



Is Now Part of



ON Semiconductor®

To learn more about ON Semiconductor, please visit our website at
www.onsemi.com

ON Semiconductor and the ON Semiconductor logo are trademarks of Semiconductor Components Industries, LLC dba ON Semiconductor or its subsidiaries in the United States and/or other countries. ON Semiconductor owns the rights to a number of patents, trademarks, copyrights, trade secrets, and other intellectual property. A listing of ON Semiconductor's product/patent coverage may be accessed at www.onsemi.com/site/pdf/Patent-Marking.pdf. ON Semiconductor reserves the right to make changes without further notice to any products herein. ON Semiconductor makes no warranty, representation or guarantee regarding the suitability of its products for any particular purpose, nor does ON Semiconductor assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation special, consequential or incidental damages. Buyer is responsible for its products and applications using ON Semiconductor products, including compliance with all laws, regulations and safety requirements or standards, regardless of any support or applications information provided by ON Semiconductor. "Typical" parameters which may be provided in ON Semiconductor data sheets and/or specifications can and do vary in different applications and actual performance may vary over time. All operating parameters, including "Typicals" must be validated for each customer application by customer's technical experts. ON Semiconductor does not convey any license under its patent rights nor the rights of others. ON Semiconductor products are not designed, intended, or authorized for use as a critical component in life support systems or any FDA Class 3 medical devices or medical devices with a same or similar classification in a foreign jurisdiction or any devices intended for implantation in the human body. Should Buyer purchase or use ON Semiconductor products for any such unintended or unauthorized application, Buyer shall indemnify and hold ON Semiconductor and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that ON Semiconductor was negligent regarding the design or manufacture of the part. ON Semiconductor is an Equal Opportunity/Affirmative Action Employer. This literature is subject to all applicable copyright laws and is not for resale in any manner.

An analysis is presented describing a numerical algorithm that develops loss prediction techniques for IGBTs operating in switched mode power circuits. A 600W zero-current switching boost PFC (Power Factor Correction) circuit is analyzed as a design example. Predicted losses are validated by test data measured from an operating circuit.

Nomenclature

ΔI_L	Boost inductor peak to peak current.
$E_{off300}(I, T_J)$	Turn-off loss energy at 300V as a function of current and junction temperature.
$E_{off480}(I, T_J)$	Turn-off loss energy at 480V as a function of current and junction temperature.
$E_{off}(V, I, T_J)$	Turn-off loss as a function of peak clamp voltage, IGBT collector current and junction temperature.
f_s	IGBT switching frequency.
$k_a(T_J), k_b(T_J), k_c(T_J), k_d(T_J)$	Curve fit vectors for switching loss function $E_{off480}(I, T_J)$.
I	IGBT collector current.
$I_{gT_{TurnOffLoss}}(V_{ac}, P_{out}, t, T_J)$	Average IGBT turn-off loss at a particular instant in time.
$I_{gT_{TurnOffWatts}}(V_{ac}, P_{out}, T_J)$	Average IGBT turn-off loss as a function of V_{ac} , output power and T_J .
$I_{toff}(V_{ac}, P_{out}, t)$	Collector current at IGBT turn-off.
L	Boost inductor value.
η	Power supply efficiency.
P_{out}	Boost regulator output power.
t	Time.
T	Time period per AC mains cycle.
T_J	IGBT junction temperature.
V_{ac}	Input mains RMS voltage.
V_{clamp}	Maximum IGBT voltage at turn-off.
V_{OFF}	IGBT voltage during off-state period.
$R_{\theta JA}$	IGBT junction to ambient thermal impedance in °C/watt.
ω	AC mains radian frequency.

Introduction

An analysis is presented describing a numerical algorithm for determining IGBT losses. A math worksheet program such as MathCAD™ may be used for this application. The algorithm flow chart is shown in Figure 1. The required IGBT parametric test data is obtained from basic device test circuits used by semiconductor manufacturers.

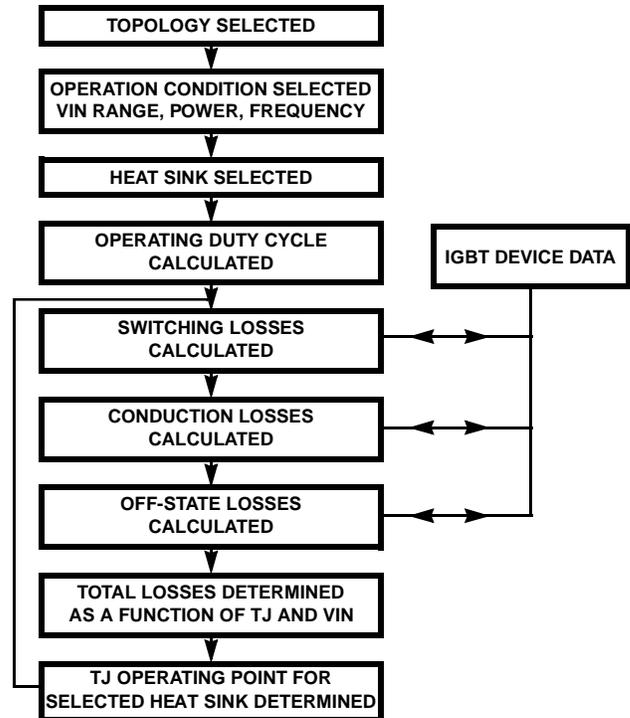
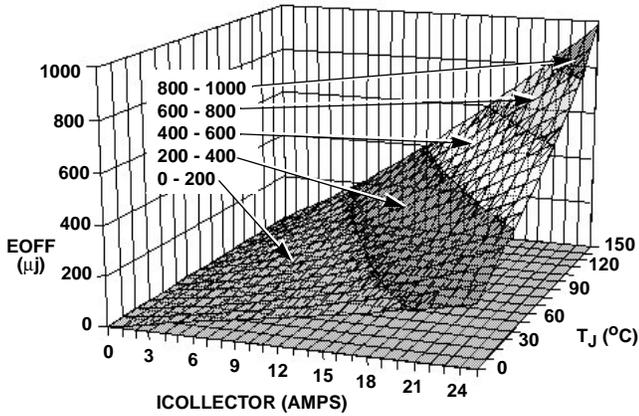


FIGURE 1. LOSS CALCULATION ALGORITHM

Determining switching device losses in power circuits such as active power factor correction (PFC) circuits, AC output UPS systems and solid state AC motor drives that utilize IGBTs as the switching device is extremely complex. The switching device conduction duty cycle and switch current are continually changing as a function of the instantaneous magnitude of the AC mains input or AC output voltage. The problem is further exacerbated by the fact that the IGBT losses are a complex function of turn-off clamp voltage, collector current and junction temperature. The relationship between turn-off energy, collector current and junction temperature is illustrated for a single turn-off clamp voltage of 480V in the surface plot of Figure 2.

Conventional time domain SPICE analysis requires lengthy simulations that generate massive output files. SPICE models representing IGBT switching characteristics may only be run for preset junction temperatures. In addition, IGBT manufacturer data sheets do not provide sufficient information to analyze a device's losses under all switching conditions.



NOTE: Eoff (Vclamp = 480V) HG TG40N60B3

FIGURE 2. TURN-OFF ENERGY AS A FUNCTION OF ICOLLECTOR AND TJUNCTION

Previous Work

Previous efforts to evaluate transistor operating losses to determine the device junction temperature do not relate the information to the device characteristic in an interactive fashion [2], [3], [4]. IGBT conduction loss is a function of the conducted current and junction temperature. Turn-on and turn-off switching losses are a function of the IGBT collector voltage, current, and junction temperature.

The transistor junction temperature is in turn a function of the combined transistor losses and heatsink temperature.

Methods

In this paper, mathematical models are developed for IGBT turn-off, turn-on, on-state and off-state losses. The models are based on equations developed by curve fitting laboratory test data. The equations describe IGBT losses as a function of junction temperature, collector current and collector clamp voltage. These equations are applied to determine the total losses in transistor Q1 in the continuous mode boost PFC circuit illustrated in Figure 3.

The empirical data used in the curve fit equations was developed utilizing test fixtures that closely represent the PFC circuit operating conditions.

Figure 4 illustrates the basic test circuit used for developing the turn-off losses depicted in Figure 2. The energy loss measurements were made for a single pulse with the device preheated to the specific junction temperature. The energy loss per pulse was recorded as the integral of the total turn-off energy pulse including collector current tailing.

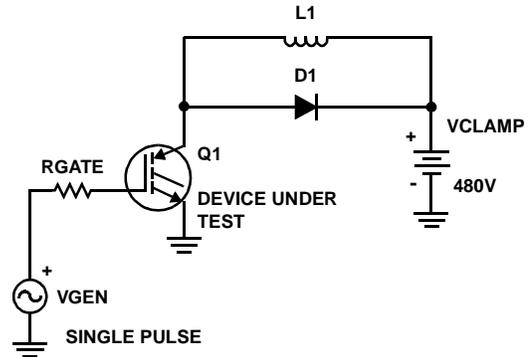


FIGURE 4. IGBT TURN-OFF LOSS TEST CIRCUIT

Turn-Off Switching Loss

Equation 1 expresses the basic form of turn-off losses in an IGBT at a fixed clamp voltage of 480V. This equation evaluates turn-off losses in joules per turn-off cycle as a function of the IGBT collector current and junction temperature. Information obtained from this equation is plotted in Figure 2. Vectors $ka(T_J)$, $kb(T_J)$, $kc(T_J)$, $kd(T_J)$ in Equation 1 are determined by curve fitting the empirical inductive turn-off data. Each of these vectors represents a function that shapes the Eoff equation as a function of junction temperature and collector current.

$$E_{off_{480}}(I, T_J) = ka(T_J) \cdot I^3 + kb(T_J) \cdot I^2 + kc(T_J) \cdot I + kd(T_J) \quad (EQ. 1)$$

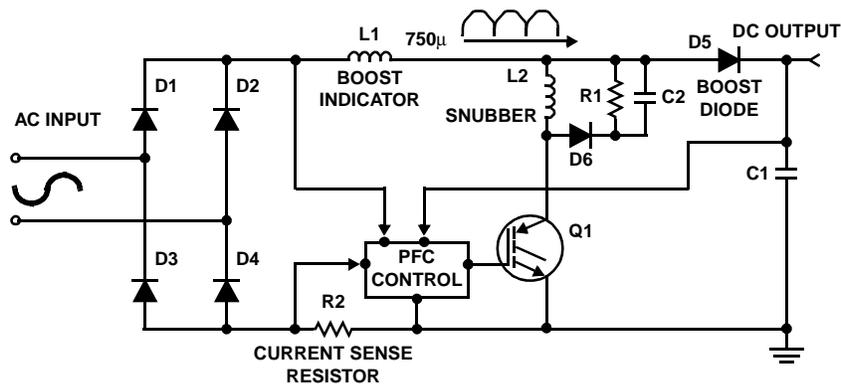


FIGURE 3. BOOST PFC CIRCUIT

The technique used to generate Equation 1 is repeated at a 300V clamp voltage. These two equations are then combined to form Equation 2, which calculates Eoff at intermediate clamp voltages.

$$E_{off}(V, I, T_J) = \left(\frac{V-300}{180} \cdot E_{off_{480}}(I, T_J) - E_{off_{300}}(I, T_J) \right) + \dots \quad (EQ. 2)$$

This function is then applied in Equation 3 to develop a time varying turn-off loss equation.

$$IGBT_{TurnOffLoss}(Vac, P_{out}, t, T_J) = f_s \cdot E_{off}(V_{clamp}, |I_{toff}(Vac, P_{out}, t)|, T_J) \quad (EQ. 3)$$

The turn-off current I_{toff} in Equation 3 has the form shown in Equation 4. The absolute value of I_{toff} is used in Equation 3 to represent the rectification of the AC input current.

$$I_{toff}(Vac, P_{out}, t) = \frac{\sqrt{2} \cdot P_{out}}{\eta \cdot Vac} \cdot \sin(\omega \cdot t) + \frac{\Delta I_L(t)}{2} \quad (EQ. 4)$$

Integrating Equation 3 over a quarter cycle of the AC mains calculates the IGBT average turn-off loss as a function of AC mains voltage, output power and junction temperature.

$$IGBT_{TurnOffWatts}(Vac, P_{out}, T_J) = \frac{T}{4} \cdot \int_0^{\frac{T}{4}} IGBT_{TurnOffLoss}(Vac, P_{out}, t, T_J) \cdot dt \quad (EQ. 5)$$

The IGBT turn-off losses as a function of junction temperature for minimum and maximum mains voltages are plotted in Figure 5. The conditions of Figure 5 are the operation of the boost PFC circuit in Figure 3 with an output load of 600W and a switching frequency of 78kHz. Similar curves may be generated to evaluate the IGBT losses as a function of switching frequency.

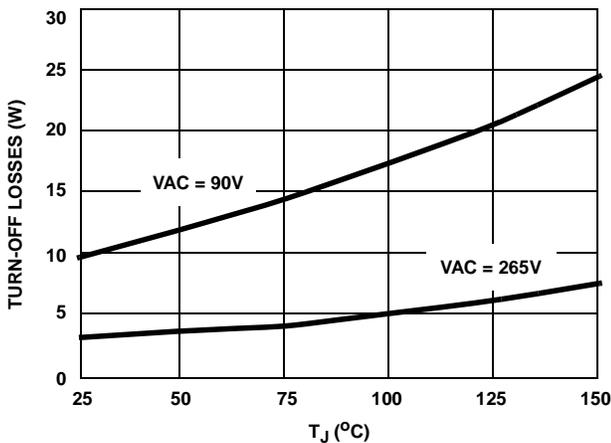


FIGURE 5. IGBT TURN-OFF LOSSES

Turn-On Switching Loss

Q1's turn-on switching losses are determined using similar techniques. It is important to insure that the empirical curve fitting turn-on loss data is representative of the actual circuit operation. In this application the snubber inductor L2 (reference Figure 3) reduces the IGBT turn-on energy loss by permitting the collector voltage to approach its VCE(SAT) value before the peak reverse recovery current occurs in the boost diode D5.

Off-State Loss

The IGBT off-state losses are typically insignificant with respect to turn-on, on-state and turn-off losses. IGBT data sheets provide values for ICES at 25°C and 150°C. These values are for the BVCE(S) voltage condition and do not represent the actual circuit conditions. A meaningful ICES value should be determined for the specific application Voff blocking voltage and operating T_J. The off-state loss Equation 6 is the product of Voff times ICES times the average IGBT off time over a quarter cycle of the AC mains.

$$IGBT_{OffStateLoss}(V_{OFF}, Vac, I_{CES}, T_J) = V_{OFF} \cdot I_{CES} \cdot \frac{4}{T} \cdot \int_0^{\frac{T}{4}} [1 - D_{ON}(Vac, t)] \cdot dt \quad (EQ. 6)$$

Conduction Loss

Equation 10 expresses the basic form of on-state saturation voltage as a function of collector current and junction temperature.

$$V_{f_{IGBT}}(I, T_J) = V_{f150}(I) + (V_{f25}(I) - V_{f150}(I)) \cdot \left[\frac{150 - T_J}{125} \right] \quad (EQ. 7)$$

where

$$V_{f25}(T_J) = A_{25} \cdot f(T_J) \quad (EQ. 8)$$

and

$$V_{f150}(T_J) = A_{150} \cdot f(T_J) \quad (EQ. 9)$$

$$f(x) = \begin{bmatrix} e^{-x} \\ x^{1.4} \\ x \\ 1 \end{bmatrix} \quad (EQ. 10)$$

Vectors A₂₅ and A₁₅₀ are determined based on curve fitting IGBT saturation voltages at 25°C and 150°C as a function of current with a 3rd order expression f(x), Equation 10. A general expression for the saturation voltage $V_{f_{IGBT}}(I, T_J)$ is then determined by the application of a linear extrapolation between the 25°C and 150°C equations.

Application Note 7520

The IGBT on-state loss versus time is expressed in Equation 11 as the switching device's forward drop times the boost inductor current times the duty cycle factor.

$$IGBTOnStateWatts(Vac, Pout, T_J, t) = \quad (EQ. 11)$$

$$|I_{line}(Vac, Pout, t)| \cdot V_{f_{igbt}}(|I_{line}(Vac, Pout, t)|, T_J) \cdot D(Vac, t)$$

Integrating Equation 11 over a quarter cycle of the AC mains calculates the IGBT average on-state loss as a function of AC mains voltage, output power and junction temperature.

$$IGBT_{AvgOnStateWatts}(Vac, Pout, T_J) = \quad (EQ. 12)$$

$$\frac{1}{T} \int_0^{\frac{T}{4}} IGBTOnStateWatts(Vac, Pout, T_J, t) \cdot dt$$

Total IGBT Losses

Once expressions are developed for all of the loss components, an expression for the total losses may be developed to illustrate the switching device performance.

Figure 6 illustrates one of the calculated results from the loss equations. IGBT total losses are plotted as a function of AC mains input voltage at junction temperatures of 25°C and 120°C. The circuit conditions for Figure 6 are the same as those outlined in Figure 5.

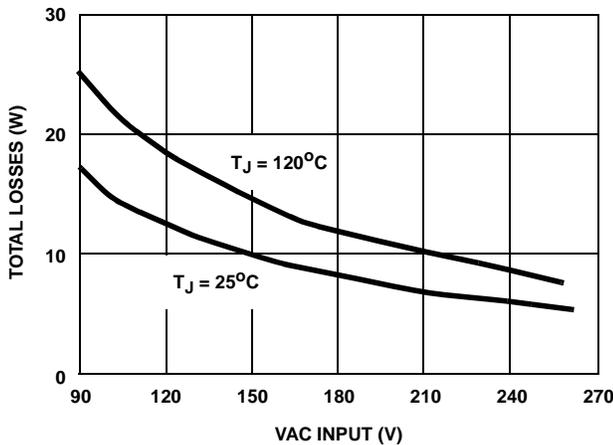


FIGURE 6. TOTAL IGBT LOSSES

Iterative Solution

Once expressions are developed for all of the loss components, an iterative technique is used to determine the IGBT operating temperature as a function of ambient temperature and junction to ambient thermal impedance.

This technique illustrated by Equation 14 determines the operating junction temperature compensating for the change in transistor losses as a function of the junction temperature calculated in the prior iteration. Each iteration of Equation 14

follows the loop illustrated in the lower left of Figure 1. A 15-iteration plot of junction temperature for the conditions of minimum AC mains input, 600W output and a switching frequency of 78kHz is illustrated in Figure 7.

Initializing the junction temperature at T_A

$$T_{J0} = T_{Ambient} \quad (EQ. 13)$$

$$n = 1 \dots 15$$

The iterative process of Equation 14 is powerful in that it provides a visual illustration of the thermal stability of a design. If the design is near thermal runaway it will be apparent through divergence in Figure 7. This methodology may also be used to test a design's safety margin by increasing the ambient temperature above the anticipated worst case and testing the convergence of the operating junction temperature.

$$T_{Jn} = \quad (EQ. 14)$$

$$IGBT_TotalLosses(Vac, Pout, I_{CES}, T_{J(n-1)}) \cdot R_{\theta JA} + T_{Amb}$$

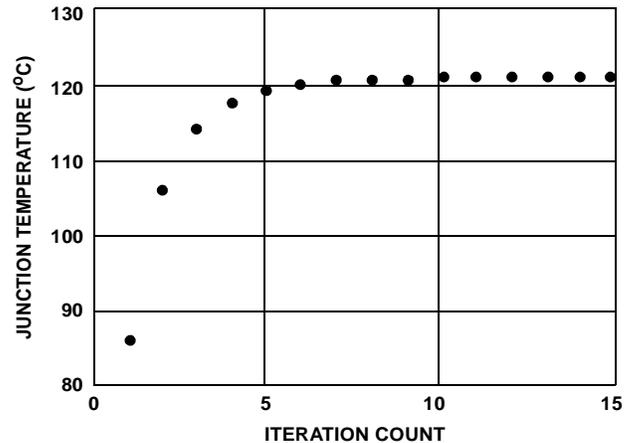


FIGURE 7. ITERATIVE T_J DETERMINATION

Results

A 600W boost PFC circuit Figure 3 was tested using an Fairchild HGTG30N60B3 IGBT as the switching device. For the worst case loss conditions of full load and minimum AC mains input, total IGBT losses were measured to be 23.8W in a 24°C ambient. This measured result compares closely with the 25.2W calculated using the described numerical algorithm. The design approach was further validated by changing the circuit operating frequency from 78kHz to 50kHz, achieving loss correlation to within 3W.

Summary

The techniques described in this paper provide a practical method to accurately predict losses in an IGBT operating in a switched mode power circuit. The predicted losses are itemized such that the designer can make a rapid paper design analysis to predict the performance of one IGBT type versus another. This method also provides an iterative

Application Note 7520

means of determining the maximum junction temperature as a function of the device junction to ambient thermal impedance.

The methodology is flexible and may be applied to other circuit topologies by describing the switching device duty cycle, switch current, off-state voltage and switching frequency as a function of time. The accuracy is limited only by the validity of the data with which the component is curve fit to equations.

References

For Fairchild documents available on the internet, see web site <http://www.Fairchildsemi.com> AnswerFAX (321) 724-7800.

- [1] Kolar, J.W., Ertl, H., and Zsch, F.C. (1998)
How to Include the Dependency of the $R_{ds(on)}$ of Power MOSFETs on the Instantaneous Value of the Drain Current into the Calculation of the Conduction Losses of High-Frequency Three-Phase PWM Inverters.
IEEE Trans. Ind. Electronics, Vol. 45, No.3, pp. 369-375, June 1998.
- [2] Masserant, B. and Stuart, T.A., (1996)
Experimental Verification of Calculated IGBT Losses in PFCs.
IEEE Transactions on Aerospace and Electronic Systems, Vol. 32, No. 3, pp. 1154-1158, July 1996.
- [3] Stuart, T.A., and Shaoyan Ye (1995)
Computer Simulation of IGBT Losses in PFC Circuits.
IEEE Transactions on Aerospace and Electronic Systems, Vol. 31, No. 3, pp. 1167-1173, July 1995.
- [4] Stuart, T.A., and Shaoyan Ye (1994)
Computer Simulation of IGBT Losses in PFC Circuits.
IEEE 4th Workshop on Computers in Power Electronics, pp.85-90, 1994.
- [5] *HGTG30N60B3 Data Sheet*, Fairchild Corporation, AnswerFAX Doc. No. 4444, 1998.

TRADEMARKS

The following are registered and unregistered trademarks Fairchild Semiconductor owns or is authorized to use and is not intended to be an exhaustive list of all such trademarks.

ACE _x [™]	FAST [®]	MICROWIRE [™]	SILENT SWITCHER [®]	UHC [™]
Bottomless [™]	FAST _r [™]	OPTOLOGIC [®]	SMART START [™]	UltraFET [®]
CoolFET [™]	FRFET [™]	OPTOPLANAR [™]	SPM [™]	VCX [™]
CROSSVOLT [™]	GlobalOptoisolator [™]	PACMAN [™]	STAR*POWER [™]	
DenseTrench [™]	GTO [™]	POP [™]	Stealth [™]	
DOME [™]	HiSeC [™]	Power247 [™]	SuperSOT [™] -3	
EcoSPARK [™]	I ² C [™]	PowerTrench [®]	SuperSOT [™] -6	
E ² CMOS [™]	ISOPLANAR [™]	QFET [™]	SuperSOT [™] -8	
EnSigna [™]	LittleFET [™]	QS [™]	SyncFET [™]	
FACT [™]	MicroFET [™]	QT Optoelectronics [™]	TinyLogic [™]	
FACT Quiet Series [™]	MicroPak [™]	Quiet Series [™]	TruTranslation [™]	

STAR*POWER is used under license

DISCLAIMER

FAIRCHILD SEMICONDUCTOR RESERVES THE RIGHT TO MAKE CHANGES WITHOUT FURTHER NOTICE TO ANY PRODUCTS HEREIN TO IMPROVE RELIABILITY, FUNCTION OR DESIGN. FAIRCHILD DOES NOT ASSUME ANY LIABILITY ARISING OUT OF THE APPLICATION OR USE OF ANY PRODUCT OR CIRCUIT DESCRIBED HEREIN; NEITHER DOES IT CONVEY ANY LICENSE UNDER ITS PATENT RIGHTS, NOR THE RIGHTS OF OTHERS.

LIFE SUPPORT POLICY

FAIRCHILD'S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS WRITTEN APPROVAL OF FAIRCHILD SEMICONDUCTOR CORPORATION. As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, or (c) whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in significant injury to the user.
2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

PRODUCT STATUS DEFINITIONS

Definition of Terms

Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

ON Semiconductor and  are trademarks of Semiconductor Components Industries, LLC dba ON Semiconductor or its subsidiaries in the United States and/or other countries. ON Semiconductor owns the rights to a number of patents, trademarks, copyrights, trade secrets, and other intellectual property. A listing of ON Semiconductor's product/patent coverage may be accessed at www.onsemi.com/site/pdf/Patent-Marking.pdf. ON Semiconductor reserves the right to make changes without further notice to any products herein. ON Semiconductor makes no warranty, representation or guarantee regarding the suitability of its products for any particular purpose, nor does ON Semiconductor assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation special, consequential or incidental damages. Buyer is responsible for its products and applications using ON Semiconductor products, including compliance with all laws, regulations and safety requirements or standards, regardless of any support or applications information provided by ON Semiconductor. "Typical" parameters which may be provided in ON Semiconductor data sheets and/or specifications can and do vary in different applications and actual performance may vary over time. All operating parameters, including "Typicals" must be validated for each customer application by customer's technical experts. ON Semiconductor does not convey any license under its patent rights nor the rights of others. ON Semiconductor products are not designed, intended, or authorized for use as a critical component in life support systems or any FDA Class 3 medical devices or medical devices with a same or similar classification in a foreign jurisdiction or any devices intended for implantation in the human body. Should Buyer purchase or use ON Semiconductor products for any such unintended or unauthorized application, Buyer shall indemnify and hold ON Semiconductor and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that ON Semiconductor was negligent regarding the design or manufacture of the part. ON Semiconductor is an Equal Opportunity/Affirmative Action Employer. This literature is subject to all applicable copyright laws and is not for resale in any manner.

PUBLICATION ORDERING INFORMATION

LITERATURE FULFILLMENT:

Literature Distribution Center for ON Semiconductor
19521 E. 32nd Pkwy, Aurora, Colorado 80011 USA
Phone: 303-675-2175 or 800-344-3860 Toll Free USA/Canada
Fax: 303-675-2176 or 800-344-3867 Toll Free USA/Canada
Email: orderlit@onsemi.com

N. American Technical Support: 800-282-9855 Toll Free
USA/Canada
Europe, Middle East and Africa Technical Support:
Phone: 421 33 790 2910
Japan Customer Focus Center
Phone: 81-3-5817-1050

ON Semiconductor Website: www.onsemi.com
Order Literature: <http://www.onsemi.com/orderlit>
For additional information, please contact your local
Sales Representative