

## Programmable NiCd/NiMH Fast-Charge Management IC

Check for Samples: [bq24400](#)

### FEATURES

- Safe Management of Fast Charge for NiCd and NiMH 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), 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

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

### GENERAL DESCRIPTION

The bq24400 is a programmable, monolithic IC for fast-charge management of nickel cadmium (NiCd) and nickel metal-hydride (NiMH) in single or multi-cell applications.

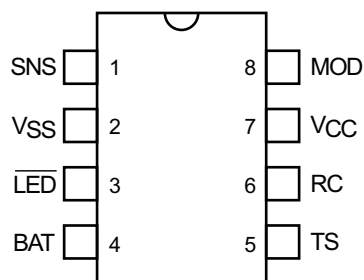
The bq24400 provides these charge termination criteria:

- Peak voltage, PVD
- Maximum temperature
- Maximum charge time

For safety, the bq24400 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 bq24400 uses trickle-charge to condition the battery. For NiMH batteries, the bq24400 provides an optional top-off charge to maximize the battery capacity.

The integrated high-speed comparator allows the bq24400 to be the basis for a complete, high-efficiency battery charger circuit for nickel-based chemistries.

#### 8-Pin DIP or Narrow SOIC or TSSOP



#### Pin Names

SNS	Current-sense input
V <sub>SS</sub>	System ground
LED	Charge-status output
BAT	Battery-voltage input
TS	Temperature-sense input
RC	Timer-program input
V <sub>CC</sub>	Supply-voltage input
MOD	Modulation-control output



Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.



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 bq24400 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<sub>SS</sub>** System Ground

Connect to the battery's negative terminal

### **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<sub>CC</sub> and a resistor to ground connect to this pin.

### **V<sub>CC</sub>** Supply-voltage input

Recommended bypassing is 10μF + 0.1μF to 0.22μF 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 bq24400 is a versatile, NiCd and NiMH battery charge control device. See [Figure 1](#) for a functional block diagram and [Figure 2](#) for a state diagram.

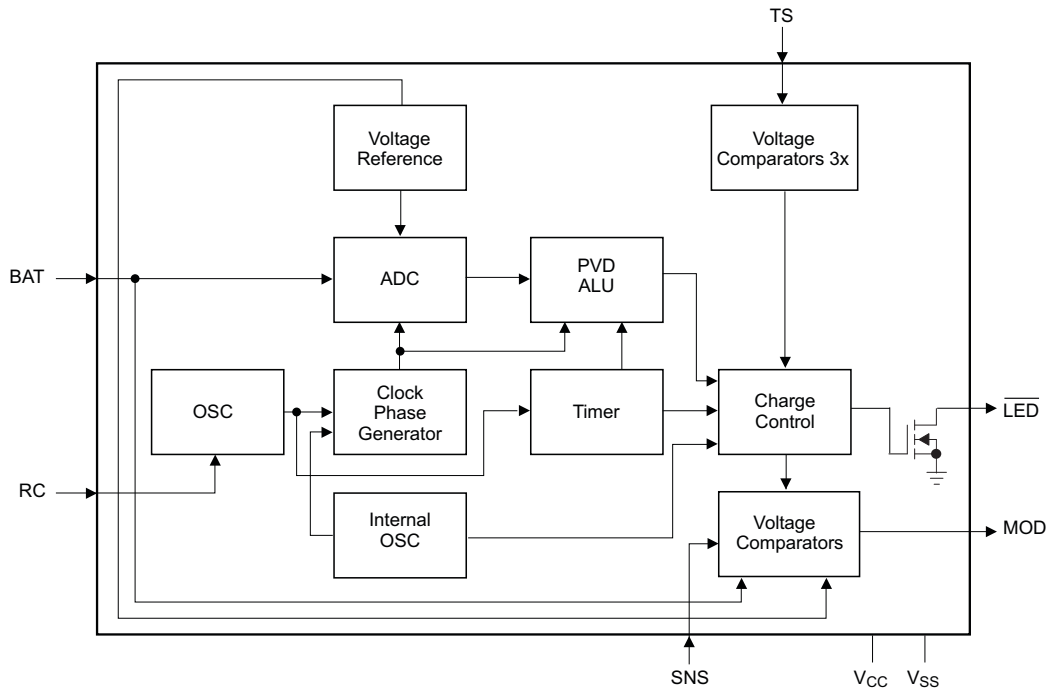
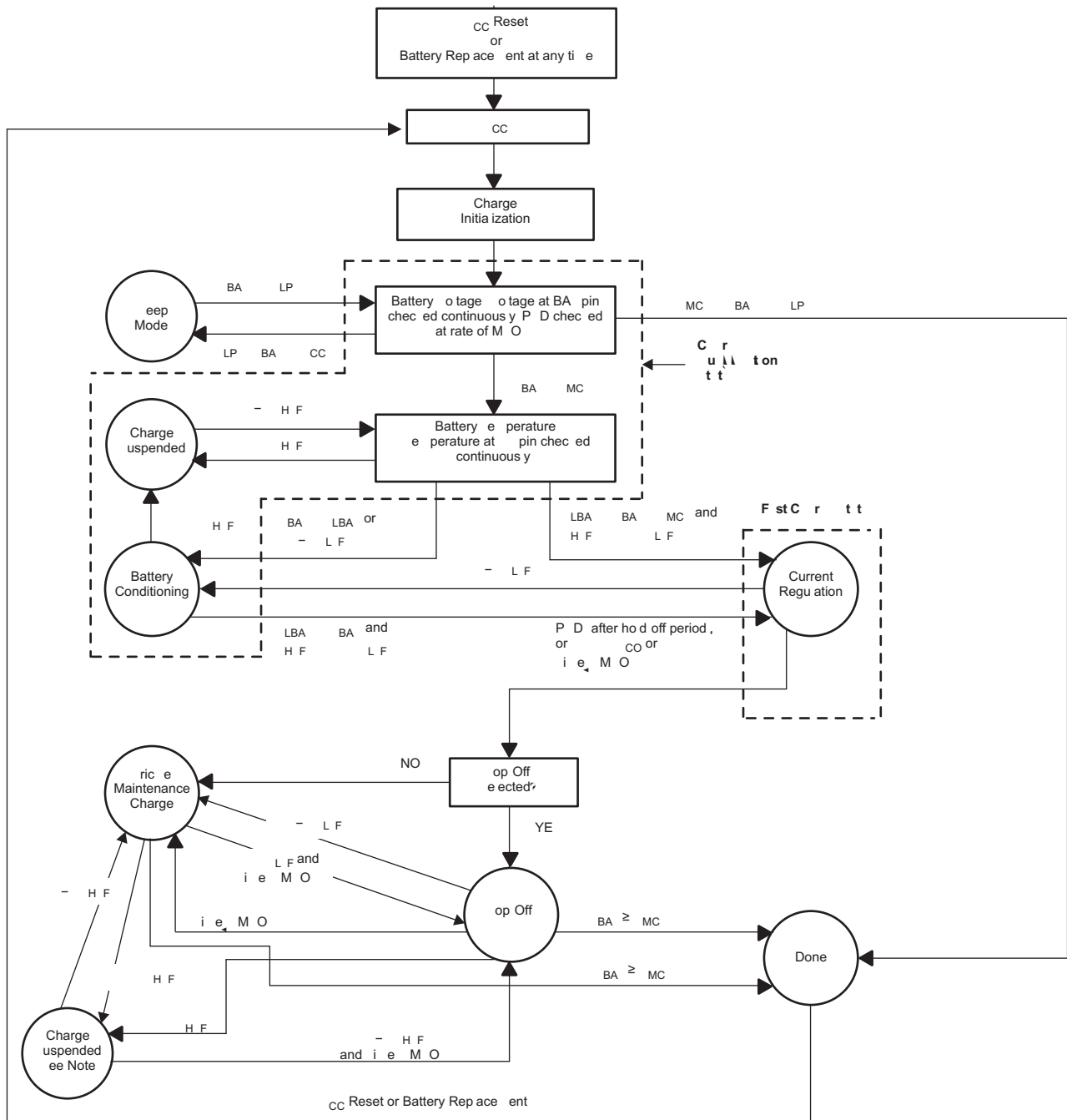


Figure 1. Functional Block Diagram



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



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## Initiation and Charge Qualification

The bq24400 initiates a charge cycle when it detects

- Application of power to  $V_{CC}$
- Battery replacement
- Exit from sleep mode

Immediately following initiation, the IC enters a charge-qualification mode. The bq24400 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 bq24400 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 bq24400 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 bq24400 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.

## Fast Charge (Current Regulation)

Following charge qualification (which includes trickle charge, if required), the bq24400 begins fast charge fast 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. While in the fast charge state, the  $\overline{LED}$  pin is pulled low (the LED is on). 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  $V_{MCV}$ .

Table 1 summarizes the charging process.

**Table 1. Charge Algorithm**

BATTERY CHEMISTRY	CHARGE ALGORITHM
NiCd or NiMH Batteries ( $V_{BAT} < V_{MCV}$ always)	<ol style="list-style-type: none"> <li>1. Charge qualification</li> <li>2. Trickle charge, if required</li> <li>3. Fast charge (constant current)</li> <li>4. Fast charge termination (peak voltage, maximum charge time = 1 MTO)</li> <li>5. Top-off (optional)</li> <li>6. Trickle charge</li> </ol>

## FAST CHARGE TERMINATION

### Initial Hold-Off Period

The bq24400 incorporates a user programmable hold-off period to avoid premature fast charge termination that can occur with brand new nickel 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 bq24400 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.

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



### Maximum Charge Time

The bq24400 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 fast charge, the bq24400 proceeds to top-off charge (if top-off is enabled) or trickle maintenance charge. If top-off is enabled, the timer is reset on the completion of fast charge before beginning top-off charge. Figure 3 shows a typical connection.

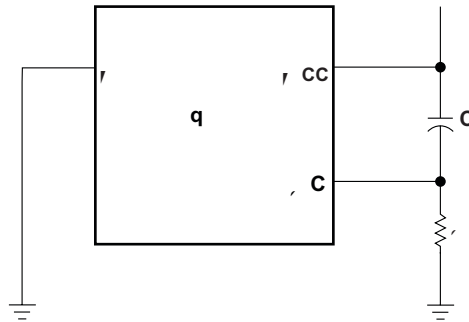


Figure 3. Typical Connection for the RC Input

The following equation shows the relationship between the  $R_{MTO}$  and  $C_{MTO}$  values and the maximum charge time (MTO) for the bq24400:

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

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 for details.)

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

### Maximum Temperature

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 4 shows a typical temperature-sensing circuit.

Figure 4. Temperature Monitoring Configuration

During fast charge, the bq24400 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 bq24400 terminates fast charge, moves to the charge suspended state, and turns off the LED. When  $V_{TS}$  rises above  $V_{HTF}$ , the bq24400 will resume charging in the trickle maintenance charge state, per Figure 2. In 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

The bq24400 uses a peak-voltage detection (PVD) scheme to terminate fast charge for NiCd and NiMH batteries. The bq24400 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 bq24400 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 fast charge. As shown in Figure 5, a resistor voltage-divider between the battery pack's positive terminal and  $V_{SS}$  scales the battery voltage measured at the BAT pin. A low-pass filter then smooths out this voltage to present a clean signal to the BAT pin.

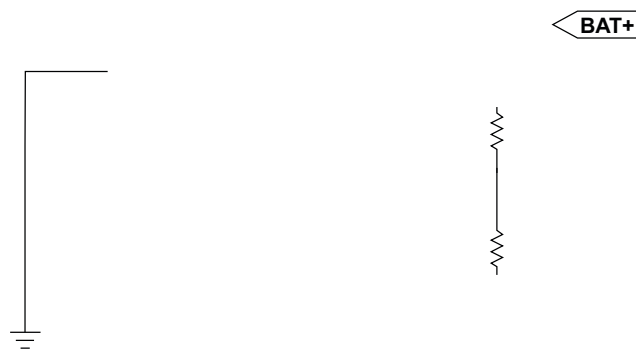


Figure 5. Battery Voltage Divider and Filter

The resistor values  $R_{B1}$  and  $R_{B2}$  are calculated by the following equation:

$$\frac{R_{B1}}{R_{B2}} = N - 1 \quad (3)$$

where N is the number of cells in series.  $R_{B1} + R_{B2}$  should be at least 200k and no more than 1M.

### Top-Off and Pulse-Trickle Maintenance Charge

Once constant-current fast charge has ended, the bq24400 measures the value of the  $C_{MTO}$  capacitor and then proceeds to either top-off or trickle maintenance charge. Top-off is optional and 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  $V_{CC}$  (see Figure 3) should be greater than 0.13 $\mu$ F, and the value of the resistor connected to this pin should be less than 250k. 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 each 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  $V_{TS} > V_{HTF}$ .







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 bq24400 is designed to remain in trickle maintenance charge forever (excluding the two faults just mentioned) in order to keep the Nickel pack full.

### Charge Current Control

The bq24400 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 bq24400 controls the MOD pin to regulate the current and voltage of the pack. The bq24400 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 7 for a typical current-sensing circuit.

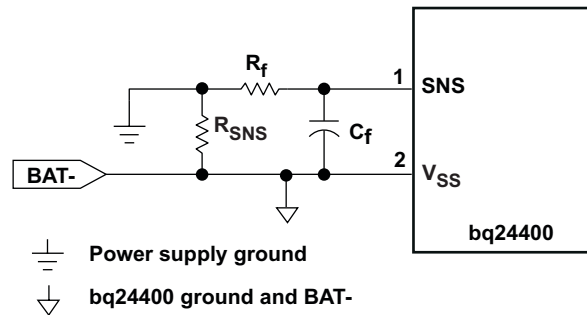


Figure 7. Current-Sensing Circuit

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

$$I_{MAX} = \frac{V_{SNSLO} - V_{SNSHI}}{R_{SNS}} \tag{4}$$

If the voltage at the SNS pin is greater than  $V_{SNSLO}$  or less than  $V_{SNSHI}$ , the bq24400 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 bq24400 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 (see Figure 8). 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  $C_f$ .

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

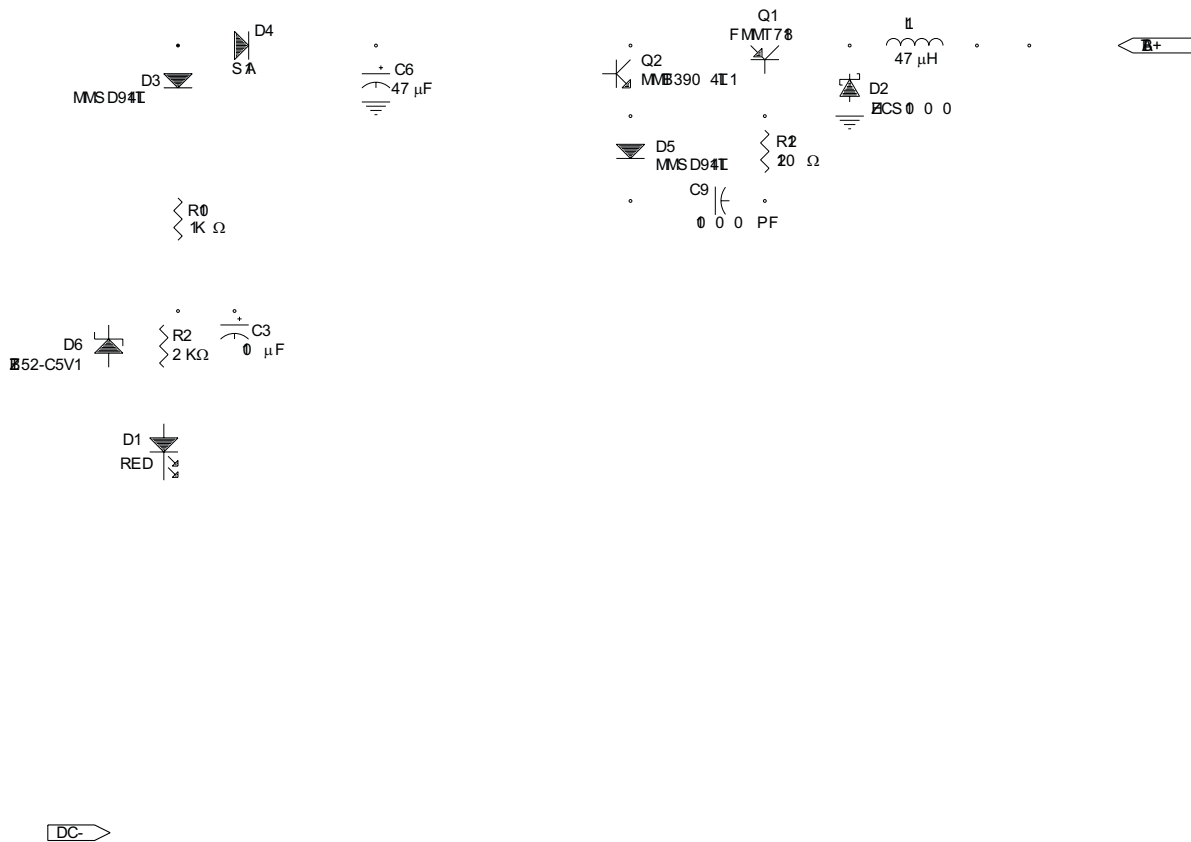


Figure 8. 3-Cell NiCd/NiMH 1A Charger

Being a hysteretic controller, the switching frequency of the bq24400 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 bq24400). 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 9 and Figure 10 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  $\mu$ H,  $R_{SNS}$  value of 50 m $\Omega$ , and  $C_{HYS}$  value of 4.7 pF. Typical switching frequencies for the bq24400 are between 100 and 200 kHz, though it is possible to achieve switching frequencies in excess of 300kHz.

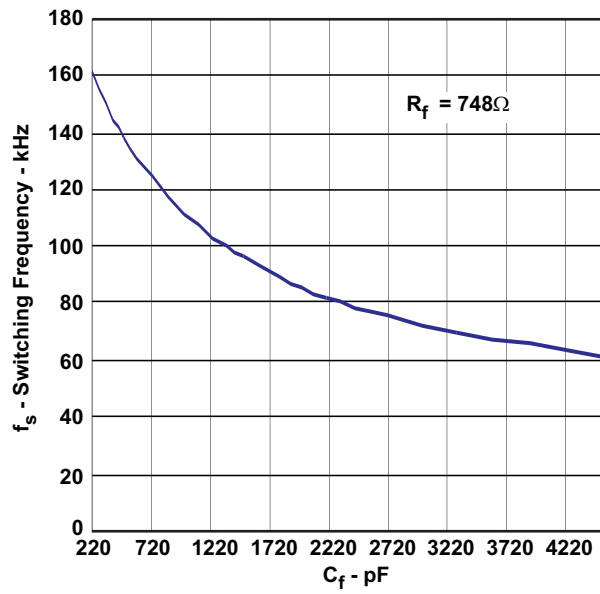


Figure 9. Switching Frequency vs Capacitance

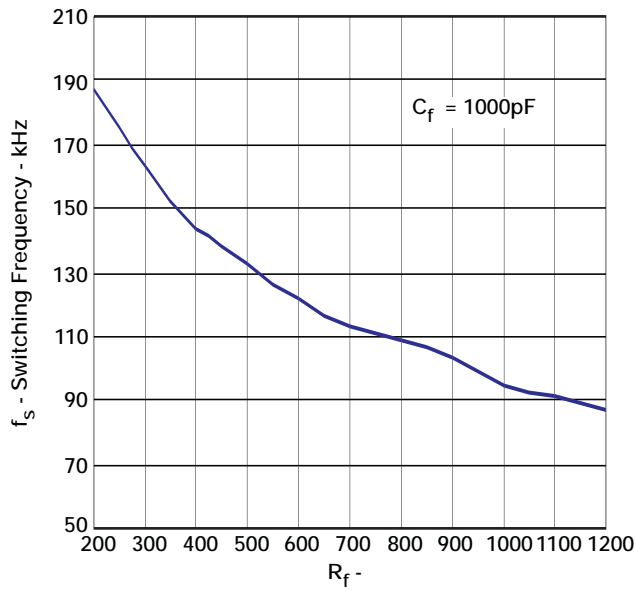


Figure 10. Switching Frequency vs Resistance



**TEMPERATURE MONITORING**

The bq24400 measures the temperature by the voltage at the TS pin. This voltage is typically generated by a negative-temperature-coefficient thermistor. The bq24400 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 bq24400 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 bq24400 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 charge, stops conditions, 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


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## Charge Status Display

The charge status is indicated by open-drain output  $\overline{\text{LED}}$ . [Table 5](#) summarizes the display output of the bq24400. A temperature fault or timer expiring changes the charge state immediately (according to [Figure 2](#)) and will thus change the  $\overline{\text{LED}}$  status immediately and accordingly.

**Table 5. Charge Status Display**

bq24400 CHARGE STATE	$\overline{\text{LED}}$ STATUS
Charge qualification (including battery conditioning and charge suspended)	1 Hz flash
Fast charge (current regulation)	Low
Top-off charge	High impedance
Trickle maintenance charge (after fast charge)	
Charge complete	
Battery absent	
Sleep mode	

## Sleep Mode

The bq24400 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,  $V_{\text{SLP}}$ . During sleep mode, the bq24400 shuts down all unnecessary internal circuits, drives the  $\overline{\text{LED}}$  output to high-impedance state, and drives the MOD pin low. Restoring BAT below the  $V_{\text{MCV}}$  threshold initiates the IC and starts a fast-charge cycle. Normally, the bq24400 only enters sleep mode when there is no battery connected on the output and the charger is idling with nothing to charge. In addition,  $V_{\text{IN}}$  needs to be high enough such that when  $V_{\text{IN}}$  is present on the output,  $V_{\text{BAT}}$  would be greater than  $V_{\text{SLP}}$ . In sleep mode, the output voltage will decay to  $V_{\text{MCV}}$  at which point the bq24400 turns on and pulses the MOD pin several times. With no battery connected, the output will rise to near  $V_{\text{IN}}$  at which point the bq24400 re-enters sleep mode. During sleep mode, the RC pin will be at  $V_{\text{SS}}$  potential. A typical sleep mode waveform is shown in [Figure 17](#).



### TYPICAL CHARACTERISTICS

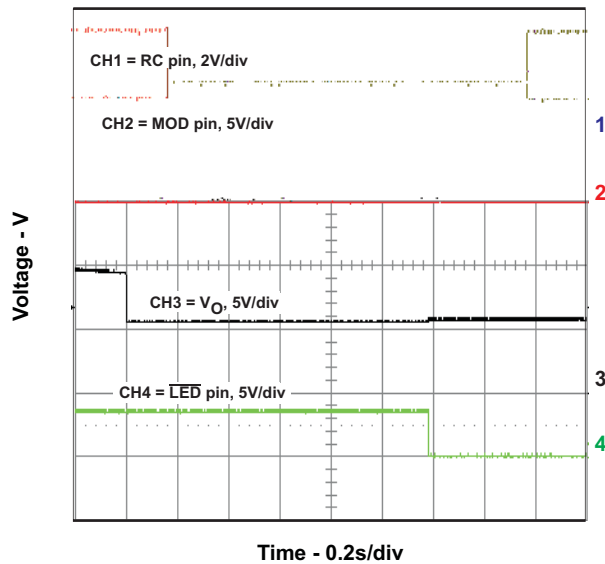


Figure 11. bq24400 Start-up on Battery Insertion

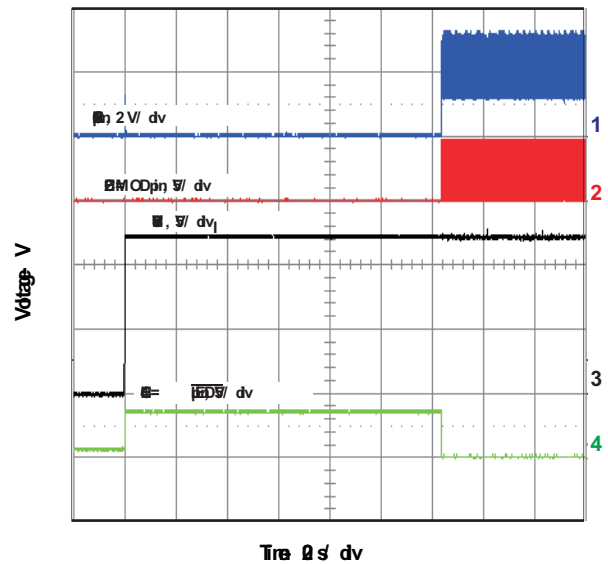


Figure 12. bq24400 Start-up on Vin

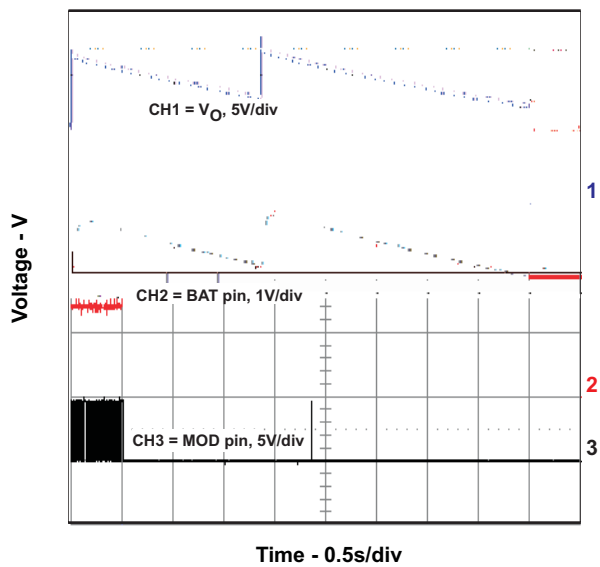


Figure 13. Battery Removal During Fast Charge

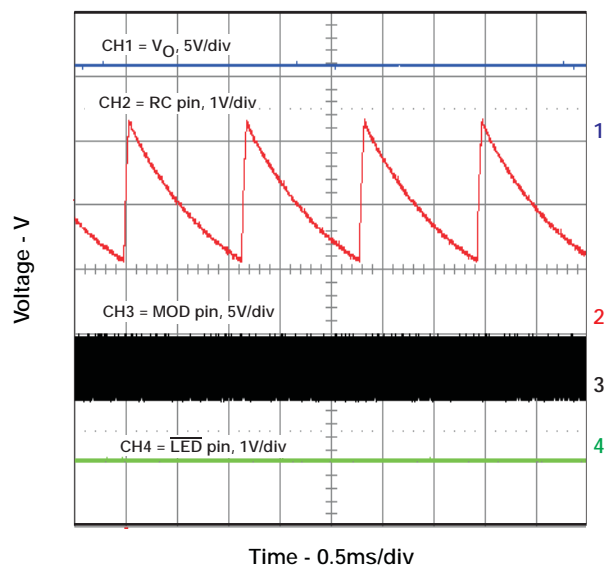


Figure 14. bq24400 in Fast Charge



TYPICAL CHARACTERISTICS (continued)

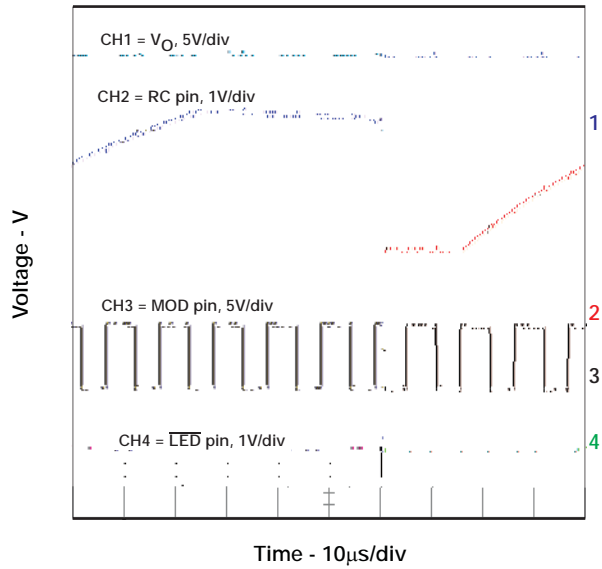


Figure 15. bq24400 in Fast Charge

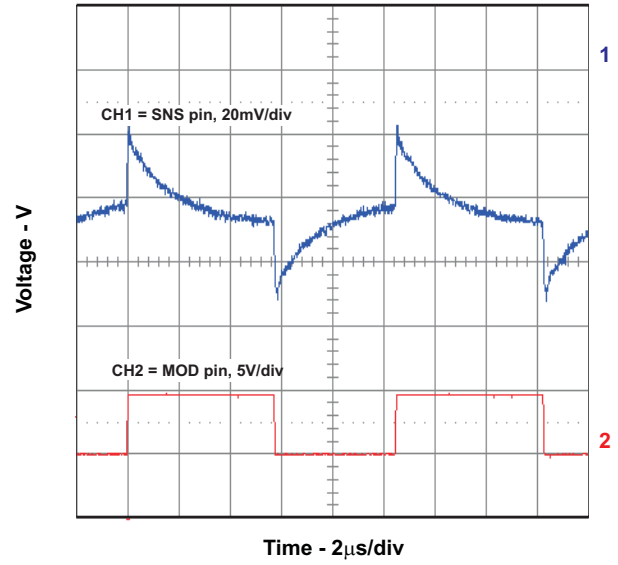


Figure 16. bq24400 Fast Charge SNS and MOD Waveforms

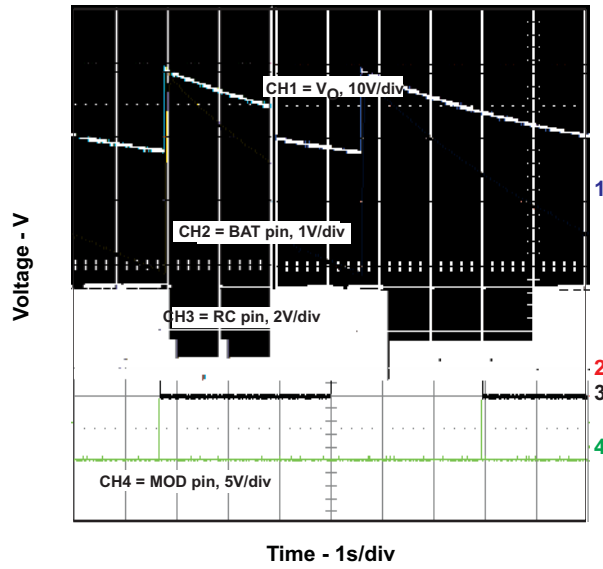


Figure 17. bq24400 Cycling In and Out of Sleep Mode (No battery present)





## REVISION HISTORY

**Changes from Revision September 2001 (\*) to Revision A** **Page**

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- Changed the data sheet format. The data sheet was originally from Benchmark Products. In revision A, the data sheet was converted to the TI format, and a re-write of the data sheet was implemented ..... 1
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## PACKAGING INFORMATION

Orderable Device	Status <sup>(1)</sup>	Package Type	Package Drawing	Pins	Package Qty	Eco Plan <sup>(2)</sup>	Lead/Ball Finish	MSL Peak Temp <sup>(3)</sup>
BQ24400D	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM
BQ24400DG4	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM
BQ24400DR	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM
BQ24400DRG4	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM
BQ24400PW	ACTIVE	TSSOP	PW	8	150	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR
BQ24400PWG4	ACTIVE	TSSOP	PW	8	150	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR
BQ24400PWR	ACTIVE	TSSOP	PW	8	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR
BQ24400PWRG4	ACTIVE	TSSOP	PW	8	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR

<sup>(1)</sup> The marketing status values are defined as follows:

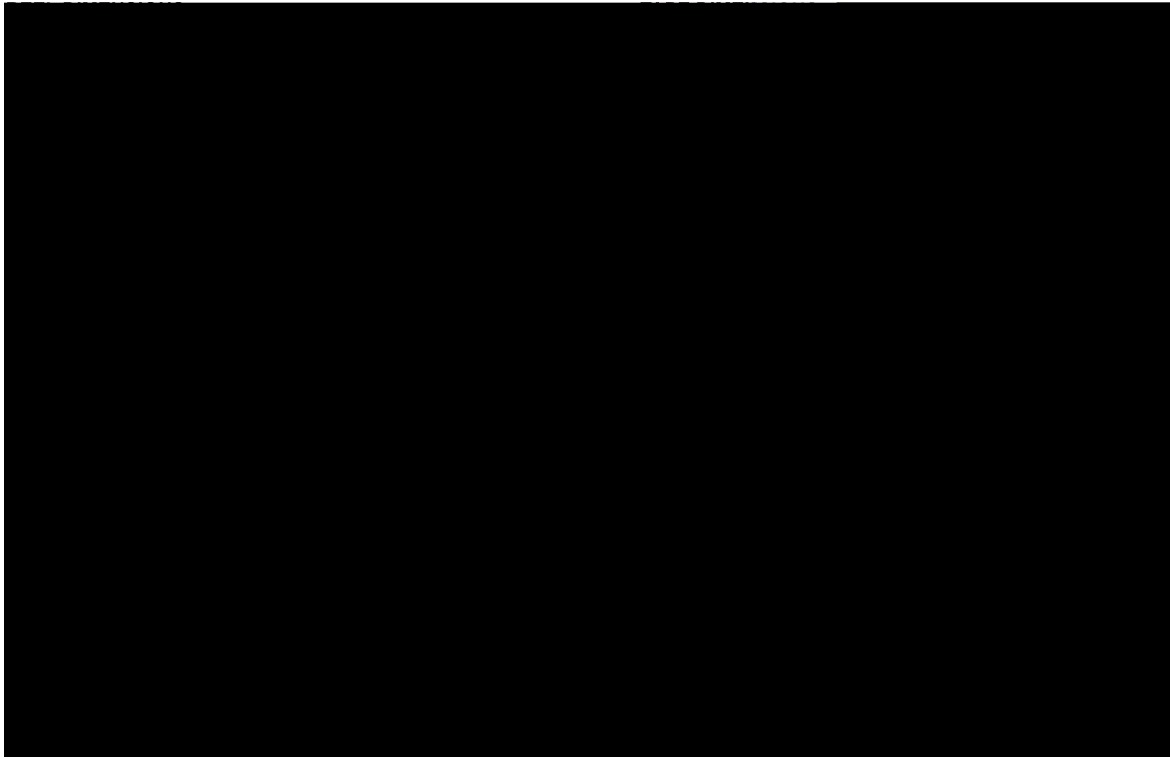
**ACTIVE:** Product device recommended for new designs.

**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.

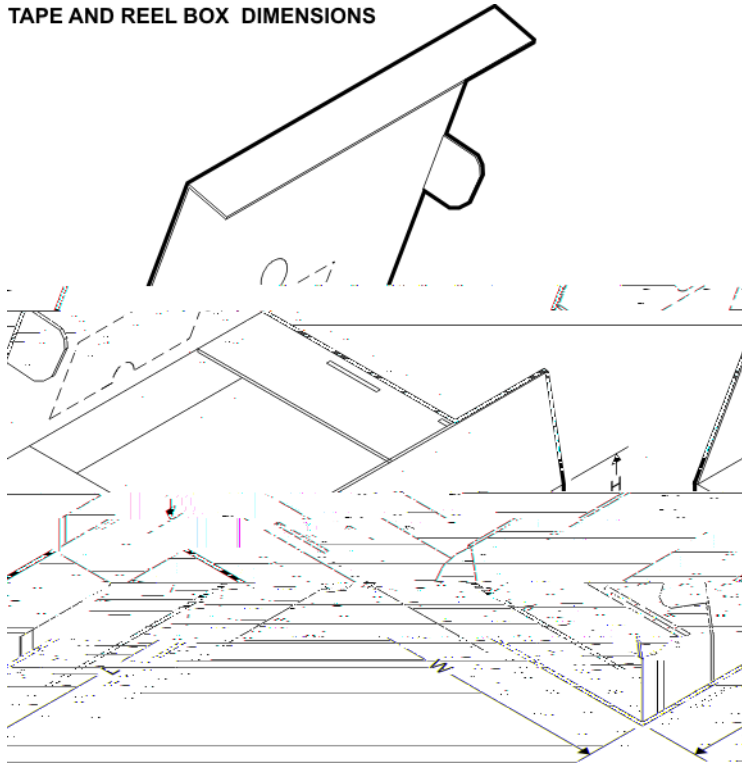
**OBSOLETE:** TI has discontinued the production of for new

**TAPE AND REEL INFORMATION**


\*All dimensions are nominal

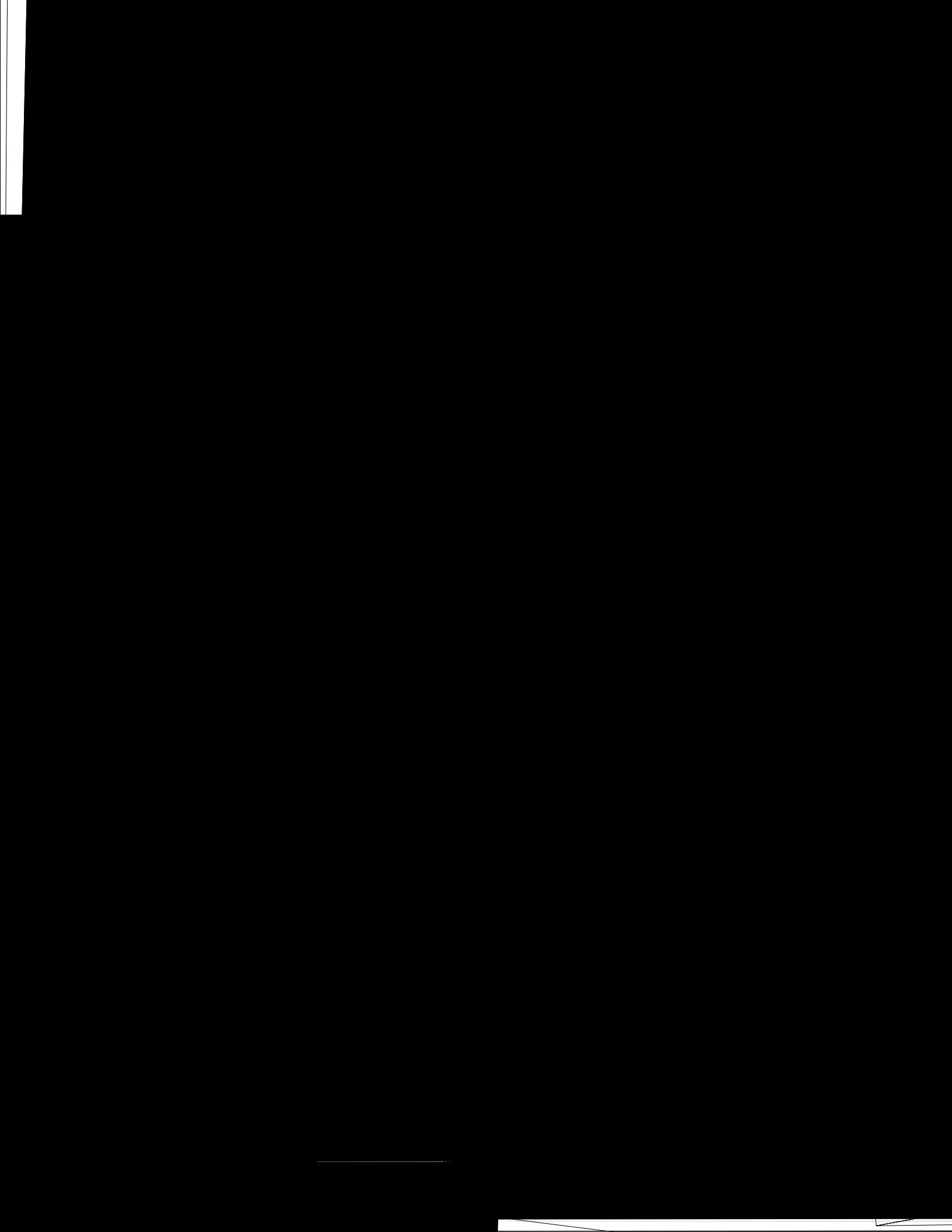
Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
BQ24400DR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
BQ24400PWR	TSSOP	PW	8	2000	330.0	12.4	7.0	3.6	1.6	8.0	12.0	Q1

**TAPE AND REEL BOX DIMENSIONS**



\*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
BQ24400DR	SOIC	D	8	2500	367.0	367.0	35.0
BQ24400PWR	TSSOP	PW	8	2000	367.0	367.0	35.0



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Solder Mask trapezoidal walls and also rounding corners will offer better paste release. Custo

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C. Publication IPC-7351 is recommended for alternate designs.

E. Customers should contact their

and around si j

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5 NOM

