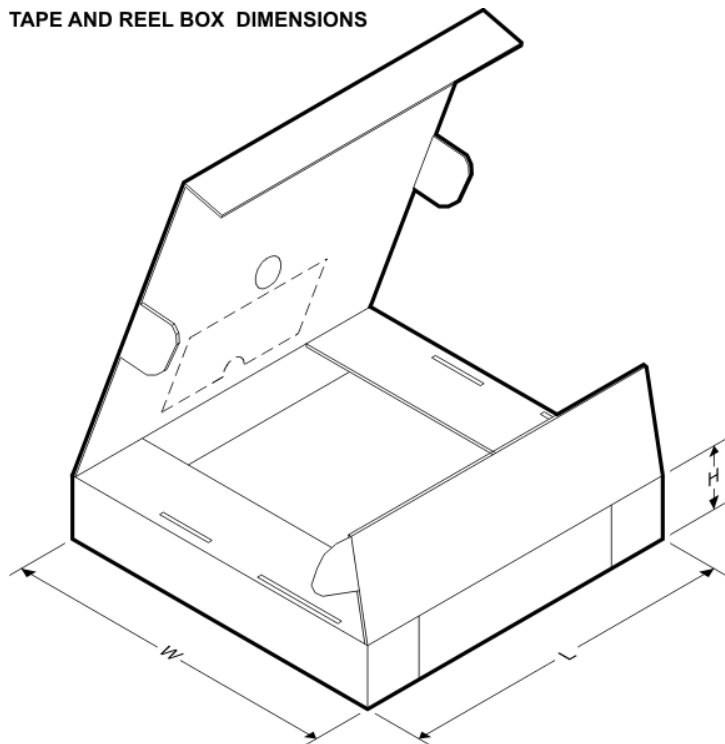
TAPE AND REEL INFORMATION



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
BQ2000PWR	TSSOP	PW	8	2000	330.0	12.4	7.0	3.6	1.6	8.0	12.0	Q1
BQ2000SN-B5TR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1

TAPE AND REEL BOX DIMENSIONS



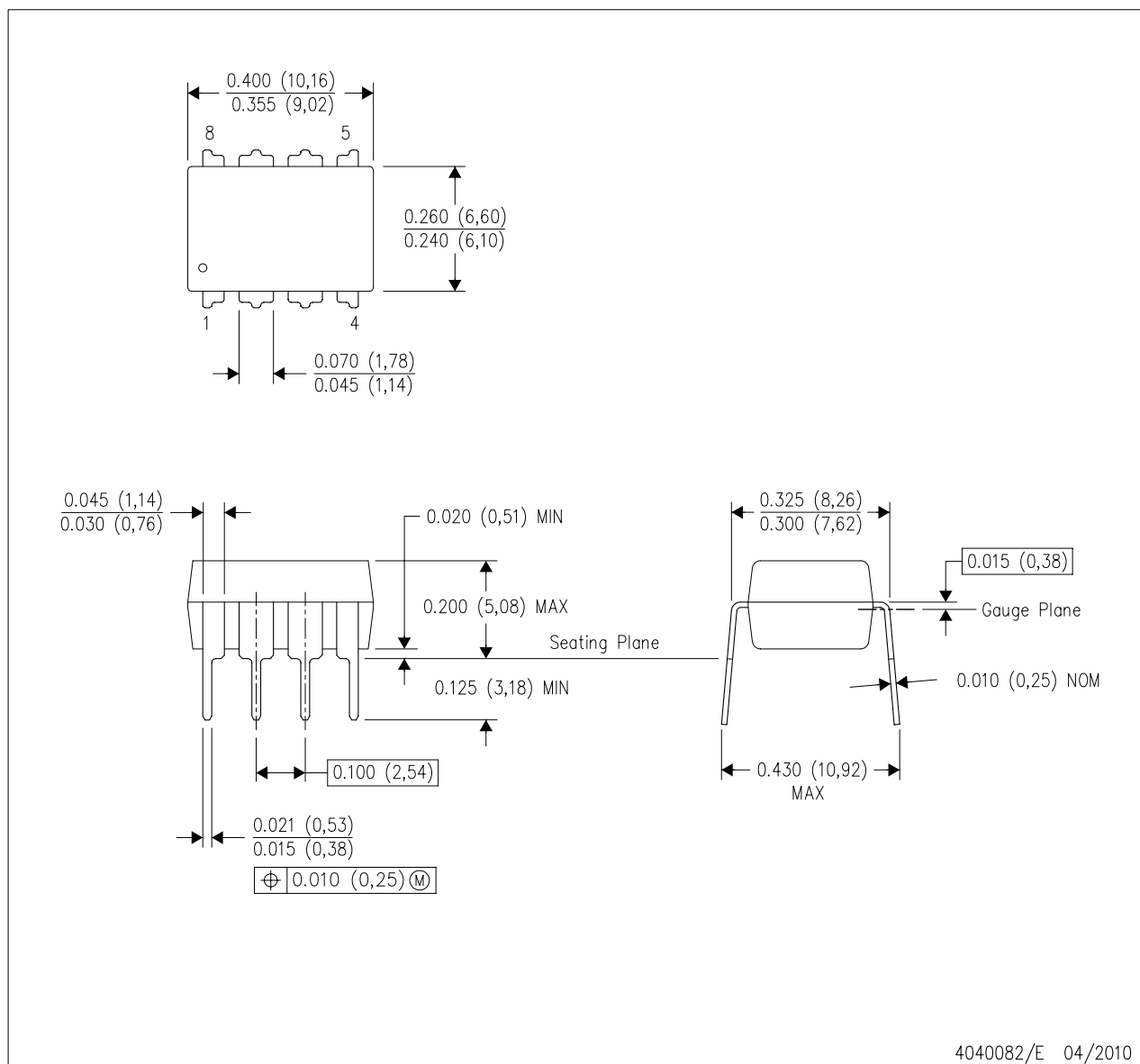
*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
BQ2000PWR	TSSOP	PW	8	2000	367.0	367.0	35.0
BQ2000SN-B5TR	SOIC	D	8	2500	367.0	367.0	35.0

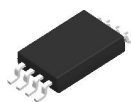
MECHANICAL DATA

P (R-PDIP-T8)

PLASTIC DUAL-IN-LINE PACKAGE



- NOTES:
- A. All linear dimensions are in inches (millimeters).
 - B. This drawing is subject to change without notice.
 - C. Falls within JEDEC MS-001 variation BA.

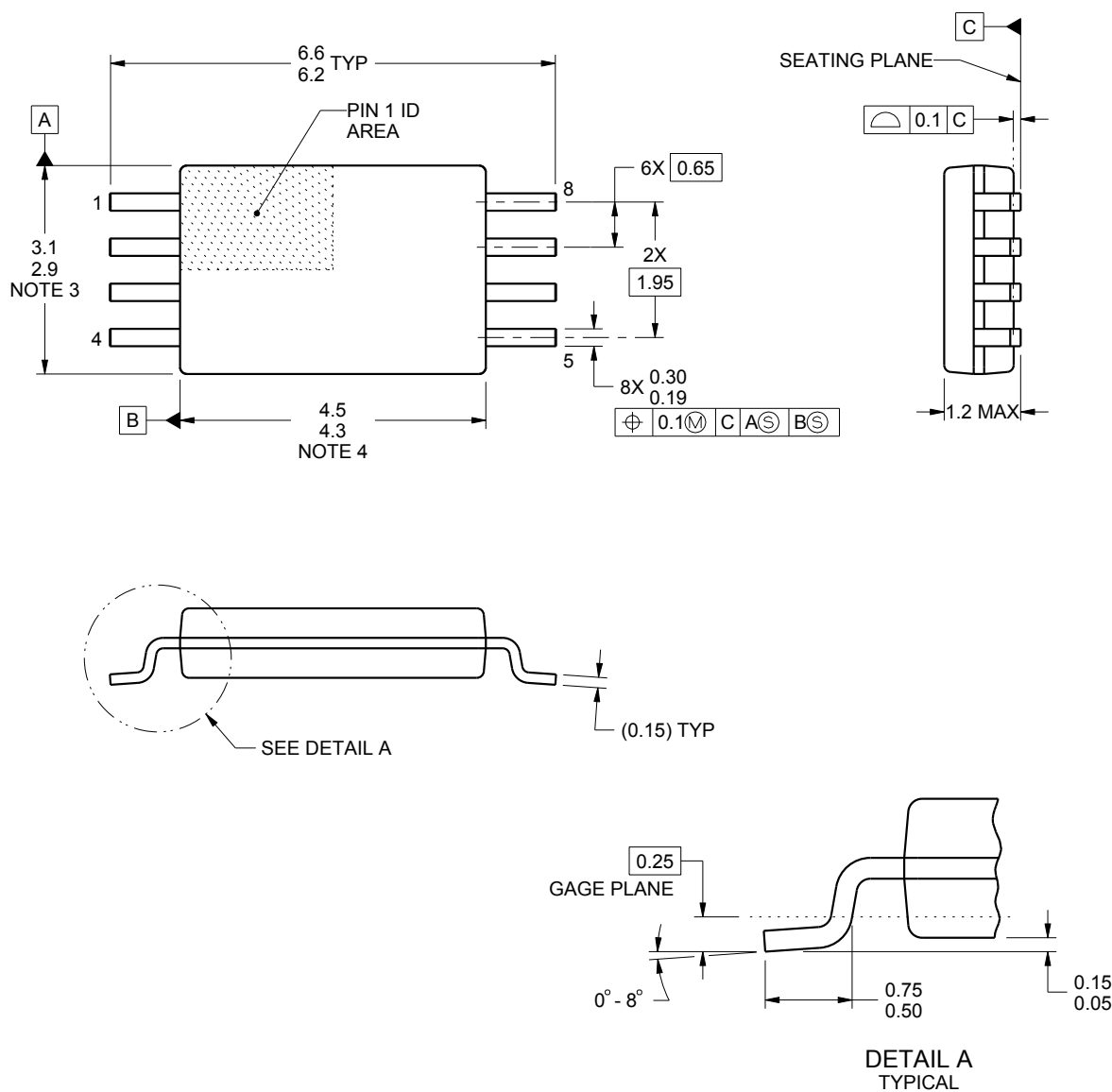


PACKAGE OUTLINE

PW0008A

TSSOP - 1.2 mm max height

SMALL OUTLINE PACKAGE



4221848/A 02/2015

NOTES:

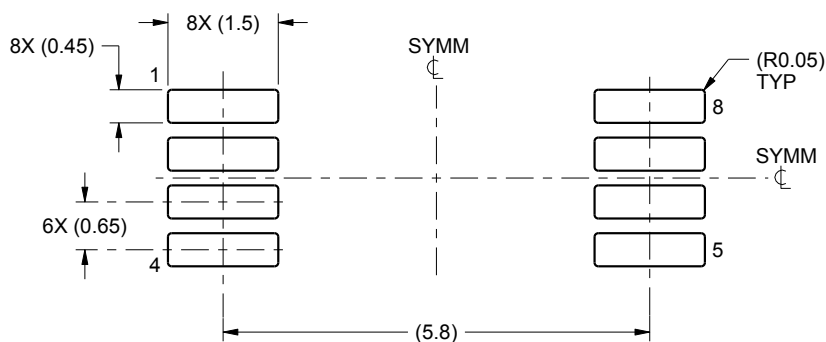
1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.
4. This dimension does not include interlead flash. Interlead flash shall not exceed 0.25 mm per side.
5. Reference JEDEC registration MO-153, variation AA.

EXAMPLE BOARD LAYOUT

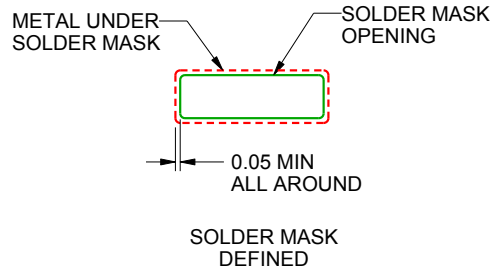
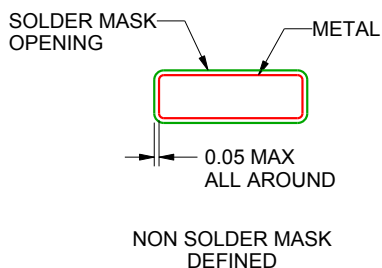
PW0008A

TSSOP - 1.2 mm max height

SMALL OUTLINE PACKAGE



LAND PATTERN EXAMPLE
SCALE:10X



SOLDER MASK DETAILS
NOT TO SCALE

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NOTES: (continued)

6. Publication IPC-7351 may have alternate designs.

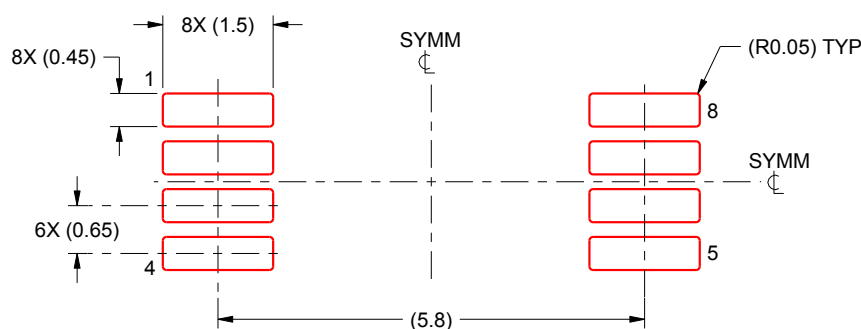
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.

EXAMPLE STENCIL DESIGN

PW0008A

TSSOP - 1.2 mm max height

SMALL OUTLINE PACKAGE



SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE:10X

4221848/A 02/2015

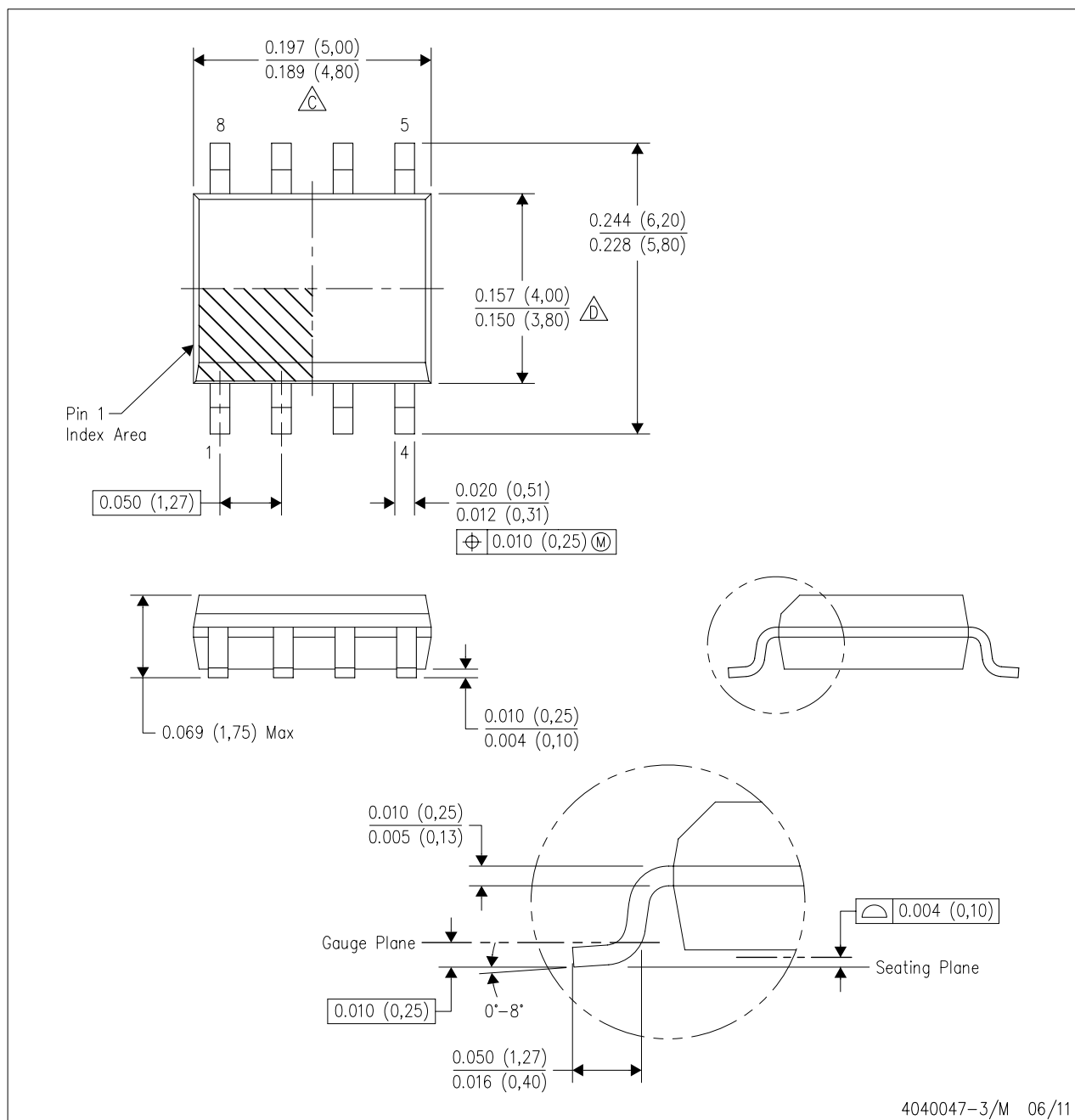
NOTES: (continued)

8. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
9. Board assembly site may have different recommendations for stencil design.

MECHANICAL DATA

D (R-PDSO-G8)

PLASTIC SMALL OUTLINE

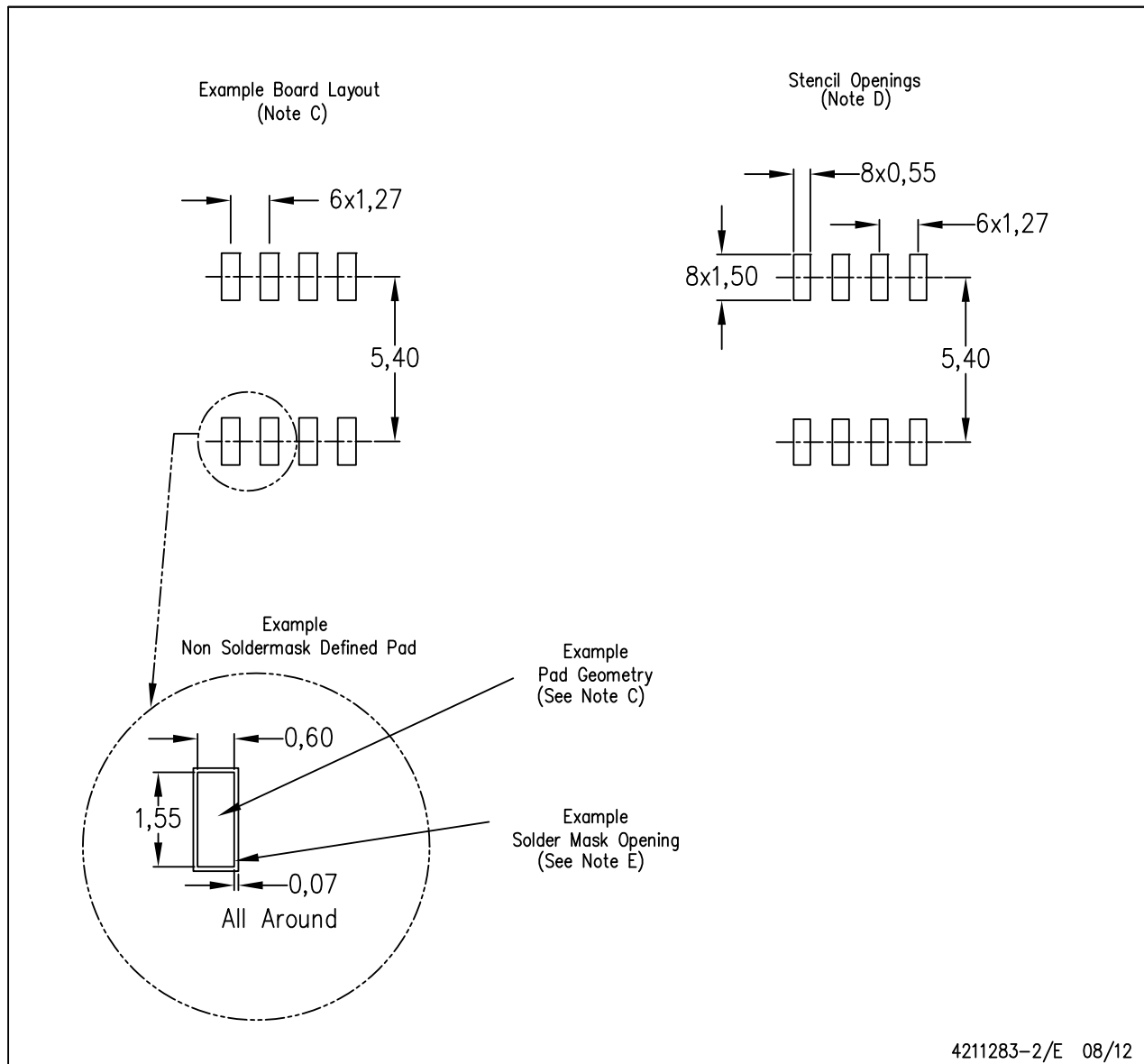


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 - B. This drawing is subject to change without notice.
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 - D. Body width does not include interlead flash. Interlead flash shall not exceed 0.017 (0,43) each side.
 - E. Reference JEDEC MS-012 variation AA.

LAND PATTERN DATA

D (R-PDSO-G8)

PLASTIC SMALL OUTLINE



- NOTES:
- All linear dimensions are in millimeters.
 - This drawing is subject to change without notice.
 - Publication IPC-7351 is recommended for alternate designs.
 - Laser cutting apertures with trapezoidal walls and also rounding corners will offer better paste release. Customers should contact their board assembly site for stencil design recommendations. Refer to IPC-7525 for other stencil recommendations.
 - Customers should contact their board fabrication site for solder mask tolerances between and around signal pads.

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