International Rectifier

APPLICATION NOTE

Application Note AN-968

Selecting and Designing In the Right Schottky Rectifier

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International Rectifier offers a broad line of Schottky rectifiers with a variety of packages, rated currents, voltages and rated junction temperatures. These Schottky rectifiers are intended for use in a variety of power supply applications. This application note has the following purposes:

- Fundamentals of IR's Schottky product range
- Review and explanation of the Schottky data sheet.
- Review the application performance trade-offs between different Schottky types
- Design procedures to determine the worst-case design operating point
- Review the techniques for suppressing switching voltage transients
- Present a comprehensive "Schottky Selection Guide for Power Supplies

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Selecting and Designing In the Right Schottky Rectifier

Summary
International Rectifier offers a broad line of Schottky rectifiers with a variety of packages, rated currents, voltages and rated junction temperatures. These Schottky rectifiers are intended for use in a variety of power supply applications.

This application note has the following purposes:

- Provide a familiarization with the fundations of IR's Schottky product range by reviewing the different packages, die sizes, and electrical characterisitics of the various Schottky processes. Show how these all come together to form an overall product matrix that serves the design needs of virutally any power supply application.
- Review and explain the Schottky data sheet.
- Review the application performance trade-offs between different Schottky types, and give *Guidelines* that steer the user to the best choice of Schottky to meet given application requirements.
- Give design procedures to determine the worst-case design operating point, estimate the losses and select the heatsink for the Schottkys, in the the most common power supply circuits.
- Review the techniques for suppressing switching voltage transients and the fundamentals of snubber design.
- Present a comprehensive "Schottky Selection Guide for Power Supplies," that shows, at a glance, the different possible Schottky choices and performance trade-offs for a wide range of different power supply requirements, for the most common power supply circuits.

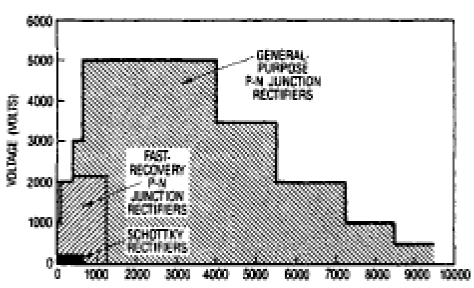


Figure 1. Available ratings of Schottky rectifiers ralative to P-N junction rectifiers.

Why a Schottky rectifier?
Schottky rectifiers occupy a small corner of the total spectrum of available rectifier voltage and current ratings illustrated in Figure 1. They are, nonetheless, the rectifier of choice for low voltage switching power supply applications, with output voltages up to a few tens of volts. particularly at high switching frequency. For this reason, Schottkys account for a major segment of today's total rectifier usage. This is illustrated in Figure 2.

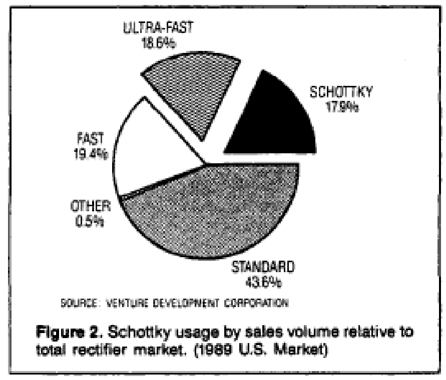


Figure 2. Schottky usage by sales volume relative to total rectifier market. (1999 US market)

The Schottky rectifier's unique electrical characteristics set them apart from conventional P-N junction rectifiers in the following aspects:

- Lower forward voltage drop
- Lower blocking voltage
- Higher leakage current
- Virtual absence of reverse recovery charge

The two fundamental characteristics of the Schottky that make it a winner over the P-N junction rectifier in low voltage switching power supplies are its *lower forward voltage drop* and *virtual absence of minority carrier reverse recovery.*

The absence of minortity carrier reverse recovery means virtual absence of switching losses within the Schottky itself. Perhaps more significantly, the problem of switching voltage transients and attendant oscillations is less severe for Schottkys than for P-N junction rectifiers. Snubbers are therefore smaller and less dissipative.

The lower forward voltage drop of the Schottky means lower rectification losses, better efficiency and smaller heatsinks.

Forward voltage drop is a function of the Schottky rectifier's reverse voltage rating. The maximum voltage rating of today's Schottky rectifiers is about 150V. At this voltage, the Schottky's forward voltage drop is lower than that of a fast recovery epitaxial PN junction rectifier by 150 to 200 mV. At lower voltage ratings, the lower forward voltage drop of the Schottky becomes progressively more pronounced, and more of an advantage.

I. SCHOTTKY PRODUCT RANGE

International Rectifier's Schottky product range, when viewed for the first time through a glance at the catalog or at individual product data sheets, may appear daunting to the engineer who wants to focus quickly on the best choice of product for his needs.

The quickest route to familiarity with the product range is an understanding of its basic ingredients. Figure 3 illustrates that all members of the IR Schottky product matrix stem from three basic categories of ingredients:

A. Schottky Process Type
B. Schottky Die
C. Package

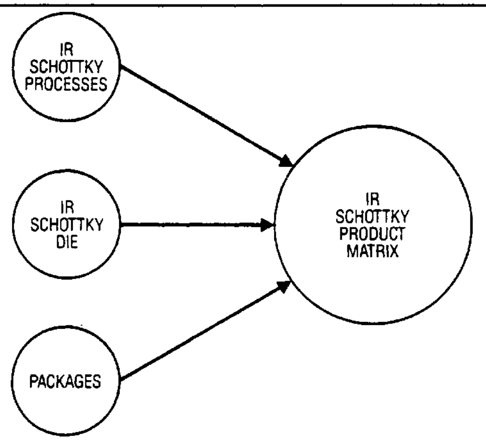


Figure 3. Basic ingredients of the International Rectifier Schottky product matrix.

A familiarity with the above ingredients helps the user gain an understanding of the factors that will lead to the right Schottky choice to satisfy given application requirements.

A. Schottky Processes

International Rectifier offers Schottkys made by several different processes. Each process produces a different mix of electrical characteristics.

The four most application-important characteristics of a Schottky are:

Forward voltage drop
Reverse leakage current
Reverse blocking voltage
Maximum permissible junction temperature

The basic hallmarks of any process are its maximum rated junction temperature — the T_{Jmax} Class and the "prime"[1] rated voltage, the V_{RRM} Class. These two basic hallmarks are set by the process; they in turn determine the forward voltage drop and reverse leakage current characteristics.

Table 1 shows a listing of the basic IR Schottky processes.

TABLE 1
Basic Schottky processes.

T_{Jmax} CLASS	V_{RRM} CLASS
100	15
125	45
150	30
150	45
150	60
175	45
175	100
175	150

1. How the Schottky Process Effects the Forward Voltage Drop

Forward Voltage Drop vs V_{RRM} Class

For any given current density, the Schottky's forward voltage drop increases as its V_{RRM} Class increases. (As would be expected, forward voltage drop also increases as operating current density increases.)

Figures 4 and 5 show relationships between forward voltage drop and V_{RRM} Class at different operating current densities for 150°C and 175°C T_{Jmax} Class Schottkys respectively.

[1]The "prime" rated voltage is the highest voltage rating offered for the process. Lower voltage ratings are also offered within the same process, but the other electrical characteristics remain the same.

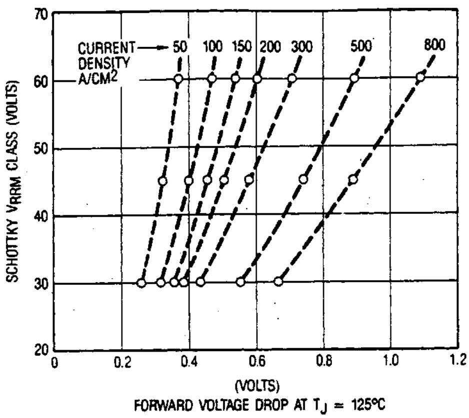


Figure 4. Relationships between Schottky V_{RRM} class and forward voltage drop, for 150°C T_{Jmax} class Schottkys.

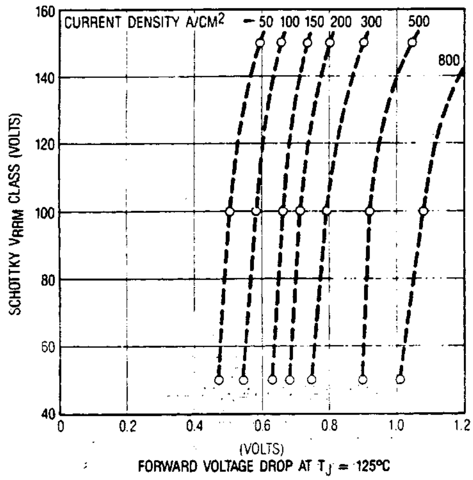


Figure 5. Relationships between Schottky V_{RRM} class and forward voltage drop for 175°C T_{Jmax} class Schottkys.

Forward Voltage Drop vs T_{Jmax} Class

Forward voltage drop generally increases as the T_{Jmax} Class increases, though this is a function also of the operating current density and junction temperature.

Figure 6 shows the relationships between forward voltage drop, operating current, and T_{Jmax} Class, for a given (45V) V_{RRM} Class, at 125°C junction temperature.

For current density below about 800A/cm², the forward voltage drop *increases* as the T_{Jmax} Class *increases*. At about 800A/cm², the forward voltage drop of all classes become approximately the same. Above 800A/cm², the characteristics actually crossover.

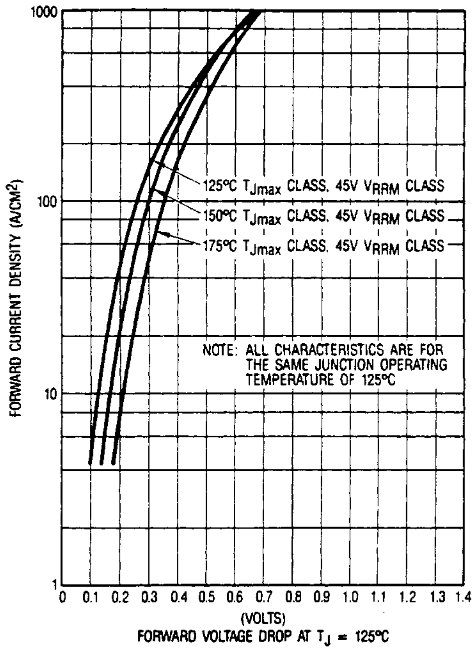


Figure 6. Relationships between forward current density and forward voltage drop for different Schottky T_{Jmax} classes.

In most applications the operating current density will be below the crossover point, typically in the range of 400 to 600A/cm². Flyback converters are an exception, because they operate with rather high peak to average current ratio.

2. Relationships Between Forward Voltage Drop, Operating Current and Junction Temperature.

Typical relationships between forward voltage drop, current and operating temperature, for 45V, 150 and 175°C T_{Jmax} Class Schottkys, are illustrated in Figures 7 and 8 respectively.

Forward voltage drop decreases quite significantly as junction temperature increases. Thus forward conduction losses *decrease* as operating junction temperature *increases.*

3. How the Schottky Process Effects Leakage Current

Figure 9(a) through (d) shows typical relationships between leakage current and applied reverse voltage for each of the IR Schottky processes at different operating junction temperatures. This demonstrates how the leakage current depends both on the T_{Jmax} and V_{RRM} Classes.

For a given T_{Jmax} Class, leakage current at rated V_{RRM} and rated T_{Jmax} decreases as the V_{RRM} Class increases, as illustrated by points A in Figure 9(c) for the 150°C T_{Jmax} Class families and points B in Figure 9(d), for the 175°C

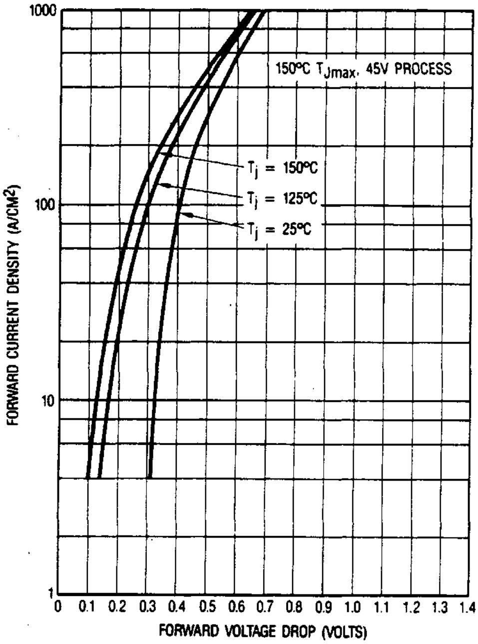


Figure 7. Relationships between forward current density and forward voltage drop for the 150°C/45V Schottky process at different operating junction temperatures.

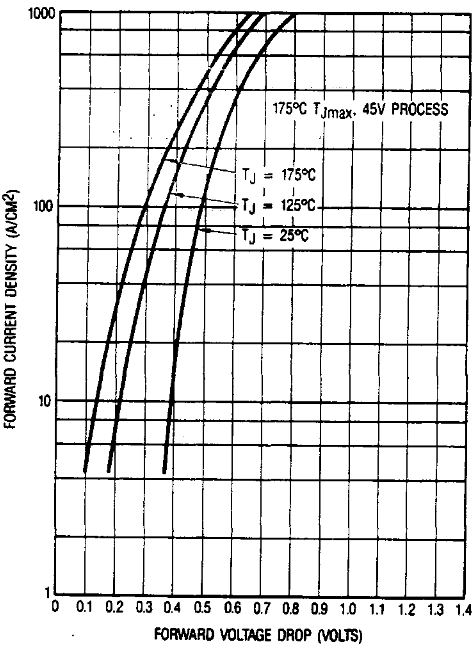


Figure 8. Relationships between forward current density and forward voltage drop for the 175°C/45V Schottky process, at different operating junction temperatures.

T_{Jmax} Class families. At any given operating junction temperature and applied voltage, the higher the T_{Jmax} Class, the lower the leakage current. This is immediately evident from Figure 9. Also, within any given T_{Jmax} Class, the higher the V_{RRM} Class the lower the leakage current.

Note that the leakage current scale in Figure 9 is logarithmic. Thus, for a given applied voltage and junction operating temperature, there is about an order of magnitude difference in leakage current between the 175°C and 150°C T_{Jmax} Classes. The 100°C, 15V process has a leakage current which is almost two orders of magnitude higher than for the 150°C, 30V process.

4. Relationships Between Leakage Current, Reverse Voltage and Junction Temperature

Figure 9 also shows the dependence of leakage current on the operating voltage and junction temperature within any given process. Reverse leakage current increases with applied reverse voltage, and with junction temperature. The variation of leakage current with voltage at a given temperature follows an approximately "proportional" relationship, until the applied voltage approaches the "avalanche" region. The relationship between leakage current and temperature, at a given voltage, on the other hand, is "exponential."

Figure 10 shows typical relationships between operating temperature and leakage current, at rated V_{RRM}, for the 150°C/45V and 175°C/45V Schottky processes.

5. Junction Capacitance

An important circuit-characteristic of the Schottky is its junction capacitance. This is a function of the area and thickness of the Schottky die, and of the applied voltage.

The higher the V_{RRM} Class, the greater the die thickness, and the lower the junction capacitance. This is illustrated in Figure 11.

Junction capacitance is essentially independent of the Schottky's T_{Jmax} Class, and of operating temperature.

6. Summary of Effect of Schottky Process and Operating Conditions on Electrical Characteristics

Table 2 gives a qualitative summary of the effect of Schottky process on conduction voltage, leakage current, and capacitance.

Table 3 gives a summary of the effects of operating junction temperature, forward current, and reverse voltage on conduction voltage, leakage current, and capacitance.

B. Schottky Die Sizes

The size of the Schottky die (in combination with the package), determines the current rating. IR's Schottky die sizes, for current ratings of 8A and above, are shown in Table 4.

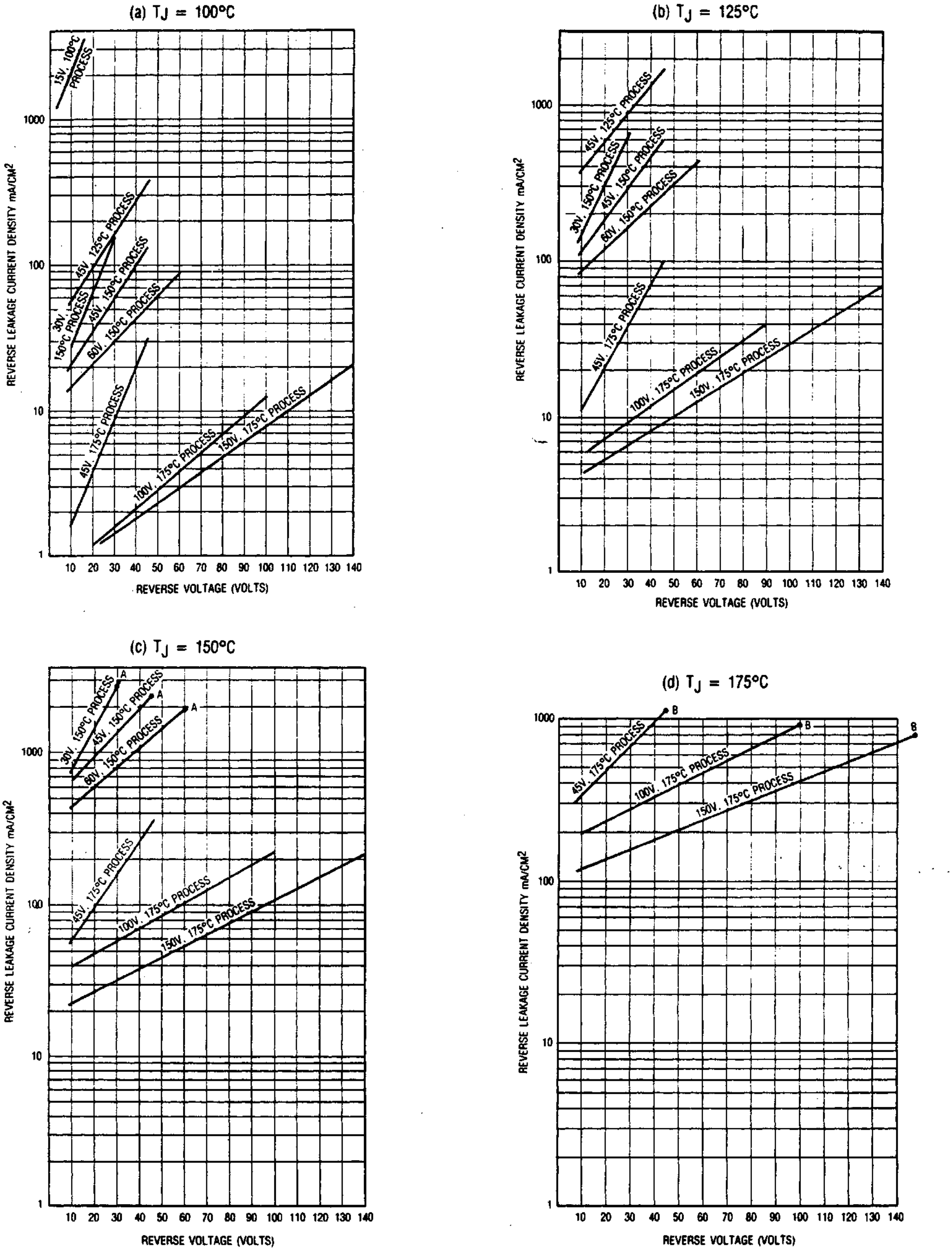


Figure 9. Relationships between reverse leakage current density and applied reverse voltage for different Schottky process types for operating junction temperatures as indicated.

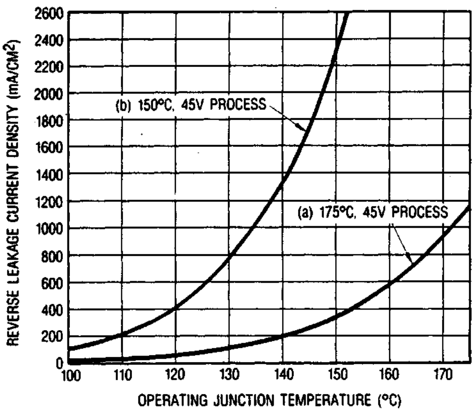


Figure 10. Typical relationships between reverse leakage current density and operating junction temperature.

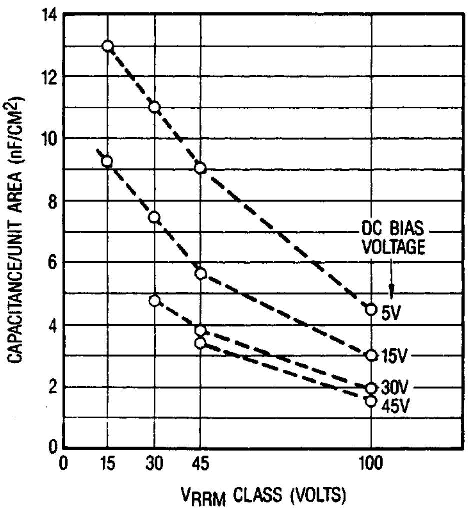


Figure 11. Typical Schottky self-capacitance versus V_{RRM} class, measured at various bias voltages.

TABLE 2
Effect of process on Schottky characteristics.

SCHOTTKY PROCESS CHARACTERISTIC	RESULTING EFFECT ON				
	V_F AT GIVEN T_J	V_F AT T_{Jmax}	I_R AT GIVEN T_J	I_R AT T_{Jmax}	C
T_{Jmax} CLASS ↑	↑	↑ SLIGHTLY	↓	↓	—
V_{RRM} CLASS ↑	↑	↑	↓	↓	↓

TABLE 3
Effect of operating conditions on Schottky characteristics for a given Schottky process.

IMPOSED OPERATING CONDITION	RESULTING EFFECT ON		
	V_F	I_R	C
T_J ↑	↓	↑	—
I_F ↑	↑	—	—
V_R ↑	—	↑	↓

TABLE 4
Schottky die sizes.

SCHOTTKY DIE SIZE EACH SIDE		TYPICAL CURRENT RANGE (A)
THOUSANDTHS INCH	MM	
90	2.29	10 – 15
125	3.18	10 – 30
150	3.81	18 – 40
175	4.45	30 – 40
200	5.08	50 – 100

Schottkys with current ratings above the capability of the single largest die use combinations of parallel die.

C. Packages

International Rectifier Schottky packages are shown in Figure 12. These range from surface mount and axial lead types, with ratings of a few amperes, to large dual Schottky modules with ratings in excess of 400A.

Most of these packages are industry standards and do not require special discussion. The following notes draw attention to specific features.

1. Dual Schottkys

Many IR packages contain two Schottkys connected in the common-cathode configuration. This provides the complete output rectifier function of the common transformer "center tap" and "forward" rectifier circuits in a single package.

2. Isolated Packages

The Schottky is most usually connected electrically to the cooling surface of the package. The cooling surface serves the double duty of transmitting heat away from the package and of being one of the electrical connections.

The D-60 and TO-249AA packages (Figure 12) are an exception. The cooling surface of these packages is electrically isolated. This allows the use of a grounded heatsink, as well as minimizing capacitively coupled ground current.

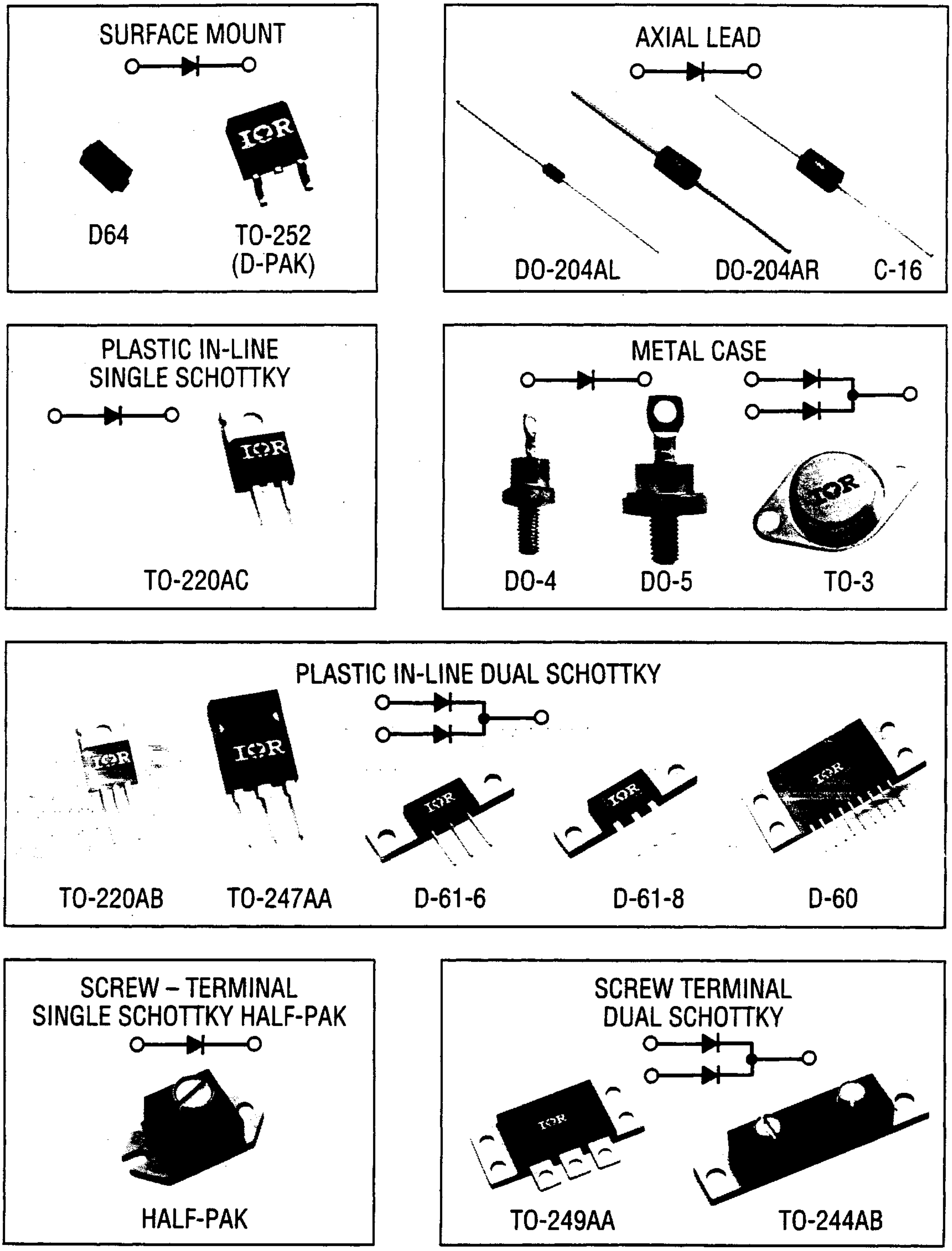


Figure 12. Schottky packages.

3. HALF-PAK®

IR's HALF-PAK module (Figure 12) contains a single Schottky. The HALF-PAK is a development from the TO-244AB dual Schottky module, hence the name HALF-PAK.

The International Rectifier HALF-PAK offers the advantage of greater compactness, flexibility of physical layout, and ease of connections to the high frequency output transformer of the power supply. It also offers flexibility in the choice of current rating and allows physically similar Schottkys but with different current ratings to be used in forward converters. This can be more compatible with the *forward* and *freewheeling* functions of the circuit than using equally-rated Schottkys.

TABLE 5(a)
Schottky product matrix.

PROCESS		DIE SIZE		NO. LEGS	NO. DIE PER LEG	PACKAGE	FAMILY
T_{Jmax} °C	V_{RRM} V	INCH	MM				
100	15	0.125	3.18	1	1	DO-204AR	95SQ
		0.150	3.81	1	1	TO-220AC	19TQ
		0.200	5.08	1	1	DO-5	95HQ
					2	HALF-PAK	125NQ
					3		185NQ
					4		225CNQ
				2	1	D-61-8	85CNQ
125	45	0.200	5.08	2	1	D-61-8	84CNQ
				2	2	TO-244AB	224CNQ
					4		444CNQ
150	30	0.125	3.18	2	1	TO-220AB	32CTQ
		0.200	5.08	1	1	DO-5	55HQ
				1	2	HALF-PAK	122NQ
					3		182NQ
					4		242NQ
				2	1	D-61-6	62CNQ
						D-61-8	82CNQ
				2	1	D-60	152CMQ
						TO-249AA	162CMQ
				2	2	TO-244AB	220CNQ
				2	4		440CNQ
150	45	0.125	3.18	1	1	DO-204AR	90SQ
						TO-220AC	12TQ
		0.150	3.81				20TQ
		0.175	4.45			DO-4	20FQ
							21FQ
		0.200	5.08			DO-5	50HQ
							51HQ
					2	HALF-PAK	120NQ
					3		180NQ
					4		240NQ
		0.090	2.29	2	1	TO-220AB	15CTQ
		0.125	3.18				25CTQ
						TO-247AA	30CPQ045
		0.175	4.45				40CPQ045
		0.200	5.08			D-61-6	60CNQ
						D-61-8	80CNQ
						D-60	150CMQ
						TO-249AA	160CMQ
					2	TO-244AB	200CNQ
					4		400CNQ
150	60	0.125	3.18	2	1	TO-220AB	30CTQ060
						TO-3P	30CPQ060
		0.175	4.45				40CPQ060

D. The Schottky Product Matrix

In the previous sections the individual ingredients of the IR Schottky product range — process, die size and package — have been described. Given these basic ingredients, many variations of specific products are possible.

The International Rectifier Schottky product matrix represents those combinations of ingredients that are most commonly needed in power supply designs. Evolving new power supply requirements and evolving Schottky processes and packages will continue to add new types to the range.

Table 5 shows the combinations of processes, die sizes, and packages that form IR's overall Schottky product matrix[2].

TABLE 5(b)
Schottky product matrix.

PROCESS		DIE SIZE		NO. LEGS	NO. DIE PER LEG	PACKAGE	FAMILY
T_{Jmax} °C	V_{RRM} V	INCH	MM				
175	45	0.125	3.18	1	1	DO-204AR	80SQ
						TO-220AC	10TQ
		0.090	2.29				6TQ
		0.150	3.81				18TQ
		0.175	4.45			DO-4	30FQ
		0.200	5.08			DO-5	75HQ
							85HQ
					2	HALF-PAK	121NQ
					4		241NQ
		0.090	2.29	2	1	TO-220AB	12CTQ
		0.125	3.18				20CTQ
							30CTQ045
		0.150	3.81			TO-247AA	40CDQ
							60CDQ
						D-61-6	61CNQ
						D-61-8	81CNQ
						D-60	151CMQ
						TO-249AA	161CMQ
					2	TO-244AB	201CNQ
					2		301CNQ
					4		401CNQ
175	100	0.125	3.18	1	1	DO-204-AR	50SQ
						TO-220AC	8TQ
		0.200	5.08			DO-5	60HQ
					2	HALF-PAK	123NQ
					3		183NQ
					4		243NQ
		0.125	2.29	2	1	TO-220AB	16CTQ
						TO-247AA	30CPQ100
		0.175	4.45				40CPQ100
		0.200	5.08			D-61-6	63CNQ
						D-61-8	83CNQ
						D-60	153CMQ
						TO-294AA	163CMQ
					2	TO-244AB	203CNQ
					3		303CNQ
					4		403CNQ
175	150	0.090	2.29	2	1	TO-220AB	10CTQ
						TO-247AA	30CPQ100

[2] These tabulations focus on ratings of 8A and above; the smaller surface mount and axial lead types are not included.

II. THE SCHOTTKY DATA SHEET

The IR Schottky data sheet provides all the pertinent information needed to design the Schottky into a specific circuit. The purpose of the following description is to provide an awareness and understanding of the information in the data sheet.

We will do this by taking a step-by-step walk through the data sheet.

A. Absolute Maximum Ratings

V_{RWM} — Maximum working peak reverse voltage

This is the maximum peak voltage that can be applied to the Schottky, without the reverse leakage current exceeding the specified limit.

$I_{F(AVE)}$ — Maximum average forward current

This is the maximum average forward current that the Schottky is rated to carry, with the stated current waveform (normally rectangular, with a 50% duty cycle), at the stated case temperature.

This rating is based on the junction temperature reaching a set value, usually somewhat less than the rated T_{Jmax}, under the stated conditions.

I_{FSM} — Maximum peak one-cycle non-repetitive surge current

This is the maximum one cycle peak current that the Schottky can carry, under a non-repetitive fault condition with full rated voltage applied immediately following the surge.

In typical switching power supply operation, fault current is detected and quite rapidly arrested by control of the switching transistor(s). The data sheet gives the Schottky's surge capability for short-time durations that are typical of the response of a power supply's protective control circuitry.

The single cycle surge rating is also stated for a 10 millisecond half-sinusoidal current pulse, which is pertinent to applications where the Schottky is used as a low voltage line-frequency rectifier.

Non-repetitive surge ratings are supplemented by a graph in the data sheet that shows the rated surge current as a function of surge duration. A representative graph is shown in Figure 13.

Note that the surge rating places no restriction on the initial case temperature, (so long as this is less than T_{Jmax}). The instantaneous junction temperature during surge significantly exceeds the Schottky's rated T_{Jmax}; the peak reverse leakage current following the current surge will also significantly exceed the maximum specified value at T_{Jmax}.

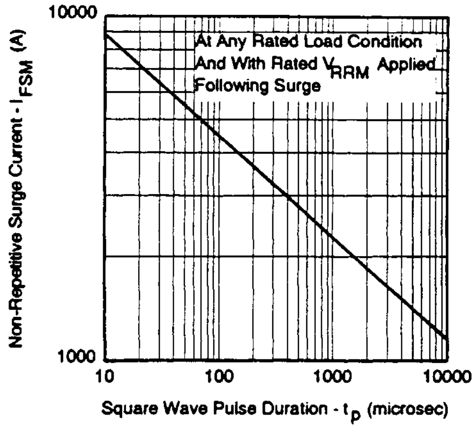


Figure 13. Maximum non-repetitive surge current for 50HQ045.

Because of the extreme operating conditions implied in this rating, the *non-repetitive* surge rating is just that. It can be regarded as a "safety net," to be called into play for *abnormal* fault conditions, which occur infrequently. It should not be used for repetitive surge events, such as start-up current surges that occur each time a power supply is switched on.

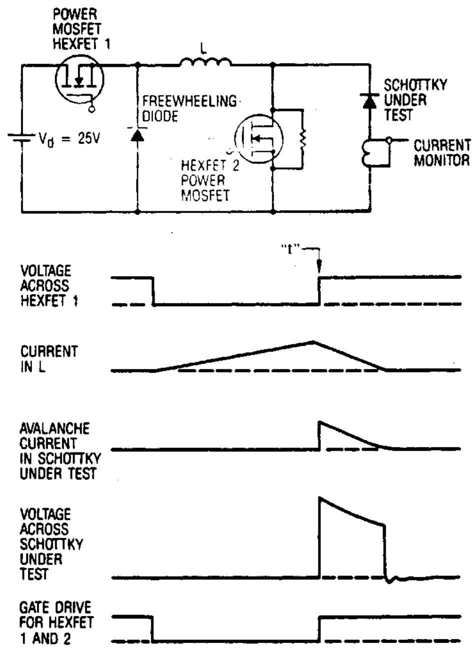


Figure 14. Avalanche energy test circuit and timing waveforms.

E_{AS} — Non repetitive avalanche energy

This is the energy that the Schottky can absorb, when reverse current is discharged into it from an inductor. The test circuit in the data sheet is shown in Figure 14. The sequence of operation is as follows:

Power MOSFETs 1 and 2 are simultaneously turned on, and current in the inductor L ramps up. At time t, the current reaches the specified test value, and both devices are simultaneously turned OFF. Current stored in the inductor now discharges into the Schottky, the circuit being completed via the freewheeling diode.

A typical oscillogram of Schottky current and voltage is shown in Figure 15. Note that the peak avalanche voltage is about 1.5x the Schottky's reverse voltage.

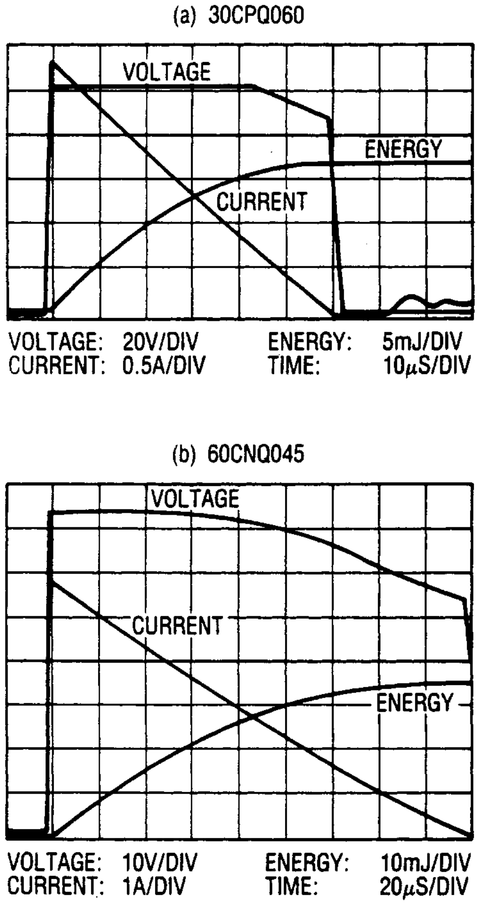


Figure 15. Typical oscillograms of voltage, current and energy for avalanche operation of Schottky.

I_{AR} — Repetitive avalanche current

This is the maximum reverse current that the Schottky can absorb repetitively, from a precharged inductor. The inductance value must be such that the current decays to zero within the specified avalanche time.

The repetitive avalanche current, I_{AR}, has the same value as the current specified for the non-repetitive E_{AS} rating. With such a high avalanche current, the peak avalanche voltage will typically "climb" to about 1.5x the Schottky's rated voltage.

An essential difference between the I_{AR} and E_{AS} ratings is that the inductance that satisfies the time constraint (1μs) of the repetitive I_{AR} rating will have a much smaller value — typically 100 to 200 times smaller — than the value specified for the non-repetitive E_{AS} test. A repetitive avalanche time of 1μs is still, however, much longer than would result from the leakage inductance of a normal switching power supply transformer.

B. Electrical Specifications

V_{FM} — Maximum Forward Voltage Drop

This is the maximum voltage drop of a "limit" device at the stated current and junction temperature.

Specific values in the data sheet tabulation are supplemented by a graph that shows maximum voltage drop versus current at various junction temperatures. A representative graph of this type is shown in Figure 16.

Both the numerical values of voltage drop given in the data sheet's tabulation, and the V_F graphs, represent the maximum voltage drop of a "limit" device. They can, therefore, be used directly for worst-case design purposes. Actual voltage drop is typically less than the maximum.

I_{RM} — Maximum reverse leakage current

This is the maximum reverse leakage current that a "limit" device will exhibit, at the rated reverse voltage, at the stated junction temperature.

The tabulated "limit" data is supplemented by graphs that show typical reverse leakage current versus reverse voltage, for a wide range of junction operating temperatures. A representative graph is shown in Figure 17.

The worst-case maximum value of leakage current for any particular operating condition can be conservatively estimated from the graph by applying the same relationship between the "limit" value in the data sheet's tabulation and the corresponding typical value in the graph.

C_T — *Maximum junction capacitance*

This is the maximum value of junction capacitance, at the stated test condition. The guaranteed "limit" value is supplemented by a graph that shows typical values as a function of reverse voltage. A representative data sheet graph is shown in Figure 18.

The Schottky's junction capacitance is essentally independent of temperature.

L_S — *Typical series inductance*

This is the typical terminal-to-terminal inductance of the Schottky.

dv/dt

This is the maximum rate of change of voltage that can be applied to the Schottky. International Rectifier Schottkys are rated at 10,000V/μs. This translates to just a few nanoseconds rise time to the Schottky's normal working voltage.

The rating is a reference to the fact that some manufacturers' Schottkys may have (or may have had) limited dv/dt capability. Some users are, therefore, sensitive to the issue. IR Schottkys have always had "practically unrestricted" dv/dt capability.

C. Thermal Specifications

T_J — *Maximum junction temperature range*

The maximum and minimum operating junction temperature range.

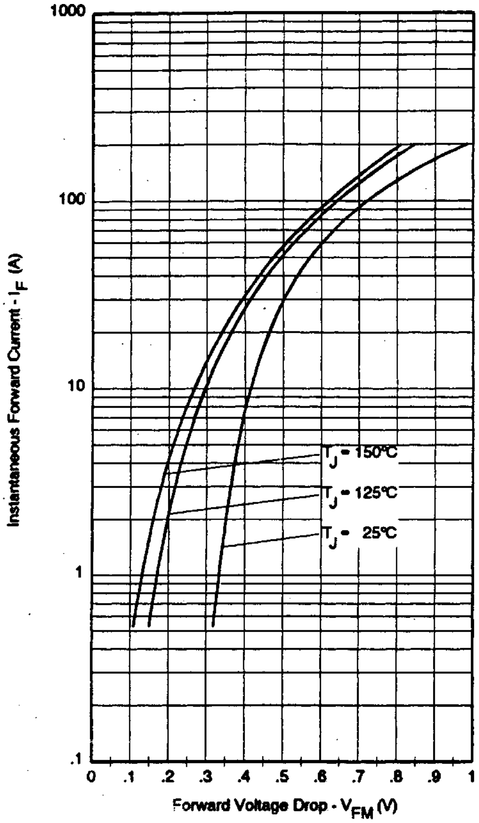


Figure 16. Maximum forward voltage drop characteristics (50HQ045).

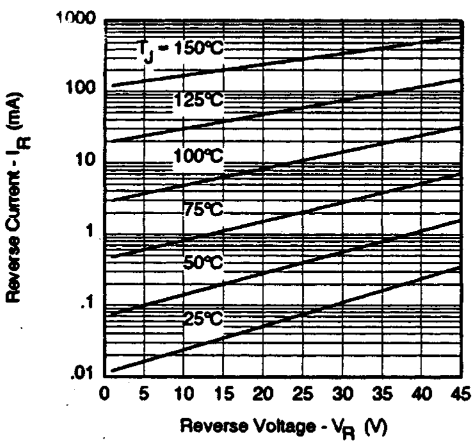


Figure 17. Typical values of reverse current vs. reverse voltage (50HQ045).

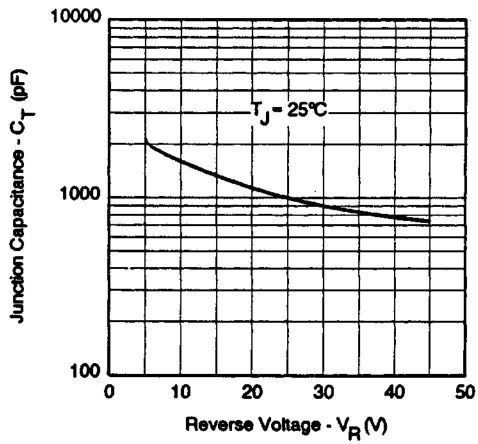


Figure 18. Typical junction capacitance vs. reverse voltage (50HQ045).

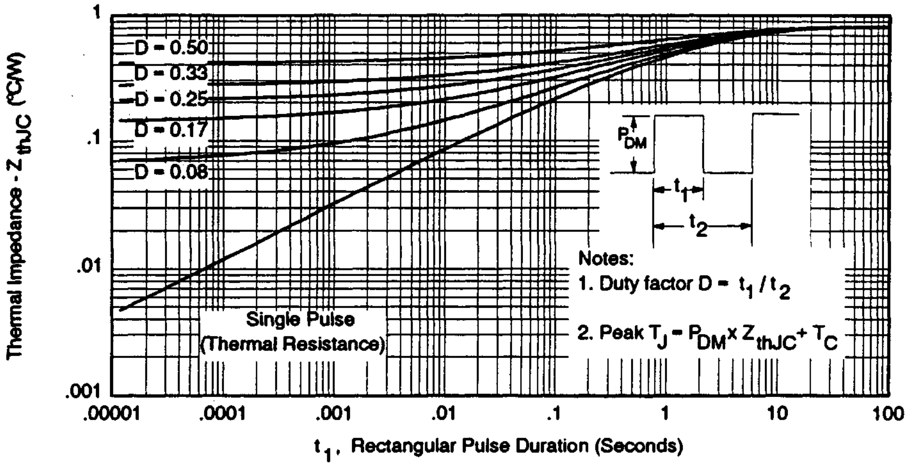


Figure 19. Maximum thermal impedance Z_{thJC} characteristics (50HQ045).

T_{Stg} — Maximum storage temperature range

The maximum and minimum storage temperature range.

R_{thJC} — Junction to case thermal resistance

This is the maximum value of junction to case thermal resistance for steady dc operation.

The value of dc thermal resistance tabulated in the data sheet is supplemented by a graph showing *single pulse* and *duty cycle* thermal impedance as a function of pulse duration. A representative graph is shown in Figure 19.

Peak junction temperature for any duty cycle application can be calculated directly from the transient thermal impedance characteristics. The curve labelled *single pulse* shows the rise of junction temperature per watt of power dissipation as a function of pulse duration. As would be expected, junction temperature rise increases as pulse duration increases — leveling off to a steady value for pulse durations above ten seconds or so.

The single pulse curve is useful for determining transient junction temperature rise for single or very low duty cycle pulses of power; it is not directly useable for repetitive power pulses, such as are usually encountered in switching power supply applications.

The duty cycle curves show effective thermal impedance for repetitive operation at different duty cycles, and allow peak junction temperature rise for repetitive operation to be calculated directly. These curves are related to the single pulse curve by the following relationship:

Effective junction to case thermal impedance for pulse duration t

$$= D \bullet R_{JC} + (1-D) \bullet R_{JC(t)}$$

where D = duty cycle

R_{JC} = steady state thermal resistance

$R_{JC(t)}$ = transient thermal impedance for pulse duration t

The above effective thermal impedance when multiplied by the power dissipation *during the conduction period t* (i.e., the power within the conduction pulse itself, not the power averaged over the whole cycle), gives the value of the repetitive peak junction-to-case temperature rise.

The effective thermal impedance for any duty cycle D increases as pulse duration increases, showing that the peak junction temperature rise increases as frequency decreases.

The reason is illustrated by the waveforms in Figure 20(a) and (b). Both sets of waveforms are for the same power dissipation and duty cycle, but for different operating frequencies. The cycle-by-cycle fluctuations of junction temperature at 1kHz in Figure 20(a) are "discernable," while those at 10kHz in Figure 20(b) are not.

As frequency increases, thermal inertia of the junction "smooths" instantaneous temperature fluctuations, and the junction responds more to average, rather than peak, power dissipation. At frequencies above a few kHz, and duty cycles above 20% or so, cycle-by-cycle temperature fluctuations are usually small, and peak junction temperature rise is essentially equal to the average power dissipation, multiplied by the dc junction-to-case thermal resistance.

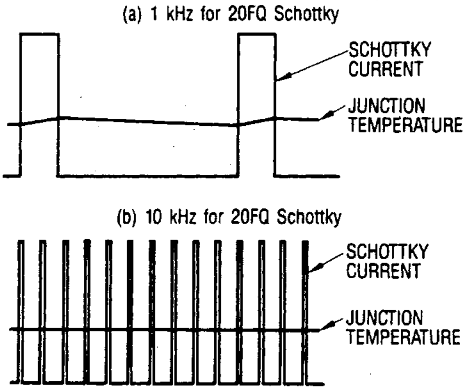


Figure 20. Idealized current and junction temperature waveforms. Conduction duty cycle = 0.17.

R_{thCS} — Case to sink thermal resistance

This is the typical value of case to sink thermal resistance, with the heatsink mounting surface smooth and thermal compound evenly applied.

T — Mounting Torque

Screw-mounted devices have both minimum and maximum values of rated torque that can be applied to the mounting screws. Stud devices have both minimum and maximum rated values of torque that can be applied to the device. These torque ratings apply to non-lubricated threads. Screw-terminal packages also have rated maximum and minimum torques that can be applied to the terminals.

Over-application of torque can result in mechanical damage to the device, while under-application may fail to achieve the proper thermal and/or electrical contact, the result being high values of thermal resistance and/or voltage drop.

III. WHICH SCHOTTKY?

As has been seen, the International Rectifier Schottky rectifier range comprises a broad matrix formed from the following basic ingredients:

- Packages
- Die sizes (i.e., current ratings)
- Processes (i.e., mixes of T_{Jmax}, V_{RRM}, V_F, and reverse leakage characteristics)

Having a grasp for the above, the next step is for the circuit designer to understand the impact of the choice of Schottky — particularly that of Schottky size and process — on circuit operating performance and heatsink requirements. The designer also needs to know how to identify and set the worst-case "limit" operating point for the Schottky in his particular application.

A. General Application Guidelines

Figure 21 shows a summary of *"General Application Guidelines"* that define the fundamentals on which the Schottky selection process should be based.

Each of these *General Guidelines* is explained in the following sections.

1. Setting the operating temperature margin

General Guideline 1: *The Schottky's maximum operating junction temperature must be less than the Schottky's rated T_{Jmax}, by a margin that keeps the reverse losses under control. The required junction temperature margin increases as the maximum design operating current density decreases.*

Power losses in a Schottky comprise two main components: Conduction losses and reverse leakage losses.

Average conduction losses are dictated by the forward current, forward voltage drop, or "conduction voltage," and conduction duty cycle, (i.e., the portion of the total cycle for which the Schottky is in conduction). Forward voltage drop is itself a function of junction temperature, decreasing somewhat with increasing temperature.

Average reverse leakage losses depend upon the reverse leakage current, the applied reverse voltage and the reverse voltage duty cycle, (i.e., the portion of the total cycle for which the Schottky blocks reverse voltage). Reverse leakage current increases exponentially with junction temperature, as already illustrated in Figure 10.

Thus, for any given set of operating conditions — current, conduction duty cycle, reverse voltage, and reverse voltage duty cycle — forward conduction losses *decrease* to some degree, while reverse leakage losses *increase* quite rapidly, with increasing junction temperature.

The relationship between the sum of the forward and reverse losses and junction temperature, for a 50HQ045 Schottky, under the stated operating conditions, is illustrated in Figure 22.

The operating point on the Schottky's power loss versus junction temperature characteristic is determined by the junction to ambient thermal resistance. This, in turn, is largely dictated by the heatsink on which the Schottky is mounted.

For a given design ambient temperature, T_{AMB}, decreasing the junction to ambient thermal resistance (by using a larger heatsink) moves the operating point to a lower junction temperature, as illustrated in Figure 22. (For example, with R_{JA} = 3.93°C/W, the operating junction temperature is 135°C; with R_{JA} = 3.27°C, it is 120°C).

DESIGN GUIDELINES

Guideline 1.

The Schottky's maximum operating junction temperature must be less than the Schottky's rated T_{Jmax}, by a margin that keeps the reverse losses under control. The required junction temperature margin increases as the maximum operating design current density decreases.

Guideline 2.

The smallest heatsink is the one that gives a safe, but not excessive, thermal margin. Sizing the heatsink to minimize the total losses, or to arbitarily add thermal margin, can require a disproportionately large heatsink.

Guideline 3.

Schottky losses and heatsink size can be decreased by selecting a larger Schottky. This can be a very effective way of decreasing the overall physical size of the output rectifier, though eventually a point of diminishing returns is reached.

Guideline 4.

A Schottky of a given size with a higher T_{Jmax} class has larger losses, but can operate at a higher heatsink temperature, and therefore with a smaller heatsink, than a Schottky with a lower T_{Jmax} class. Thus a higher T_{Jmax} class Schottky generally optimizes heatsink size, while a lower T_{Jmax} class Schottky generally optimizes efficiency.

Guideline 5.

If system constraints, not the Schottky's temperature capability, dictate the maximum permissible heatsink temperature, then the smallest heatsink will be obtained with the most efficient Schottky.

Guideline 6.

Selection of a larger Schottky can facilitate operation at a higher ambient temperature.

Guideline 7.

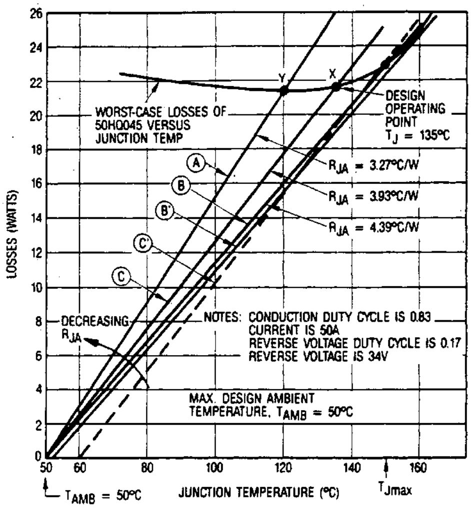
The higher the ambient temperature, the more a Schottky with higher rated T_{Jmax} will help reduce the heatsink size.

Guideline 8.

Within a given T_{Jmax} class, lowest losses and smallest heatsink will usually be obtained by selecting the Schottky from the lowest voltage class that is compatible with the circuit voltage.

Applicable General Guideline	Schottky Choice made by Designer		RESULTING EFFECT ON PERFORMANCE				
			Operating		Heatsink size	Losses	Max T_{amb}
			T_J	T_S			
1, 4, 7	RATED T_J (T_{Jmax} class)	⇑	↑	↑	↓	↑	↑
1, 3, 6	SCHOTTKY SIZE	⇑	↓	↑	↓	↓	↑
8	RATED V_{RRM} (V_{RRM} class)	⇑	↑	↓	↑	↑	
1, 2	HEATSINK SIZE	⇑	↓	↓	↑	↑↓	↑
5	HEATSINK TEMP	⇓	↓	↓	↑	↑	↓

Figure 21. Summary of general application design guidelines.



(A) LOCUS OF R_{JA} FOR MIN LOSSES

$R_{JA} = \frac{120 - 50}{21.4} = 3.27°C/W$

$R_{SA} = R_{JA} - R_{JS} = 3.27 - 1.08 = 2.19°C/W$

(B) LOCUS OF R_{JA} FOR T_J = 150°C

$R_{JA} = \frac{150 - 50}{22.8} = 4.39°C/W$

$R_{SA} = 4.39 - 1.08 = 3.31°C/W$

(B') LOCUS OF R_{JA} (B) IF AMBIENT TEMP. INCREASES BY 2°C. OPERATION BECOMES THERMALLY UNSTABLE

(C) LOCUS OF R_{JA} THAT GIVES OPERATING T_J = 150°C AT T_{AMB} = 60°C

$R_{JA} = \frac{150 - 60}{22.8} = 3.95°C/W$

$R_{SA} = 3.95 - 1.08 = 2.87°C/W$

(C) LOCUS OF R_{JA} (C) FOR T_{AMB} = 50°C OP. T_J IS 135°C. LOSSES = 21.6W

Figure 22. **Comparison of different heatsink thermal resistances and operating points.** ***(General Guidelines 1 and 2).***

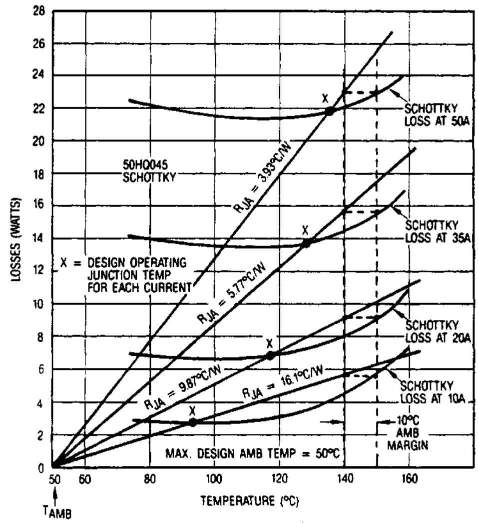
Clearly, use of a heatsink that gives a junction to ambient thermal resistance locus that is nearly tangential to the Schottky loss curve is a flirtation with thermal instability. Locus B, for example, gives an operating junction temperature of T_{Jmax}. This operating point, in this particular example, borders on instability. An increase in ambient temperature of about 2°C above the design maximum would shift locus B to position B' and thermal runaway would occur.

A safe basis for setting the heatsink thermal resistance is to size it so that the operating junction temperature reaches T_{Jmax} only when the *ambient* temperature exceeds the maximum design value by a set margin, say 10 to 15°C. Based on a 10°C margin in *ambient* temperature, the maximum junction operating temperature in the example considered in Figure 22 would be about 135°C, as illustrated.

Operation of this same Schottky at a lower value of maximum design current will translate to a higher junction temperature margin being needed for a given ambient temperature margin; this is because of the greater non-linearity between losses and junction temperature at lower operating current.

Figure 23 shows a set of relationships between the losses and junction temperature, for a given operating voltage, with varying levels of maximum design operating current. Loci of the junction to ambient thermal resistance that satisfy a fixed *ambient* temperature margin of 10°C are shown. Because the reverse losses remain constant as the design operating current decreases, the total losses and the heatsink size do not decrease proportionately with decreasing design current.

The safe design operating junction temperature (point X) decreases significantly with decreasing current, to maintain a safe distance from the point of thermal instability. Note that the fixed 10°C ambient margin translates to a junction temperature margin that varies from 15 to 55°C, as the maximum design forward current decreases.[3]



Notes: Conduction duty cycle is 0.83
Reverse voltage duty cycle is 0.17
Reverse voltage is 34V

Figure 23. **Characteristics illustrating the reduction in design operating junction temperature as the Schottky's design operating current is reduced.** ***(General Guideline 1).***

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[3]In a situation where the reverse losses are significant in relation to the forward losses, *two* intersection points are possible on the Schottky power loss curve. The higher of these intersection points is critically unstable and has no physical meaning.

This can be understood by considering that operation is at the "high" intersection point and postulating a small increase in junction temperature; this would result in immediate thermal runaway, because the losses increase faster than the heatsink can arrest them. A small decrease in temperature, on the other hand, would precipitate a further "cascading" decrease, until the lower, stable intersection point is reached.

2. Axial Lead Schottkys

An axial lead Schottky is not designed for mounting directly on a heatsink, or to have heat directly removed from the surface of the package. Heat removal from the junction is via the leads to a terminal post or a copper clad area on a PC board.

Heat removal from an axial lead Schottky cannot, therefore, be as efficient as from a "heatsinkable" package, and power density and current density must as a result be relatively low. Reverse power losses, which are independent of current, will thus be relatively high.

Operation of an axial lead Schottky is a good example of the situation discussed above, in which the operating current density is relatively low. The design operating junction temperature must be significantly less than the Schottky's rated T_{Jmax} to keep a safe margin from thermal runaway.

Loss characteristics for the International Rectifier axial leaded 50SQ100 Schottky, operating in a 15V Flyback power supply at output currents of 3.5 and 4.5A, are illustrated in Figure 24. The 3.5A design requires a junction to ambient thermal resistance of 44°C/W, while the 4.5A design requires 35°C/W. In the first case, the design junction operating temperature margin is 25°C, and in the second case, 30°C below the rated maximum. This is based on a 10°C *ambient* temperature margin.

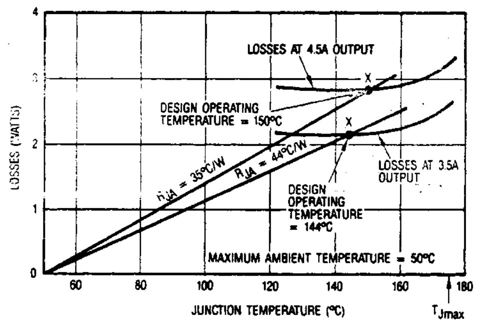


Figure 24. Operating characteristics and operating points for 50SQ100 axial lead Schottky in 15V flyback converter, at output currents of 3.5 and 4.5A.

3. Setting the Heatsink Thermal Resistance

General Guideline 2: The smallest heatsink design is the one that gives a safe but not excessive thermal margin. Sizing the heatsink to minimize the total losses, or to arbitrarily add thermal margin, can require a disproportionately large heatsink.

Thermal resistance is the *ratio* of temperature rise to losses. If minimum losses occur at a relatively low operating junction temperature, then heatsink temperature rise would have to be kept relatively low to minimize the losses, requiring a relatively low value of heatsink thermal resistance. Thus, a relatively large heatsink would be needed, particularly because the physical size of the heatsink often increases disproportionately with decreasing thermal resistance.

In the example illustrated in Figure 22, minimum total losses, 21.4W, occur at a junction temperature of about 120°C, (point Y). Line A is the locus of the required junction to ambient thermal resistance needed to achieve this operating point. This has a slope of 3.27°C C/W. The corresponding thermal resistance of the heatsink would be 3.27 — 1.08 = 2.2°C/W.

Locus C, on the other hand, which is sufficient to maintain a safe thermal margin, corresponds to a heatsink thermal resistance of about 2.9°C/W. This is a 31% higher heatsink thermal resistance than that for minimum losses; the corresponding physical size of the heatsink could typically be 30 to 40% smaller.

Arbitrary addition of thermal margin has similar disproportionate repercussions on the heatsink size. The effect is particularly compounded in a situation where reverse losses are low and conduction losses predominate. In this case, increasing the heatsink size (beyond that required for a safe design) only increases the losses, because conduction losses increase with decreasing temperature. This would require a disproportionate increase in heatsink size, while the efficiency would simultaneously be degraded.

4. Increasing the Die Size

General Guideline 3: Schottky losses and heatsink size can be decreased by selecting a larger Schottky. This can be a very effective way of decreasing the overall physical size of the output rectifier, though eventually a point of diminishing returns is reached.

For given output voltage and current, a larger Schottky will operate at lower current density, and hence with lower conduction losses. Reverse losses, however, will be higher because reverse current of a larger die will be higher. The net result, up to a point, will be lower total losses and a smaller heatsink. At some point, however, further increasing the Schottky die area may start to require a larger heatsink in order to keep the junction temperature low enough that a safe distance from thermal instability is maintained. This point will not typically be reached in practical application.

An example is illustrated in Figure 25, and summarized in Table 6. Four different 30V, 150°C Schottkys are assumed to operate in a 5V, 100A power supply, at a conduction duty cycle of 0.5, and a reverse voltage duty cycle of 0.5, with a reverse voltage of about 11V. The design operating points for the four Schottkys are shown.

The 55HQ030 (1 x 200 mil die per leg), though adequate, has total losses of about 10.4% of the output power, and requires a heatsink thermal resistance of 2.27°C/W.

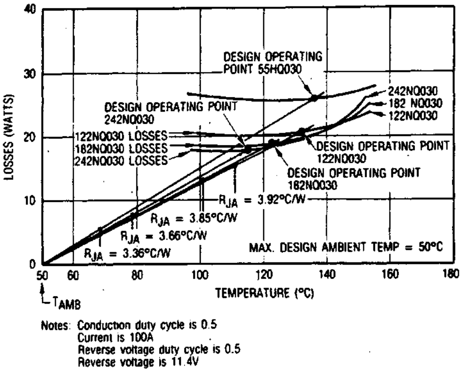


Figure 25. Operating characteristics and operating points for different sizes of Schottky in a 5V 100A power supply. *(General Guideline 3).*

The 122NQ030, (2 x 200 mil die per leg), has smaller total losses, about 8.2% of the output power. The required heatsink has a thermal resistance of 3.37°C/W and, therefore, will be significantly smaller.

The 182NQ030 (3 x 200 mil die per leg) gives a further decrease in losses to about 7.5% of the output power. The heatsink required to "suppress" the reverse loss contribution, and keep a safe operating junction temperature, has only slightly higher thermal resistance than that needed for the 120NQ030.

Finally, the 242NQ030 (4 x 200 mil sq die) has marginally lower losses. The heatsink required, however, has slightly lower thermal resistance than needed than for the 182NQ030.

To summarize, moving from the one-die 55HQ030 to the two-die 122NQ030 achieves significant improvements in efficiency and heatsink size. The larger International Rectifier 182NQ030 and 242NQ030 Schottkys, however, offer small additional advantage in terms of efficiency, and none in terms of heatsink size.

It should be stated that consideration of the larger Schottkys in this example has been done to illustrate that a point of diminishing returns can be reached, rather than to represent a "real" choice that would be seriously considered by the designer. After all, a 242NQ Schottky operating with 50% duty cycle is about a 5 to 1 "overkill," relative to the design output current of 100A.

5. Using a Higher T_{Jmax} Class to Reduce Heatsink Size

General Guideline 4: A Schottky of a given size with a higher T_{Jmax} class has larger losses, but can operate at a higher heatsink temperature and therefore with a smaller heatsink, than a Schottky with a lower T_{Jmax} class.

Thus a higher T_{Jmax} class Schottky generally optimizes heatsink size, while a lower T_{Jmax} class Schottky generally optimizes efficiency.

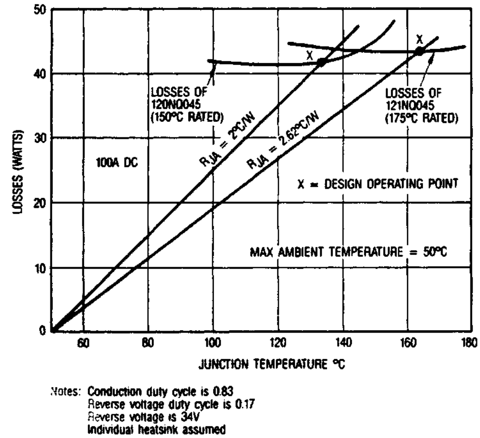


Figure 26. Operating characteristics and operating points illustrating that a 175°C rated Schottky (121NQ045) has higher losses, but requires a smaller heatsink than a comparable 150°C rated Schottky (120NQ045). *(General Guideline 4).*

TABLE 6

Summary of data illustrating that increasing the Schottky size reduces losses and heatsink size, but eventually reaches point of diminishing returns.

SCHOTTKY TYPE	LOSSES PER SCHOTTKY W	LOSSES (2 SCHOTTKYS) % OUTPUT POWER	DESIGN OPERATING T_J °C	T_{JA} °C	R_{JA} °C/W	R_{JS} °C/W	HEATSINK R_{SA} °C/W
55HQ030	26	10.4	137	87	3.35	1.08	2.27
122NQ030	20.4	8.2	130	80	3.92	0.55	3.37
182NQ030	18.7	7.5	122	72	3.85	0.45	3.4
242NQ030	18.0	7.2	116	66	3.67	0.35	3.32

NOTES: CONDUCTION DUTY CYCLE IS 0.5
CURRENT IS 100A
REVERSE VOLTAGE DUTY CYCLE IS 0.5
REVERSE VOLTAGE IS 11.4V
MAXIMUM DESIGN AMBIENT TEMPERATURE IS 50°C

This guideline represents an important choice available to the circuit designer. It is a restatement of the fact that the lowest losses don't necessarily mean the smallest heatsink.

If efficiency, minimization of total losses, and relatively low heatsink temperature are more important than minimization of the size of the heatsink, then a lower T_{Jmax} class Schottky may be the better choice. If minimization of heatsink size is more important than minimization of losses, then a higher T_{Jmax} class Schottky will generally be the better choice.

A typical example comparing the operating points and heatsink requirements of the International Rectifier 120NQ045 (150°C rated) and 121NQ045 (175°C rated) Schottkys, in a 100A, 5V forward converter, is illustrated in Figure 26.

The 150°C rated 120NQ045 Schottky has the lower losses. The higher junction to ambient temperature rise of the 175°C Schottky, however, allows a higher heatsink thermal resistance — hence a *smaller* heatsink.

These results are summarized in Table 7.

TABLE 7
Comparison of losses and heatsinks required for 150°C and 175°C "T_{Jmax} Class" Schottkys, operating in a 100A, 5V power supply. *(General Guideline 4).*

SCHOTTKY TYPE	T_{Jmax} RATING °C	SCHOTTKY LOSSES W	DESIGN OPERATING T_J °C	R_{JA} °C/W	HEATSINK R_{SA} °C/W
120NQ045	150	41.5	133	2	1.4
121NQ045	175	43.5	163	2.62	2.07

NOTES: CONDUCTION DUTY CYCLE IS 0.83
REVERSE VOLTAGE DUTY CYCLE IS 0.17
REVERSE VOLTAGE IS 34V

6. Designing for a Given Heatsink Temperature

Another consideration is whether other components are to be mounted on the heatsink with the Schottkys. Higher T_{Jmax} class Schottkys allow a higher heatsink temperature; this temperature might be too high for the other components on the same heatsink.

Sometimes, too, safety requirements may dictate that the heatsink temperature does not exceed some limit, for example 100°C. This could force the design to a larger heatsink and a Schottky with a lower rated T_{Jmax}, though if heatsink temperature as such is not an issue, a better approach might be to use a separate heatsink for the "lower temperature" components.

***General Guideline 5:** If system constraints, not the Schottky's temperature capability, dictate that the heatsink temperature must be kept to some maximum, then the smallest heatsink will be obtained with the most efficient Schottky.*

In this design situation, both the maximum heatsink temperature and the maximum ambient temperature are defined. Hence the heatsink to ambient temperature rise is defined. It is therefore axiomatic that the highest heatsink thermal resistance (i.e., the smallest heatsink) will be obtained with the lowest loss Schottky.

7. Designing for High Ambient Temperature

***General Guideline 6:** Selection of a larger Schottky can facilitate operation at a higher ambient temperature.*

As shown under *Guideline 3,* losses of a correctly chosen larger Schottky and the corresponding heatsink size, are smaller than for a smaller Schottky. This can be particularly helpful where the ambient temperature is high, and heatsink requirements are more stringent.

Table 8 shows a comparison of design operating points for International Rectifier 55HQ030 and 120NQ030 Schottkys, operating in the 5V, 100A power supply, at maximum design ambient temperatures of 50°C, 70° and 85°C.

TABLE 8
Comparison of losses and heatsinks required for 55HQ030 (1 x 0.200 x 0.200 Die) and 122NQ030 (2 x 0.200 x 0.200 Die), for design ambient temperatures of 50°C, 70°C, and 85°C. *(General Guideline 6).*

SCHOTTKY TYPE	T_{AMB} °C	SCHOTTKY LOSSES W	DESIGN OPERATING T_J °C	T_{JA} °C	R_{JA} °C/W	R_{JS} °C/W	HEATSINK R_{SA} °C/W
55HQ030	50	26	137	87	3.35	1.08	2.27
	70	26	138	68	2.62		1.54
	85	26	139	54	2.08		1.0
122NQ030	50	20.4	130	80	3.92	0.55	3.37
	70	20.5	134	64	3.12		2.57
	85	20.8	136	51	2.45		1.9

NOTES: CONDUCTION DUTY CYCLE IS 0.5
CURRENT IS 100A
REVERSE VOLTAGE DUTY CYCLE IS 0.5
REVERSE VOLTAGE IS 11.4V

The size of the heatsink required for the larger 120NQ030, particularly for ambient temperatures of 70°C and 85°C, will be considerably smaller than that needed for the smaller 50HQ030.

***General Guideline 7:** The higher the ambient temperature, the more a Schottky with a higher rated T_{Jmax} will help reduce the heatsink size.*

As ambient temperature increases, the allowable margin between junction and ambient temperature shrinks less rapidly for a Schottky with a higher rated T_{Jmax}. Thus, the required thermal resistance of the heatsink shrinks less rapidly. An example, chosen particularly to illustrate the point, is summarized in Table 9.

TABLE 9
Comparison of losses and heatsinks required for 150°C and 175°C "T_J Class" Schottkys, at ambient temperatures of 50°C and 70°C. *(General Guideline 7).*

SCHOTTKY TYPE	T_{Jmax} RATING	T_{AMB}	SCHOTTKY LOSSES	DESIGN OPERATING T_J	T_{JA}	HEATSINK R_{SA}
	°C	°C	W	°C	°C	°C/W
120NQ045	150	50	73.5	135	85	0.61
		70		137	67	0.36
121NQ045	175	50	76.5	162	112	0.91
		70		163	93	0.66

NOTES: SCHOTTKY S2 IN FORWARD CONVERTER ON INDIVIDUAL HEATSINK
CONDUCTION DUTY CYCLE IS 0.83
CURRENT IS 150A
REVERSE VOLTAGE DUTY CYCLE IS 0.17
REVERSE VOLTAGE IS 34V

At a 50°C ambient, the 150°C rated 120NQ045 requires a heatsink with a thermal resistance of 0.61°C/W; the 175°C rated 121NQ045 requires a heatsink thermal resistance of 0.91°C/W.

At 70°C ambient, the 150°C Schottky needs a heatsink with an ultra-low thermal resistance of 0.36°C per watt. The heatsink thermal resistance required for the 175°C rated Schottky is about 83% higher, and much more achievable.

8. Selecting the Right Voltage Class

General Guideline 8: Within a given T_{Jmax} class, lowest losses and smallest heatsink will usually be obtained by selecting the Schottky from the lowest voltage class that is compatible with the circuit voltage.

A lower voltage class Schottky has lower forward voltage drop and lower conduction losses. Reverse leakage losses of a lower voltage Schottky will be somewhat higher. But generally total losses will be lower and heatsink size smaller, for the Schottky with the lowest voltage class compatible with the circuit operating voltage.

A typical example is summarized in Table 10. The heatsink and losses of a "correctly chosen" 30V rated 122NQ030, versus those of a 45V rated 120NQ045, in a 5V, 150A bridge converter, are compared. Losses of the 30V Schottky are 9.6% of the output power, versus 11.8% for the 45V rated Schottky. The heatsink for the 30V Schottky has 17% higher thermal resistance and will be appropriately smaller.

TABLE 10
Comparison of losses and heatsinks for 30V and 45V class, 150°C class Schottkys, for a 5V 150A bridge converter. *(General Guideline 8).*

SCHOTTKY TYPE	T_{Jmax} RATING	VOLTAGE RATING	CONDUCTION LOSSES PER SCHOTTKY	REVERSE LOSSES PER SCHOTTKY	TOTAL LOSSES BOTH SCHOTTKYS % POWER OUT	DESIGN OPERATING JUNCTION TEMP.	MAXIMUM SINK TEMP.	HEATSINK THERMAL RESISTANCE
	°C	V	W	W	%	°C	°C	°C/W
122NQ030	150	30	34.2	1.6	9.6	130	110	0.84
120NQ045	150	45	43.1	1.25	11.8	138	114	0.72

NOTE: INPUT VOLTAGE RANGE IS 2:1

IV. OPERATING CONDITIONS IMPOSED ON THE SCHOTTKYS IN SWITCHING POWER SUPPLIES

A prerequisite to designing a Schottky into a power supply is to define the operating current and voltage waveforms that are imposed on the Schottkys. These operating waveforms depend upon the circuit.

Figures 27, 29, and 31, show the most common "forward," "bridge" and "flyback" switching power supply circuits respectively. Idealized current and voltage waveforms for each circuit are shown in Figures 28, 30, and 32 respectively.

Regulation of the output voltage is achieved by controlling the conduction duty cycle of the switching transistor (or transistors). As the input voltage increases, the conduction duty cycles of the Schottkys change; peak Schottky voltage increases, and the voltage-duty cycle (i.e., the portion of the cycle during which reverse voltage is applied) decreases.

Calculation of the conduction power losses of the Schottkys requires definition of the current waveforms, and of the range of conduction duty cycle. Calculation of the reverse power losses requires definition of the reverse voltage applied to the Schottkys and of the associated voltage-duty cycle.

The current and voltage operating conditions will now be examined. It will be assumed that the maximum conduction duty cycle of the switching transistor (or transistors) is 0.5, at the extreme end of the operating range where the input voltage is minimum and the output current is maximum. At this point, the PWM controller works "flat out" to deliver the required output voltage. As load current decreases, or as input voltage increases, the transistor conduction duty cycle is cut back by the PWM controller to maintain a constant output voltage.

TABLE 9
Comparison of losses and heatsinks required for 150°C and 175°C "T_J Class" Schottkys, at ambient temperatures of 50°C and 70°C. *(General Guideline 7).*

SCHOTTKY TYPE	T_{Jmax} RATING °C	T_{AMB} °C	SCHOTTKY LOSSES W	DESIGN OPERATING T_J °C	T_{JA} °C	HEATSINK R_{SA} °C/W
120NQ045	150	50	73.5	135	85	0.61
		70		137	67	0.36
121NQ045	175	50	76.5	162	112	0.91
		70		163	93	0.66

NOTES: SCHOTTKY S2 IN FORWARD CONVERTER ON INDIVIDUAL HEATSINK
CONDUCTION DUTY CYCLE IS 0.83
CURRENT IS 150A
REVERSE VOLTAGE DUTY CYCLE IS 0.17
REVERSE VOLTAGE IS 34V

At a 50°C ambient, the 150°C rated 120NQ045 requires a heatsink with a thermal resistance of 0.61°C/W; the 175°C rated 121NQ045 requires a heatsink thermal resistance of 0.91°C/W.

At 70°C ambient, the 150°C Schottky needs a heatsink with an ultra-low thermal resistance of 0.36°C per watt. The heatsink thermal resistance required for the 175°C rated Schottky is about 83% higher, and much more achievable.

8. Selecting the Right Voltage Class

General Guideline 8: Within a given T_{Jmax} class, lowest losses and smallest heatsink will usually be obtained by selecting the Schottky from the lowest voltage class that is compatible with the circuit voltage.

A lower voltage class Schottky has lower forward voltage drop and lower conduction losses. Reverse leakage losses of a lower voltage Schottky will be somewhat higher. But generally total losses will be lower and heatsink size smaller, for the Schottky with the lowest voltage class compatible with the circuit operating voltage.

A typical example is summarized in Table 10. The heatsink and losses of a "correctly chosen" 30V rated 122NQ030, versus those of a 45V rated 120NQ045, in a 5V, 150A bridge converter, are compared. Losses of the 30V Schottky are 9.6% of the output power, versus 11.8% for the 45V rated Schottky. The heatsink for the 30V Schottky has 17% higher thermal resistance and will be appropriately smaller.

IV. OPERATING CONDITIONS IMPOSED ON THE SCHOTTKYS IN SWITCHING POWER SUPPLIES

A prerequisite to designing a Schottky into a power supply is to define the operating current and voltage waveforms that are imposed on the Schottkys. These operating waveforms depend upon the circuit.

Figures 27, 29, and 31, show the most common "forward," "bridge" and "flyback" switching power supply circuits respectively. Idealized current and voltage waveforms for each circuit are shown in Figures 28, 30, and 32 respectively.

Regulation of the output voltage is achieved by controlling the conduction duty cycle of the switching transistor (or transistors). As the input voltage increases, the conduction duty cycles of the Schottkys change; peak Schottky voltage increases, and the voltage-duty cycle (i.e., the portion of the cycle during which reverse voltage is applied) decreases.

Calculation of the conduction power losses of the Schottkys requires definition of the current waveforms, and of the range of conduction duty cycle. Calculation of the reverse power losses requires definition of the reverse voltage applied to the Schottkys and of the associated voltage-duty cycle.

The current and voltage operating conditions will now be examined. It will be assumed that the maximum conduction duty cycle of the switching transistor (or transistors) is 0.5, at the extreme end of the operating range where the input voltage is minimum and the output current is maximum. At this point, the PWM controller works "flat out" to deliver the required output voltage. As load current decreases, or as input voltage increases, the transistor conduction duty cycle is cut back by the PWM controller to maintain a constant output voltage.

TABLE 10
Comparison of losses and heatsinks for 30V and 45V class, 150°C class Schottkys, for a 5V 150A bridge converter. *(General Guideline 8).*

SCHOTTKY TYPE	T_{Jmax} RATING °C	VOLTAGE RATING V	CONDUCTION LOSSES PER SCHOTTKY W	REVERSE LOSSES PER SCHOTTKY W	TOTAL LOSSES BOTH SCHOTTKYS % POWER OUT %	DESIGN OPERATING JUNCTION TEMP. °C	MAXIMUM SINK TEMP. °C	HEATSINK THERMAL RESISTANCE °C/W
122NQ030	150	30	34.2	1.6	9.6	130	110	0.84
120NQ045	150	45	43.1	1.25	11.8	138	114	0.72

NOTE: INPUT VOLTAGE RANGE IS 2:1

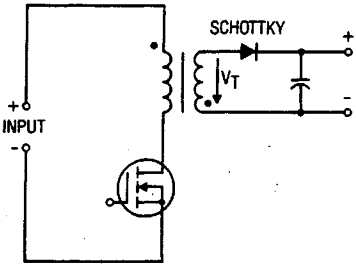


Figure 31. Basic schematic of flyback converter.

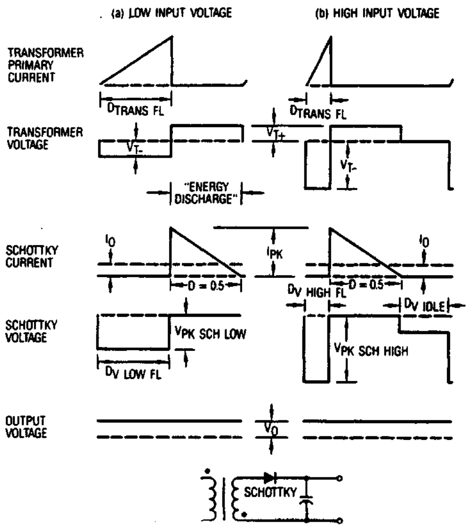


Figure 32. Idealized Schottky voltage and current waveforms in flyback converter.

A. Forward and Double Forward Converters

Forward and Double Forward converters impose essentially the same operating current and voltage waveforms on the output Schottky rectifiers.

The output rectifier circuit and idealized waveforms are shown in Figure 28.

1. Schottky Current and Conduction Duty Cycle

Low Input Voltage

At full load and low input voltage, the conduction duty cycle of Schottky 1 is:

$$D_{1maxFL} = 0.5 \qquad (1)$$

Likewise, the conduction duty cycle of Schottky 2 is:

$$D_{2minFL} = 0.5 \qquad (2)$$

At all conduction duty cycles, each Schottky is assumed to carry a constant current, I_O, throughout its conduction period. (This ignores the small super-imposed ripple component.)

High Input Voltage

At full load and high input voltage, the conduction duty cycle of Schottky 1 is:

$$D_{1minFL} = 0.5 \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \qquad (3)$$

The conduction duty cycle of Schottky 2 is

$$D_{2maxFL} = 1 - D_{1minFL}$$

$$= 1 - 0.5 \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \qquad (4)$$

$V_{IN\ LOW\ FL}/V_{IN\ HIGH\ FL}$ is the ratio of low to high input voltage at full output current.

2. Schottky Voltage and Voltage-Duty Cycle

The general relationship between the peak transformer voltage, V_T, (which is essentially the same as the peak Schottky voltage, $V_{PK\ SCH}$) the output voltage, V_O, and the conduction duty cycle D_{1FL} of Schottky 1, at full output current is:

$$V_T = \frac{(1 + y)\ V_O + V_F}{D_{1FL}} \qquad (5)$$

$$= V_{PK\ SCH}$$

where y = voltage drop across the smoothing inductor at full load, expressed as a fraction of V_O

V_F = forward voltage drop of Schottky at full current

Substituting a typical value for y, of 0.04, and for V_F, of 0.5, gives:

$$V_T = V_{PK\ SCH} = \frac{1.04\ V_O + 0.5}{D_{1FL}} \qquad (6)$$

Low Input Voltage

Substituting $D_{1maxFL} = 0.5$ (equation (1)), into equation (6), the peak Schottky voltage at low input voltage and full load is:

$$V_{P\ SCH\ LOW} = \frac{1.04V_O + 0.5}{0.5} \qquad (7)$$

The voltage-duty cycle at full load and low input voltage, $D_{V\ LOW\ FL}$, is:

$$D_{V\ LOW\ FL} = D_{ImaxFL} = 0.5 \quad (8)$$

High Input Voltage

Substituting for D_{IminFL} (equation (3)) into equation (6), the peak Schottky voltage at high input voltage and full load is:

$$V_{PK\ SCH\ HIGH} = \frac{(1.04V_O + 0.5)}{0.5} \frac{V_{IN\ HIGH\ FL}}{V_{IN\ LOW\ FL}} \quad (9)$$

The voltage duty cycle at full load and high input voltage, $D_{V\ HIGH\ FL}$, is:

$$D_{V\ HIGH\ FL} = D_{IminFL}$$

$$= 0.5 \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \quad (10)$$

The above assumes that the input voltage has a steady value of $V_{IN\ HIGH\ FL}$. In practice, this voltage will have some superimposed ripple.

The actual peak Schottky voltage could perhaps be 10% higher than that given by equation (9). The Schottky voltage will also be somewhat higher than given by equation (9) at no load, due to "natural" input voltage rise as load current decreases.

B. Half- and Full-Bridge Circuits

Half- and Full-Bridge converters impose essentially the same operating waveforms on the Schottky output rectifiers.

The output rectifier circuit and idealized current and voltage waveforms are shown in Figure 30.

1. Schottky Current and Conduction Duty Cycle

Low Input Voltage

At full load and low input voltage, the conduction duty cycles of both Schottkys are

$$D_{maxFL} = 0.5 \quad (11)$$

Each Schottky is assumed to carry a constant current I_O throughout its conduction period.

High Input Voltage

At full load and high input voltage, each Schottky carries the full load current I_O for duty cycle D_{minFL}, given by:

$$D_{minFL} = 0.5 \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \quad (12)$$

During the intervening "freewheeling" periods, each Schottky carries half the full load current, $I_O/2$, for a total duty cycle D'_{maxFL}, given by:

$$D'_{maxFL} = 1 - \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \quad (13)$$

2. Schottky Voltage and Voltage Duty Cycle

Inspection of the voltage waveforms in Figures 28 and 30 shows that the relationships between peak Schottky voltage, output voltage, and input voltage are the same for the bridge circuits as for the forward converter circuits.

Equations (7) through (10) therefore apply.

C. Flyback Circuit

The flyback circuit can be operated in either of two different modes. Energy stored in the transformer secondary during the flyback period can either be partially discharged or totally discharged. The latter mode is common and will be assumed here.

The output rectifier circuit, and idealized waveforms of current and voltage associated with the "total energy discharge" mode, are shown in Figure 32.

1. Schottky Current and Conduction Duty Cycle

The duration of the energy discharge period, during which the Schottky conducts, is a function of the output voltage, the output current, and the inductance of the transformer's secondary. It is *not* related to the power supply's input voltage.

Thus, for a given output voltage and full load output current, the Schottky conduction period remains *constant,* regardless of the input voltage. Thus, the Schottky's full load conduction duty cycle typically will remain constant at 0.5, independent of the input voltage. This is assumed to be the case here.

Unlike the case in the forward and bridge converters, the Schottky current waveform is triangular, as illustrated. The current ramps down from an initial peak, I_{PK}, of 4x the average load current, to zero, over half the output cycle.

The average and rms values of the Schottky current are:

$$I_{AV\ SCH} = I_O \quad (14)$$

$$I_{RMS\ SCH} = 4 \frac{I_O}{\sqrt{3}} \quad (15)$$

2. Schottky Voltage and Voltage Duty Cycle

During the Schottky conduction period, the positive transformer secondary voltage is:

$$V_{T+} = V_O + V_F \tag{16}$$

where V_F is the Schottky's forward voltage drop. Assuming V_F has a nominal value of 0.5V, then:

$$V_{T+} = V_O + 0.5 \tag{17}$$

During the transistor conduction period, D_{TRANS}, the negative voltage-integral across the transformer secondary is equal and opposite to the voltage integral during the Schottky's conduction period. Therefore:

$$V_{T-} D_{TRANS\ FL} = (V_O + 0.5)\ 0.5 \tag{18}$$

The peak Schottky voltage, $V_{PK\ SCH}$, during the transistor conduction period is the sum of V_O and V_T.

$$V_{PK\ SCH} = V_O + \frac{(V_O + 0.5)\ 0.5}{D_{TRANS\ FL}} \tag{19}$$

The corresponding voltage duty cycle is:

$$D_{V\ FL} = D_{TRANS\ FL} \tag{20}$$

During the idle period, when both the transistor and the Schottky are OFF:

$$V_{PK\ SCH} = V_O \tag{21}$$

The corresponding idle voltage duty cycle is:

$$D_{V\ IDLE} = 0.5 - D_{TRANS} \tag{22}$$

Low Input Voltage

At low input voltage and full load, $D_{TRANS\ FL} = 0.5$. Substituting into equation (19):

$$V_{PK\ SCH\ LOW} = V_O + (V_O + 0.5)$$

$$= 2\ V_O + 0.5 \tag{23}$$

Substituting into equation (20):

$$D_{V\ LOW\ FL} = 0.5 \tag{24}$$

High Input Voltage

The conduction duty cycle of the transistor at full load and high input voltage is:

$$D_{TRANS} = 0.5\ \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \tag{25}$$

Substituting into equation (19):

$$V_{PK\ SCH\ HIGH} = V_O + (V_O + 0.5)\ \frac{V_{IN\ HIGH\ FL}}{V_{IN\ LOW\ FL}} \tag{26}$$

Substituting into equation (20) and (25):

$$D_{V\ HIGH\ FL} = D_{TRANS\ FL}$$

$$= 0.5\ \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \tag{27}$$

Substituting into equation (22) and (25):

$$D_{V\ IDLE} = 0.5 - D_{TRANS}$$

$$= 0.5 - 0.5\ \frac{V_{IN\ LOW\ FL}}{V_{IN\ HIGH\ FL}} \tag{28}$$

As load current decreases, the conduction duty cycle of the transistor will decrease, shortening the period during which the Schottky is exposed to the highest peak voltage.

The amplitude of the peak Schottky voltage will increase somewhat above that given by equation (26), due to natural voltage rise as load current diminishes.

D. Summary of Circuit Operating Conditions

1. General Relationships

Table 11 gives a summary of the general relationships between Schottky current, output current, and input voltage range, and between Schottky voltage, output voltage, voltage duty cycle and input voltage range, for forward, bridge, and flyback circuits.

2. Quantification of Output Voltage and Input Voltage Range, as a Function of Schottky Voltage Rating

The output voltage and permissible range of input voltage, against which the power supply is able to maintain a constant output voltage, can now be quantitatively established for each Schottky voltage class, for each type of power supply circuit considered. Table 12 gives a summary. This information is derived from the general relationships shown in Table 11.

Table 12 assumes that the maximum Schottky voltage at full load and maximum input voltage is about 75% of the Schottky's repetitive voltage rating. This leaves about a 33% margin for switching voltage transients. This will generally be adequate, especially in view of the transient avalanche capability of International Rectifier Schottkys.

TABLE 11
General relationships for Schottky current and voltage.

CIRCUIT	SCHOTTKY CURRENT @ DUTY CYCLE				SCHOTTKY VOLTAGE @ DUTY CYCLE	
	AT MINIMUM INPUT VOLTAGE		AT MAXIMUM INPUT VOLTAGE		AT FULL LOAD, MINIMUM INPUT VOLTAGE	AT FULL LOAD, MAXIMUM INPUT VOLTAGE
	S1	S2	S1	S2	S1 AND S2	S1 AND S2
FORWARD CONVERTER DOUBLE FORWARD CONVERTER	I_O @ 0.5	I_O @ 0.5	I_O @ $0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$	I_O @ $1 - 0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$	$2\,(1.04\ V_O + 0.5)$ @ 0.5	$2\,(1.04\ V_O + 0.5) \frac{V_{IN\ HIGH}}{V_{IN\ LOW}}$ @ $0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$
HALF BRIDGE FULL BRIDGE	I_O @ 0.5	I_O @ 0.5	I_O @ $0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$ AND $\frac{I_O}{2}$ @ $1 - \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$		$2\,(1.04\ V_O + 0.5)$ @ 0.5	$2\,(1.04\ V_O + 0.5) \frac{V_{IN\ HIGH}}{V_{IN\ LOW}}$ @ $0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$
FLYBACK	$I_{PK} = 4\ I_O$ @ 0.5	—	$I_{PK} = 4\ I_O$ @ 0.5	—	$2\,(V_O + 0.5)$ @ 0.5	$(0.5 + V_O) \frac{V_{IN\ HIGH}}{V_{IN\ LOW}} + V_O$ @ $0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$ AND V_O @ $0.5 - 0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$

TABLE 12
Output voltage and input voltage range versus Schottky voltage class.

SCHOTTKY VOLTAGE CLASS	OUTPUT VOLTAGE	FORWARD, DOUBLE FORWARD, HALF-BRIDGE AND BRIDGE CONVERTERS			FLYBACK CONVERTERS		
		MAXIMUM RATIO HIGH TO LOW INPUT VOLTAGE	TYPICAL AC LINE INPUT VOLTAGE RANGE	MAXIMUM SCHOTTKY VOLTAGE (EXCLUDING TRANSIENTS)	MAXIMUM RATIO HIGH TO LOW INPUT VOLTAGE	TYPICAL AC LINE INPUT VOLTAGE RANGE	MAXIMUM SCHOTTKY VOLTAGE (EXCLUDING TRANSIENTS)
30	2.5	3.5:1	80 TO 280	22			
30	5	2:1	80 TO 160 160 TO 320	23	3:1	85 TO 255	22
45	5	3:1	85 TO 255	34	5:1	60 TO 300	33
	12				1.75:1	90 TO 155 180 TO 310	34
60	5	4:1	65 TO 260	46			
	12	1.7:1	90 TO 155 180 TO 310	44	2.6:1	65 TO 170 130 TO 340	45
	15				2:1	80 TO 160 150 TO 300	46
100	12	3:1	85 TO 255	78	5:1	60 TO 300	75
	15	2.3:1	70 TO 160	74	4:1	75 TO 300	77
150	15	3.4:1	80 TO 270	110	6:1	60 TO 360	108

E. Impact of Input Power Factor Correction

It has been tactily assumed so far that a conventional line input rectifier, as shown in Figure 33(a), is used to convert the incoming ac line voltage to primary dc voltage. The steady state primary voltage rises and falls in direct relationship to rising and falling ac line input voltage. The conduction duty cycle of the transistor (or transistors) in the high frequency switching converter is regulated to keep a fixed output voltage.

In a "universal" power supply, designed to operate from nominal line voltages of, say, 115 and 240V, (without change of input rectifier circuit connection), the total range of conduction duty cycle of the transistors could be about 3 to 1. The output Schottkys would, therefore, be exposed to about a 3 to 1 range of applied reverse voltage.

While such designs are common, particularly at lower power levels, many higher power designs, (above a few hundred watts) are expected in future to use a primary boost converter, as shown in Figure 33(b).

The major purpose of the boost converter is to correct the power factor of the input ac line current, by actively forcing a sinusoidal ac line current to flow. A secondary benefit of the boost converter is that its output voltage — the voltage across the reservoir capacitor C — can be regulated to a constant value, as the input ac line voltage varies. For example, the output voltage of the boost converter could be held at 400V, over a range of input line voltage from, say, 80 to 280V.

With this front-end regulation, the high frequency switching converter is not exposed to widely varying input voltage, and therefore does not need to provide a wide range of conduction angle control, at least in normal operation.

A reduced range of input voltage for the switching converter means a lower peak voltage applied to the output Schottkys. This opens the door for improving the efficiency of the output rectifier by using Schottkys with a lower V_{RRM} class and correspondingly lower forward voltage drop.

In the ideal case (for the Schottkys), a design could be conceived where each Schottky operates at a constant 50% conduction duty cycle, and is exposed to just twice the output voltage. Thus, a 5V power supply could use a 15V Schottky.

A common design requirement, though, must not be ignored. This is that the output power must be maintained, uninterrupted, in the event of transient (typically one or two cycle) loss of input ac line voltage. When this occurs, the input boost converter can no longer keep a constant voltage on the primary reservoir capacitor, because temporarily there is "nothing to boost." The reservoir capacitor must now continue to deliver energy to the load, while holding a sufficient voltage that the switching converter, by its own pulse width control, can maintain the required output voltage.

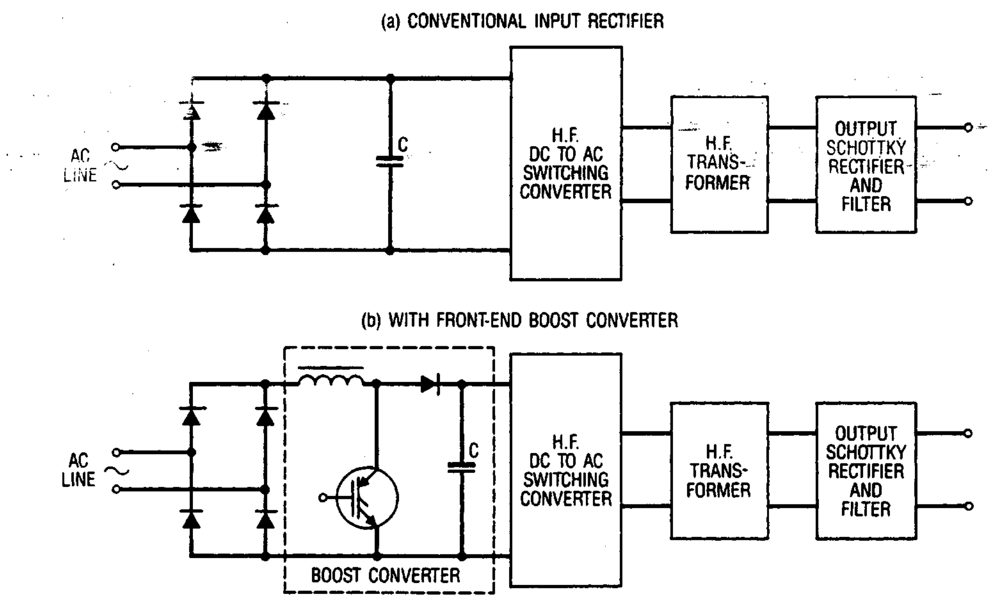


Figure 33. Functional diagrams of switching power supplies with (a) conventional input line rectifier and with (b) boost converter to correct the input line power factor.

How much the voltage on the primary reservoir capacitor will decay under this transient condition depends upon the duration of the power outage, and the size of the reservoir capacitor. In any event, the only means of regulating the output voltage in this situation is by duty cycle control of the transistors of the switching converter. This means, unfortunately, that the normal operating duty cycle of the switching converter must be cut back to keep the necessary reserve in hand for temporary line outages. The resulting peak voltage applied to the Schottkys will be less than the ideal minimum.

Thus, though the range of Schottky conduction duty cycle and applied reverse voltage can be reduced by a front-end boost converter, some range of regulation within the switching converter will often still be needed, and the required Schottky voltage rating will "suffer" accordingly.

Nonetheless, for a given output voltage, it will often be possible to "drop down" a Schottky voltage class. Thus, a 5V power supply might now typically use a 30V rated Schottky, where previously it needed a 45V rating. Likewise, 12 and 15V power supplies might drop from 60 or 100V Schottkys, to 45V types.

The required Schottky voltage rating will depend upon the duration of ac line outage over which output power must be maintained, and upon the size the primary reservoir capacitor.

Table 13 shows the range of primary voltage droop permissible for various "reduced voltage class" Schottkys, for 5, 12, and 15V outputs, where a front-end regulator is used. It is assumed that the peak voltage applied to the Schottky (exclusive of switching transients) would be about 70% of the rated repetitive working voltage.

TABLE 13

Permissible voltage drop on primary reservoir (boost converter) capacitor, for various V_{RRM} class Schottkys and various output voltages.

SCHOTTKY V_{RRM} CLASS	OUTPUT VOLTAGE	MAX. PERMISSIBLE TRANSIENT VOLTAGE DROOP P.U. OF NOMINAL OPERATING VOLTAGE
15	2.5	0.6
30	5	0.5
45	12	0.82
60	12	0.6
	15	0.77

CIRCUIT-RELATED DESIGN GUIDELINES

Guideline 1.

In a Forward Converter with two similar Schottkys, Schottky 2 generally has greater losses than Schottky 1. The heatsink must be sized to keep the junction temperature of Schottky 2 within safe limits, under the worst-case condition of high input voltage and full load current.

Guideline 2.

Judicious selection of "Mixed Schottkys" for a Forward Converter that operates over a wide range of input voltage can allow Schottky 1 to be a "lower-rated" device than Schottky 2. Total losses will be a little higher, but heatsink size will be virtually the same.

Guideline 3.

A common heatsink for both Schottkys in a Forward Converter allows the Schottky with the highest losses to take advantage of the other's "share" of heatsink. The size of a single common heatsink will generally be physically smaller than the combined size of the heatsinks needed for each Schottky individually.

Guideline 4.

Total Schottky losses in the Forward and Bridge converters are essentially the same, using the same Schottkys. The heatsink for a Bridge converter, however, can be significantly smaller, because the symmetrical operation of the Bridge versus the assymetrical operation of the Forward converter results in equal power sharing between the Schottkys and a lower individual junction to sink temperature rise.

Guideline 5.

Schottkys of a given die size and process type have essentially the same worst-case design losses, regardless of their package type, for given output current, output voltage, and input voltage range. But Schottky package type will determine heatsink thermal resistance.

Guideline 6.

In a Flyback Converter, a 175°C rated Schottky will generally offer similar or better efficiency, while requiring a significantly smaller heatsink, than a 150°C rated Schottky.

Figure 34. Summary of **circuit-related** design guidelines.

V. DESIGNING THE SCHOTTKY INTO A SWITCHING POWER SUPPLY

General guidelines have been presented that outline the fundamental basics behind choosing a Schottky, sizing the heatsink and setting a safe operating temperature.

Knowing a power supply's output voltage, output current, input voltage range and maximum ambient temperature, and having tentatively chosen a candidate Schottky, the engineer can now get down to the final design task of determining the required heatsink thermal resistance, operating junction temperature, and worst-case losses.

It will generally be assumed, for Forward and Bridge converters, that both Schottkys are mounted on a common heatsink. (The Flyback converter, of course, has only one Schottky.) A common heatsink is inherent for a dual Schottky, where both rectifiers are housed in a single package. It will also be the most frequent choice where individual Schottkys are used.

During the course of the following design presentation, several important points relating to Schottky requirements and their performance in the different circuits will emerge. These *Circuit Related Guidelines* are collected together in Figure 34, and are offered, for the moment, without explanation. Each will be discussed as it is encountered.

A. Heatsink Temperature Determined by Schottky Temperature Capability

It is assumed in the following sections, that for any chosen Schottky, of whatever T_{Jmax} or V_{RRM} class, the objective is to minimize the size of the heatsink, consistent only with maintaining a safe operating temperature margin for the Schottkys.

In some designs an overriding requirement may exist that the heatsink temperature must not exceed a given maximum. Depending upon the choice of Schottky, this may or may not be coincidentally satisfied by a "minimum heatsink" design. If not, the heatsink size will have to be increased beyond the minimum that gives a safe thermal design for the Schottky. This design situation will be addressed later.

1. Forward and Double-Forward Converters

a. Schottky 1 and Schottky 2 the same

The design procedure will be illustrated by considering a 200A, 5V forward (or double-forward) converter, using two International Rectifier 240NQ045 Schottkys. The maximum ambient temperature is 50°C; the range of input voltage variation is 3:1.

As defined in Table 11, the range of conduction duty cycle of Schottky 1 is 0.5 to 0.17, and of Schottky 2, the range is 0.5 to 0.83. The maximum reverse voltage applied to each Schottky occurs at maximum input voltage and is 34V (excluding switching transients), at a duty cycle of 0.17.

Operation at high input voltage

The worst-case design operating condition will be at full output current and high input voltage. At this point, Schottky 2 carries the output current for most of the cycle (83%) and will have significantly higher losses than Schottky 1. The heatsink must be sized to ensure that Schottky 2 operates safely within its thermal limits at this point.

The first step in determining the heatsink thermal resistance is to derive the relationship between the total (forward and reverse) losses of each Schottky, at full load and high input voltage, as a function of junction temperature.

The conduction losses of Schottky 1 at junciton temperature T_J are:

$$P_{COND1} = I_O \bullet (V_F @ I_O @ T_J) \bullet D_{1\,minFL} \qquad \textbf{(29)}$$

where I_O is the output current and $(V_F @ I_O @ T_J)$ is the limiting forward voltage drop at current I_O and junction temperature T_J.

The reverse losses of Schottky 1 at junction temperature T_J are:

$$P_{REV1} = V_R \bullet (I_R @ V_R @ T_J) \bullet D_{1minFL} \qquad \textbf{(30)}$$

where V_R is the applied reverse voltage and $(I_R @ V_R @ T_J)$ is the maximum reverse leakage current at reverse voltage V_R and junction temperature T_J.

The total losses of Schottky 1 at junction temperature T_J are:

$$P_{TOT1} = P_{COND1} + P_{REV1} \qquad \textbf{(31)}$$

The conduction losses of Schottky 2 at junction temperature T_J are:

$$P_{COND2} = I_O \bullet (V_F @ I_O @ T_J) \bullet (1 - D_{1minFL}) \qquad \textbf{(32)}$$

The reverse losses of Schottky 2 at junction temperature T_J are:

$$P_{REV2} = V_R \bullet (I_R @ V_R @ T_J) \bullet D_{1minFL} \qquad \textbf{(33)}$$

The total losses of Schottky 2 at junction temperature T_J are:

$$P_{TOT2} = P_{COND2} + P_{REV2} \qquad \textbf{(34)}$$

Figure 35 shows the power losses of Schottkys 1 and 2, as a function of junction temperature, calculated from equations (29) through (33), for the 240NQ045 Schottkys operating in the above 200A 5V Forward Converter, at the worst-case asymmetrical operating condition, at which D_{1minFL} is 0.17.

The forward voltage drop and reverse leakage current data given in the data sheet for the 240NQ045 have been used to calculate the losses. The relationships given in the data sheet between reverse leakage current, junction temperature and reverse voltage, are representative of a typical device. A conservative multiplier of 1.5 has been applied to the reverse loss component of the total losses shown in Figure 35, to represent an absolute worst-case design.

We are now set to calculate the required thermal resistance of the heatsink. As discussed in Section A1, a good design criterion is to base the heatsink thermal resistance on the hypothetical scenario that it would take an increase of 10°C in the *ambient* temperature *above* the design maximum, for the Schottky's operating junction temperature to reach T_{Jmax}.

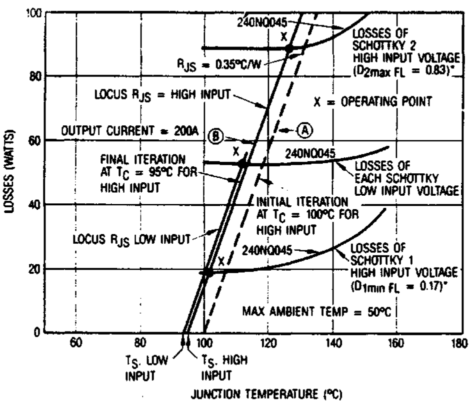
The total losses under this hypothetical scenario can be conservatively estimated by assuming that both Schottkys would simultaneously operate at T_{Jmax}. This is pessimistic, because Schottky 1 actually runs cooler than Schottky 2; therefore, the total losses assumed for it would be a bit higher than "reality," (adding a bit more conservatism to the resulting design).

From the power loss curves for Schottky 1 and Schottky 2 in Figure 35:

$$P_{TOT2} = 99\ \text{W} \ @\ T_J = 150°\text{C}$$

$$P_{TOT1} = 33\ \text{W} \ @\ T_J = 150°\text{C}$$

$$P_{TOT1} + P_{TOT2} = 132\ \text{W}$$



Notes: Conduction duty cycle at high input is 0.17/0.83 for Schottky 1 and 2
Conduction duty cycle at low input is 0.5/0.5 for Schottky 1 and 2
Reverse voltage duty cycle at high input is 0.17/0.17 for Schottky 1 and 2
Reverse voltage at high input is 34V
Reverse voltge duty cycle at low input is 0.5/0.5 for Schottky 1 and 2
Reverse voltage at low input is 11.4V
*See Figure 28

Figure 35. Operating characteristics for 200A, 5V forward converter "same Schottky" design. Both Schottkys are 240NQ045. *(Common Heatsink).*

The junction to ambient temperature rise of Schottky 2 under this condition is:

$$T_{JA,S2} = 150 - (T_{AMB} + 10)$$

$$= 150 - (50 + 10)$$

$$= 90°\text{C}$$

$$T_{JS,S2} = P_{TOT2}\, R_{JS2}$$

$$= 99 \bullet 0.35$$

$$= 34.7°\text{C}$$

$$T_{SA} = T_{JA,S2} - T_{JS,S2}$$

$$= 90 - 34.7$$

$$= 55.3°\text{C}$$

$$R_{SA} = \frac{T_{SA}}{(P_{TOT1} + P_{TOT2})}$$

$$= \frac{55.3}{132}$$

$$= 0.42°\text{C/W}$$

Having determined the required heatsink thermal resistance, it remains now to determine the operating points for Schottkys 1 and 2, at the actual maximum design ambient temperature of 50°C.

This is done by a simple reiterative procedure:

Start by picking a sink temperature T_S (for example, 100°C.) In Figure 35, draw the straight line locus of $R_{J\text{-}S}$ (0.35°C/W for the 240NQ045) that intersects the temperature axis at 100°C (Line A). Read the losses of Schottky 1 and Schottky 2 at the intersection points of line A with the Schottky loss curves:

$$P_{TOT2} = 89.5\ \text{W}$$

$$P_{TOT1} = 19\ \text{W}$$

Compare the already established design value of R_{SA} (0.42°C/W) with the value of R_{SA} that would yield the assumed sink to ambient temperature rise (in this case, 100 - 50 = 50°C), when operating with the above combined Schottky losses:

$$R_{SA} = \frac{100 - 50}{89.5 + 19}$$

$$= 0.46°\text{C/W}$$

The above value of R_{SA} is higher than the already established known design value. Therefore, the originally assumed value of T_S of 100°C was too high.

Reiterate with a lower value of T_C. Try:

$$T_S = 95°C$$

From the intersection of the new locus (B) of R_{JS} with the Schottky loss curves:

$$P_{TOT2} = 89W \text{ (@ } T_J \text{ of } 126°C)$$

$$P_{TOT1} = 19W \text{ (@} T_J \text{ of } 102°C)$$

$$R_{SA} = \frac{95 - 50}{(89 + 19)}$$

$$= 0.42°C/W$$

The above value of R_{SA} is the already established "known" design value. Therefore the assumed value of T_S of 95°C was correct.

A summary of the above data is shown in Table 14.

Operation at low input voltage

The foregoing design analysis has dealt with the worst-case operating condition, under which the conduction duty cycle and power dissipation of Schottky 2 is much higher than that of Schottky 1. At this point Schottky 2 runs at a higher junction temperature, 126°C, versus 102°C for Schottky 1. The heatsink must, therefore, be sized to keep the necessary operating temperature margin for Schottky 2.

At the low end of the input voltage range, both Schottkys operate at the same duty cycle, (it is assumed here to be 0.5). At this point, the conduction losses of Schottky 1 will be higher than at high input voltage, while those of Schottky 2 will be lower. The combined conduction losses of both Schottkys will be about the same as at high input voltage, because the output current is the same and Schottky forward voltage drops are virtually the same (i.e., ignoring small differences of junction temperature).

At low input voltage, a much lower reverse voltage, about 11V, is applied to each Schottky. Though the voltage-duty cycle is longer (0.5 versus 0.17), the reverse losses will be lower.

Total combined forward and reverse losses of both Schottkys will, therefore, be lower and the heatsink temperature will be lower. Schottky 1, will, however, operate at a higher junction temperature than at high input voltage, because of its greater conduction duty cycle, though it will run cooler than Schottky 2 at maximum input voltage.

Losses of the two Schottkys at minimum input voltage are shown as a function of operating junction temperature in Figure 35. Given the already established heatsink thermal resistance of 0.42°C/W, the operating point x' shown in Figure 35 is determined, by the same process of reiteration used above.

The losses of each Schottky are now 52.5W, and the operating junction temperature is about 113°C.

A summary of the above data is included in Table 14.

Unbalanced operation of Schottkys in Forward Converters

At this point, the following *Circuit Related Guideline* can be summarized.

Circuit-Related Guideline 1: *In a Forward Converter with two similar Schottkys, Schottky 2 generally has greater losses than Schottky 1. The heatsink must be sized to keep the junction temperature of Schottky 2 within safe limits, under the worst-case condition of high input voltage and full load current.*

b. Schottkys 1 and 2 different

As has been seen, a Forward Converter operates at "lopsided" duty cycles for the two Schottkys. This imposes much greater losses on Schottky 2 than on Schottky 1.

TABLE 14

Summary of data for various 5V, 200A power supply designs. Max. Ambient Temperature = 50°C; Input Voltage Range = 3.1.

CIRCUIT	HEATSINK R_{SA} °C/W	SCHOTTKY 1					SCHOTTKY 2					TOTAL LOSSES BOTH SCHOTTKYS	
		TYPE	LOW INPUT VOLTAGE		HIGH INPUT VOLTAGE		TYPE	LOW INPUT VOLTAGE		HIGH INPUT VOLTAGE		LOW INPUT VOLTAGE	HIGH INPUT VOLTAGE
			LOSSES W	WKG T_J °C	LOSSES W	WKG T_J °C		LOSSES W	WKG T_J °C	LOSSES W	WKG T_J °C		
FORWARD	0.42	240NQ045	52.5	113	19	102	240NQ045	52.5	113	89	126	105	108
FORWARD	0.43	120NQ045	64	135	22.5	111	240NQ045	53	118	89	129	117	112
FORWARD	SCHOTTKY 1 0.83 SCHOTTKY 2 0.56	120NQ045	64	138	23	82	240NQ045	53	98	90	132	117	113
BRIDGE	0.61	240NQ045	53	133	47	124	240NQ045	53	133	47	124	106	94

As illustrated in Table 14, in a 200A, 5V Forward Converter, the maximum losses of Schottky 1, of 52.5W, occur at minimum input voltage; by contrast the maximum loses of Schottky 2, of 89W, occur at maximum input voltage. Schottky 1, in reality, is under-utilized; it could be replaced by a smaller device.

Assume that Schottky 1 is replaced by the lower current 120NQ045, while Schottky 2 remains a 240NQ045. Both are still mounted on the same heatsink.

The losses of each Schottky, at the minimum and maximum input voltage operating conditions, are shown as a function of junction temperature in Figure 36.

It is not immediately obvious which operating condition (high or low input voltage) will dictate the required heatsink size. At low input voltage, Schottky 1 has higher losses and will run hotter than Schottky 2, particularly because, being a smaller device, its junction to sink thermal resistance is higher.

At high input voltage Schottky 2 has higher losses, and even though it has lower thermal resistance, will probably run hotter than Schottky 1. Total combined losses of both Schottkys will probably be somewhat greater at high input voltage because reverse losses are higher.

Each operating condition needs to be examined, to ascertain which is most severe and therefore governs the choice of heatsink.

At low input voltage, Schottky 1 definitely runs hotter than Schottky 2, (because both have the same current and conduction duty cycle, and Schottky 1 is smaller than Schottky 2). The heatsink must hold the Schottky 1 junction temperature to 150°C at an ambient of (T_{AMB} + 10°C):

$$T_{JA1} = 150 - 60$$

$$= 90°C$$

$$T_{JS1} = P_{TOT1} \bullet R_{JS1}$$

$$= 65 \bullet 0.55$$

$$= 36°C$$

$$\therefore T_{SA} = 90 - 36$$

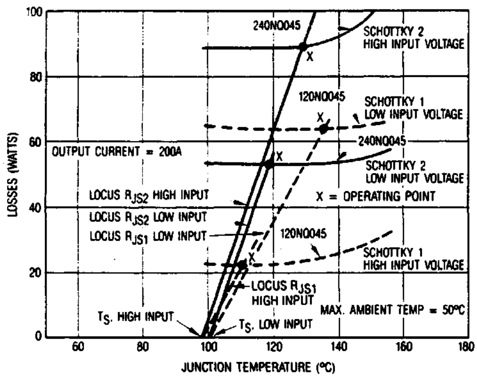
$$= 54°C$$

The total losses of both Schottkys will be assumed (conservatively) to be the sum of their losses at T_{Jmax} = 150°C

$$\therefore R_{SA} = \frac{54}{(65 + 55)}$$

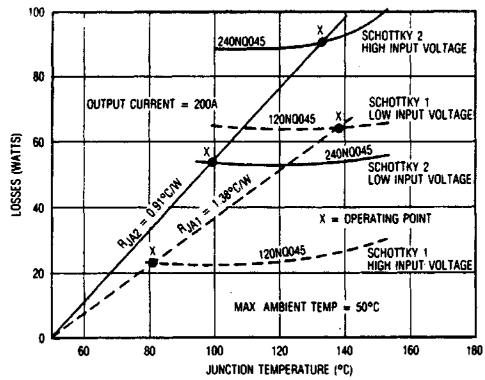
$$= 0.45°C/W \qquad \textbf{(35)}$$

At high input voltage, it needs to be checked which Schottky will have the greatest junction to sink temperature rise, under the hypothetical scenario of the operating junction temperature just reaching rated T_{Jmax} at (T_{AMB} + 10). Whichever Schottky has the greatest temperature rise under this condittion is the one which will govern the needed heatsink for this operating condition.



Notes: Conduction duty cycle at high input is 0.17/0.83 for Schottky 1 and 2
Conduction duty cycle at low input is 0.5/0.5 for Schottky 1 and 2
Reverse voltage duty cycle at high input is 0.17/0.17 for Schottky 1 and 2
Reverse voltage duty cycle at low input is 0.5/0.5 for Schottky 1 and 2
Reverse voltage at high input is 34V
Reverse voltage at low input is 11.4V

Figure 36. Operating characteristics for 200A, 5V forward converter "mixed Schottky" design. Schottky 1 is 120NQ045, Schottky 2 is 240NQ045. *(Common Heatsink).*



Notes: Conduction duty cycle at high input is 0.17/0.83 for Schottky 1 and 2
Conduction duty cycle at low input is 0.5/0.5 for Schottky 1 and 2
Reverse voltage duty cycle at high input is 0.17/0.17 for Schottky 1 and 2
Reverse voltage duty cycle at low input is 0.5/0.5 for Schottky 1 and 2
Reverse voltage at high input is 34V
Reverse voltage at low input is 1.4V

Figure 37. Operating characteristics for 200A 5V forward converter "mixed Schottky" design. Schottky 1 is 120NQ045, Schottky 2 is 240NQ045. *(Individual Heatsinks).*

Referring to Figure 36, Schottky 1 will have a junction to sink temperature rise of:

$$T_{JS1} = P_{TOT1} \bullet R_{JS1}$$

$$= 29 \bullet 0.55$$

$$= 16°C$$

Schottky 2 will have a junction to sink temperature rise of:

$$T_{JS2} = P_{TOT2} \bullet R_{JS2}$$

$$= 99 \bullet 0.35$$

$$= 34.7°C$$

Clearly, Schottky 2 governs the required heatsink.

Proceeding with the calculation for Schottky 2:

$$T_{JA2} = 150 - 60$$

$$= 90°$$

$$T_{JS2} = P_{TOT2} \bullet R_{JS2}$$

$$= 99 \bullet 0.35$$

$$= 34.7°C$$

$$\therefore T_{SA} = 90 - 34.7$$

$$= 55.3°C$$

$$\therefore R_{SA} = \frac{55.3}{99 + 29}$$

$$= 0.43°C/W \qquad (36)$$

Comparing the value of R_{SA} given by equations (35) and (36), for the low and high input voltage conditions respectively, a smaller heatsink thermal resistance (just) is required for the high input voltage condition. This, therefore, takes precedence and the required heated thermal resistance is:

$$R_{SA} = 0.43°C/W.$$

It remains now to find the actual operating point of each Schottky at the actual maximum design ambient temperature of 50°C.

Again, this is done for the minimum and maximum input voltage conditions, by assuming a sink temperature, (and hence a sink to ambient temperature difference), and drawing the locus of junction to sink thermal resistance of each Schottky, which intersects the temperature axis at the assumed sink temperature.

The losses at the intersection points of each assumed thermal resistance locus with its Schottky loss curve are summed and multiplied by the known heatsink thermal resistance of 0.43°C/W. When the resulting sink to ambient temperature equals the originally assumed value, the originally assumed sink temperature was the correct choice.

Figure 36 shows loci of the junction to sink thermal resistances of Schottkys 1 and 2 that emanate from the correct sink temperatures (98°C and 100°C) for the high and low input voltage conditions respectively.

Table 14 gives a summary of operating junction temperatures and power losses.

c. Comparison of "Same Schottky" versus "Mixed Schottky" designs

The "Same Schottky" and "Mixed Schottky" design results, shown in Table 14, call for comment.

The worst-case total losses of the "Mixed Schottky" design are about 9% higher. This is a result of substituting a smaller 120NQ045 Schottky for the larger 240NQ045, as Schottky 1.

The required heatsink, however, is virtually the same for both designs. The reason is that the worst-case design condition has shifted from Schottky 2 at high input voltage to Schottky 1 at low input voltage. This smaller Schottky can be permitted to operate at a somewhat higher junction temperature than Schottky 2 because its lower reverse leakage current requires a somewhat smaller temperature margin.

These conclusions are summarized as follows:

Circuit-Related Guideline 2: *Judicious selection of "Mixed Schottkys" for a Forward Converter that operates over a wide range of input voltage can allow Schottky 1 to be a lower-rated device than Schottky 2. Total losses will be a little higher, but heatsink size will be virtually the same.*

d. Individual heatsinks

Sometimes, where Schottkys 1 and 2 are selected as different types, to match them to the asymmetrical circuit operation, it could also be physically convenient to have each on its own heatsink, essentially thermally isolated from the other.

An individual heatsink must be sized exclusively for the highest losses of its Schottky, without being able to take relief from the fact that when one Schottky is heavily loaded, the other is lightly loaded, and vice versa.

An analysis of heatsink requirements and operating junction temperatures in the same 200A, 5V Forward Converter considered above, using mixed 120NQ045 and 240NQ045 Schottkys with individual heatsinks, is shown in Figure 37.

Schottky 1 has maximum losses at low input voltage. The locus of junction to ambient thermal resistance needed for an operating junction temperature of 150°C at (T_{AMB} + 60°C) is shown.

The intersection of the thermal resistance locus with the Schottky's power loss characteristic gives an operating junction temperature of 138°C, with corresponding losses of 64W.

$$R_{JA1} = \frac{(138 - 50)}{64}$$

$$= 1.38°C/W$$

$$\therefore R_{SA1} = R_{JA1} - R_{JS1}$$

$$= 1.38 - 0.55$$

$$= 0.83°C/W$$

Schottky 2 has maximum losses at high input voltage. The locus of junction to ambient thermal resistance needed for an operating junction temperature of 150°C at (T_{AMB} + 10) is shown.

The intersection point of the thermal resistance locus with the Schottky's power loss versus junction temperature characteristic gives an operating junction temperature of 132°C, with losses of 90W.

$$R_{JA2} = \frac{(132 - 50)}{90}$$

$$= 0.91°C/W$$

$$\therefore R_{SA2} = R_{JA2} - R_{JS2}$$

$$= 0.91 - 0.35$$

$$= 0.56°C/W$$

Table 14 summarizes the operating temperatures, power losses and heatsink requirements for the two Schottkys.

e. Common vs individual heatsinks

The above results confirm the following:

Circuit-Related Guideline 3: *A common heatsink for both Schottkys in a Forward Converter allows the Schottky with the highest losses to take advantage of the other's "share" of heatsink. The size of a single common heatsink will generally be physically smaller than the combined size of the heatsinks needed for each Schottky individually.*

2. Bridge Converters

In a bridge converter, the Schottkys operate symmetrically. Since both Schottkys deliver the same power into the heatsink, each can be considered to interact only with its "half" of the heatsink. Analytically, this is equivalent to each Schottky being mounted on an individual heatsink that has twice the thermal resistance of the single combined heatsink.

To illustrate a design example, consider again a 200A, 5V power supply with a maximum ambient temperature of 50°C, and a 3 to 1 range of input voltage, using 240NQ045 Schottkys.

Figure 38 shows the calculated losses of each Schottky as a function of junction temperature, at the maximum and minimum input voltage operating conditions. The losses, as before, are calculated from the forward voltage drop and reverse leakage current information given in the Schottky's data sheet, in combination with the Schottkys' operating conditions defined in Table 11. Note that half the total output current freewheels through both Schottkys during portions of each cycle.

Figure 38 shows that at T_{Jmax} (150°C), the losses are highest at high input voltage, due to the contribution of the reverse losses. This is the operating condition that the heatsink must cater to, under the hypothetical scenario that the ambient temperature rises 10°C above maximum.

The required locus of junction to ambient thermal resistance is shown. At high input voltage, the operating junction temperature of each Schottky is 122°C, and the losses 48W. At low input voltage, the operating junction temperature is 132°C, and the losses 53W.

$$R_{JA} = \frac{132 - 50}{53}$$

$$= 1.55°C/W$$

$$R_{SA1} = R_{SA2} = (1.55 - 0.35)$$

$$= 1.2°C/W \text{ (for each Schottky)}$$

$$R_{SA} = \frac{1.2}{2}$$

$$= 0.6°C/W \text{ (combined for both Schottkys)}$$

The above information is summarized in Table 14.

3. Comparison of Heatsink Requirements for Forward and Bridge Converters

The design results for the Forward and Bridge converters shown in Table 14 illustrate an important advantage of the Bridge Converter, so far as the output Schottkys are concerned.

Circuit-Related Guideline 4: *Total Schottky losses in the Forward and Bridge Converters are essentially the same, using the same Schottkys. The heatsink for a Bridge converter, however, can be significantly smaller, because* *the symmetrical operation of the Bridge versus the asymmetrical operation of the Forward Converter results in equal power sharing between the Schottkys and a lower individual junction to sink temperature rise.*

The reason is that the Bridge does not have the "lopsided" operating condition of the Forward converter at high input voltage. This asymmetrical operation causes uneven power-sharing between the two Schottkys. The result is that the junction temperature rise of Schottky 2 above the sink is significantly greater than that of Schottky 1, allowing less permissible sink to ambient temperature difference, and demanding a larger heatsink.

A further fact, though not specifically addressed by Table 14, is summarized as follows:

***Circuit-Related Guideline 5:** Schottkys of a given die size and process type have essentially the same worst-case design losses, regardless of their package type, for given output current, output voltage, and input voltage range. But Schottky package type will determine heatsink thermal resistance, because different package types have different junction to sink thermal resistance.*

The reason is that for a given operating junction temperature, Schottky losses are determined by the die, not (to any significant degree) by the package.

The required junction to ambient thermal resistance is set by the maximum safe junction operating temperature; for a given design ambient, this temperature will be essentially the same, regardless of Schottky package, or whether the circuit is a Forward or Bridge converter.

Differences in the junction to heatsink thermal resistance for different package types are therefore reflected directly as differences in the thermal resistance required for the external heatsink; but these differences have no significant influence on the losses. A "low" package thermal resistance means a "high" heatsink thermal resistance, and vice versa.

4. Flyback Converters

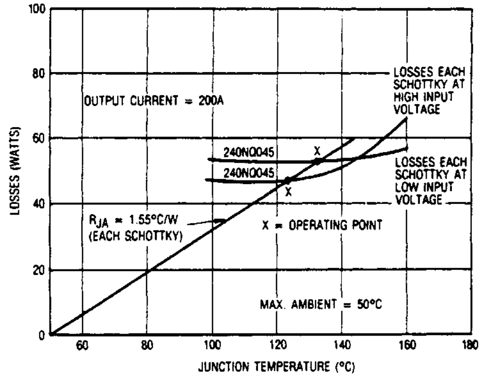
With reference to the operating waveforms shown in Figure 32, the assumed duty cycle of the Schottky current at full load is constant at 0.5, independent of the input voltage. Thus, the Schottky's full load conduction losses are independent of the input voltage.

Reverse power losses, on the other hand, are a function of the input voltage and are maximum at maximum input voltage.

a. Conduction Losses

The waveshape of the Schottky current is triangular, as shown in Figure 32.

The initial peak value of the Schottky current is 4x the dc output current. The average Schottky losses due to this



Notes: Conduction duty cycle at high input is 0.17 at 200A and 0.66 at 100A, each Schottky.
Conduction duty cycle at low input is 0.5 at 200A each Schottky.
Reverse voltage duty cycle at high input is 0.17 each Schottky.
Reverse voltage duty cycle at low input is 0.5 each Schottky.
Reverse voltage at high input is 34V.
Reverse voltage at low input is 11.4V.

Figure 38. Operating characteristics for 200A, 5V bridge converter with 240NQ045 Schottkys.

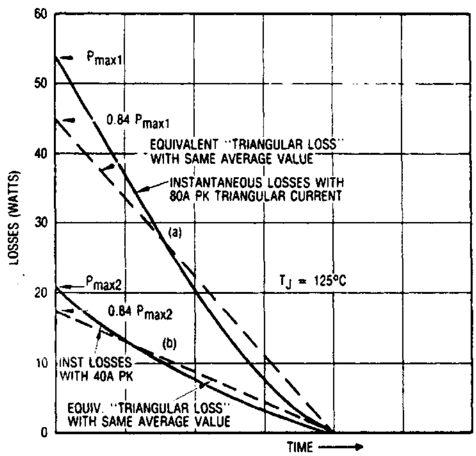


Figure 39. Instantaneous conduction losses of 20FQ045 Schottky with triangular "flyback" current waveforms of (a) 80A peak and (b) 40A peak, corresponding to average dc output currents of flyback converter of 20A and 10A respectively.

triangular current waveform need to be calculated. A simple rule of thumb for doing this will now be demonstrated, by reference to a specific example.

Instantaneous conduction losses in a 20FQ045 Schottky, with triangular current waveforms having peak values of 80A and 40A, are shown in Figure 39. As illustrated, the average losses for each current are about the same as would be obtained with an equivalent triangular loss waveform, with an initial value of approximately 0.84 x the actual initial loss value.

This gives the following empirical rule for calculating the average conduction losses:

Average conduction losses = *average value of an equivalent triangular loss waveform, having a peak value of 0.84 x the actual peak losses.*

This rule is convenient, because it eliminates the need to calculate the actual instantaneous losses over the full current waveform, as has been done in Figure 39. Instead it is necessary only to calculate the value, at the initial peak of the current, then apply the rule to find the average losses.

Application of the above rule to the specific examples shown in Figure 39 gives the following results, for a Flyback Converter using the 20FQ045 Schottky, operating with a conduction duty cycle of 0.5:

Peak Flyback Current A	Average (DC) Output A	Peak Conduction Losses W	Average Conduction Losses (Peak losses x 0.84 x 0.5 x 0.5) W
40	10	20.5	4.3
80	20	53.5	11.25

b. Reverse Power Losses

The highest reverse power losses occur at maximum input voltage. Using the information in Table 11, for junction temperature T_J:

$$P_{REV} = V_{R1} \bullet (I_R @ V_{R1} @ T_J) \bullet D_{Imin} + V_O \bullet (I_R @ V_O @ T_J) \bullet D_{V,IDLE} \quad (37)$$

where

$$V_{R1} = (0.5 + V_O) \frac{V_{IN\ HIGH}}{V_{IN\ LOW}} + V_o$$

$$D_{Imin} = \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$$

$$D_{VIDLE} = 0.5 - 0.5 \frac{V_{IN\ LOW}}{V_{IN\ HIGH}}$$

In general, the second term of equation (37), representing the reverse power loss during the idle period, is small by comparison with the first term, and can be neglected.

c. Design Example

The design procedure to determine the operating point and heatsink requirements for a flyback converter will be illustrated by considering a 5V supply, operating over a 5:1 range of input, for the output currents and Schottky types shown in the three left hand columns of Table 15.

Figure 40 shows the calculated (combined conduction and reverse) losses of the Schottky, plotted as a function of junction temperature, for each of the above designs. Junction to ambient thermal resistance loci and design operating points are also shown. The design operating points for each situation are summarized in Table 15.

d. Schottky Performance in Flyback Converters

The design results summarized in Table 15 illustrate the following:

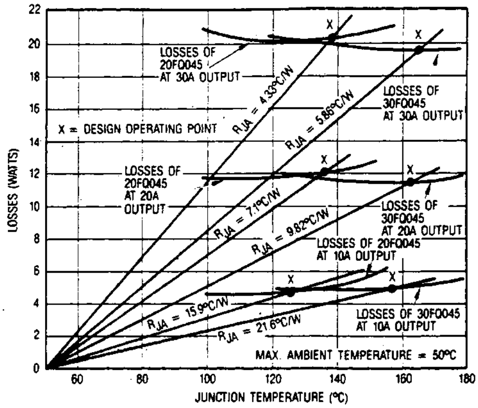
Circuit Related Guideline 6: *In a flyback converter, a 175°C rated Schottky will generally offer similar or better efficiency, while requiring a significantly smaller heatsink, than a 150°C rated Schottky.*

The reason why the 175°C rated Schottky offers the same or better efficiency stems from the forward voltage drop characteristics of the two processes, compared earlier in Figures 5 and 6. At high peak current density, the

TABLE 15

Comparisons of design data for 5V, 10, 20 and 30A flyback converters using 20FQ045 (150°C rated) and 30FQ045 (175°C rated) Schottkys.

DC OUTPUT CURRENT A	SCHOTTKY TYPE	RATED T_{Jmax} °C	R_{JA} °C/W	R_{SA} °C/W	SCHOTTKY LOSSES W	SCHOTTKY LOSSES %	OPERATING T_J °C
10	20FQ045	150	15.9	14.1	4.6	9.2	123
10	30FQ045	175	21.6	19.9	4.85	9.7	155
20	20FQ045	150	7.1	5.4	12	12	135
20	30FQ045	175	9.82	8.1	11.4	11.4	162
30	20FQ045	150	4.33	2.6	20.3	13.5	138
30	30FQ045	175	5.86	4.1	19.6	13.0	165



Notes: Conduction duty cycle is 0.5.
Reverse voltage of 33V is applied for 0.1 duty cycle.
Reverse voltage of 5V is applied for 0.4 duty cycle.

Figure 40. Operating characteristics for 5V, 30A, 20A and 10A flyback converters using 20FQ045 (150°C T_{Jmax}) and 30FQ045 (175°C T_{Jmax} Schottkys.

forward voltage drop of a 175°C rated Schottky is about the same or lower than that of a 150°C rated Schottky.

The flyback converter operates at relatively high peak current density; it therefore favors this property of the 175°C rated Schottky.

Heatsink size required for a 175°C Schottky is significantly smaller, because the allowable junction temperature rise is greater.

B. Heatsink Temperature Constrained by System Requirement

The prime objective of the design procedure outlined so far has been to size the heatsink to provide a safe operating temperature margin for the Schottky. The resulting heatsink temperature depends upon the choice of Schottky and could typically be anywhere between 80°C and 130°C.

Sometimes system requirements will dictate that the heatsink temperature does not exceed a given maximum; this may override basic Schottky thermal stability considerations.

If the maximum design operating current is close to the rated current of the chosen Schottky, the internal junction to case temperature rise will be relatively large; the heatsink temperature will need to be relatively low and therefore may anyway be less than the maximum allowed by the system. Conversely, if the maximum design operating current is significantly lower than the Schottky's rated current, the heatsink temperature for a stable thermal design can be relatively high, and may be higher than the system will allow.

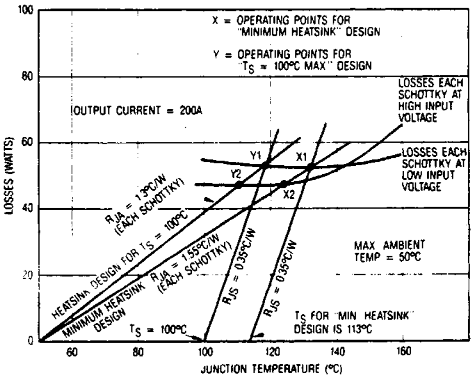
For situations where the maximum heatsink temperature must be limited, the foregoing "minimum heatsink" design procedure is valid only if the resulting heatsink temperature is lower than the allowed maximum. If not, the thermal resistance of the heatsink must be reduced, below that needed for the "minimum heatsink" design (thus adding further thermal margin to the Schottky's worst-case design operating point).

In a design where the heatsink need be determined only by the temperature capability of the Schottky, a higher T_{Jmax} class Schottky will generally yield a smaller heatsink, and a higher heatsink temperature, but not optimum efficiency.

In a design that disallows a heatsink temperature above a given maximum, a lower T_{Jmax}, more efficient, Schottky will always give a smaller heatsink, provided that the design maximum heatsink temperature allows a stable Schottky junction operating temperature.

1. Designing for a Given Heatsink Temperature

The procedure for determining the thermal resistance for a given maximum design heatsink temperature is illustrated in Figure 41.



Notes: Conduction duty cycle at high input is 0.17 at 200A and 0.66 at 100A each Schottky
Conduction duty cycle at low input is 0.5 at 200A each Schottky
Reverse voltage duty cycle at high input is 0.17 each Schottky
Reverse voltage duty cycle at low input is 0.5 each Schottky
Reverse voltage at high input is 34V
Reverse voltage at low input is 11.4V

Figure 41. Operating characteristics for 200A, 5V bridge converter with 240NQ045 Schottkys.

A maximum design heatsink temperature of 100°C is assumed for the Bridge converter previously considered in Figure 38. The heatsink temperature for the "minimum heatsink" design already considered is 113°C. This is now greater than the permitted design maximum.

The power losses in each Schottky for a heatsink temperature of 100°C are found by drawing the locus of the junction to sink thermal resistance for the Schottky (°.35°C/W), that passes through the temperature axis at 100°C. The corresponding operating points are Y1 and Y2, at low and high input voltage respectively.

The losses are highest at low input voltage, and are 53W per Schottky. Therefore:

$$R_{SA} = \frac{T_S - T_{AMB}}{\text{Total Schottky Losses}}$$

$$= \frac{(100 - 50)}{2 \times 53}$$

$$= 0.47°C/W$$

The above value of thermal resistance, 0.47°C/W, needed for a maximum heatsink temperature of 100°C, compares with the previously determined value of 0.6°C/W, for the "minimum heatsink" design.

VI. SILICON VERSUS HEATSINK TRADE-OFFS

As has been seen, the thermal resistance required of the heatsink, for a given power supply output current, can be significantly influenced by the choice of Schottky type, as well as by the choice of converter circuit. So far, we have observed the effect of Schottky and circuit choice, in terms of heatsink thermal resistance values — but have not related these values to the actual physical size of the heatsink.

Before considering some actual examples, it will be instructive to consider the fundamental relationship between Schottky power dissipation (hence operating current) and the required heatsink thermal resistance.[4]

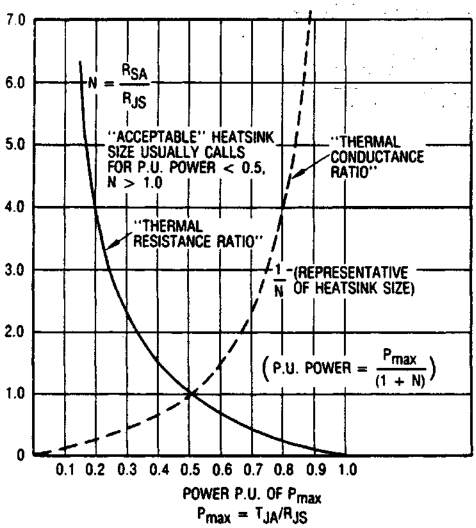


Figure 42. "Thermal resistance ratio" and "heatsink size" versus power dissipation.

[4]These fundamentals actually apply to all power semiconductors, not just Schottkys.

A. Power Dissipation vs Thermal Resistance

As the operating power dissipation in a Schottky increases, the required heatsink thermal resistance decreases more than inversely, because the increasing internal temperature rise allows less available temperture rise for the heatsink.

As more of the total available (i.e., junction to ambient) temperature rise is "used up" in the junction to sink temperature rise, less is available for the sink.

The increasing demand on the heatsink with increasing power dissipation can be expressed in terms of the *ratio* of the external (i.e., heatsink to ambient) and internal (i.e., junction to sink) thermal resistances[5]. The general relationship is shown in Figure 42. The reciprocal of the thermal resistance ratio (the thermal conductance ratio) increases much more rapidly than the increase of power.

To accentuate the problem, the physical *size* of the heatsink will generally increase more than proportionally to the thermal conductance ratio, because heatsinks become relatively less efficient thermally as they grow larger. On top of this, operating current increases less than proportionally with increasing power because the Schottky's voltage drop rises as the current rises. Thus, a point of diminishing returns is reached beyond which the heatsink size becomes disproportionate to the extra current that it permits.

For these reasons, it is rare to find a practical design for which the R_{SA}: R_{JS} *thermal resistance ratio* is less than unity. (Liquid cooling is an exception.) A *thermal resistance ratio* close to unity is representative of a design where the physical size of the heatsink will be quite large relative to the Schottky. Designs that are sensitive to heatsink size generally cannot have such a low thermal resistance ratio as this. For these designs, it will generally be necessary to use "more Schottky" and "less heatsink."

B. Design Examples

1. "Minimum heatsink" design

Figure 43 illustrates various conceivable examples of Schottky and heatsink combinations, for a 200A, 5V power supply, designed to operate over a 3:1 range of input voltage.

These examples are based upon a "minimum heatsink" design, that allows a safe operating temperature margin for the Schottky, without other constraints on the heatsink temperature. The examples consider the 200, 201, 400, and 401CNQ Schottkys, in Forward and Bridge converters.

The forced air cooled heatsink extrusion shown in Figure 45 is assumed.

The major impact of the choice of Schottky and the choice of circuit, on the heatsink size are clearly demonstrated.

[5]Case-to-sink thermal resistance is lumped with the device thermal resistance in this ratio.

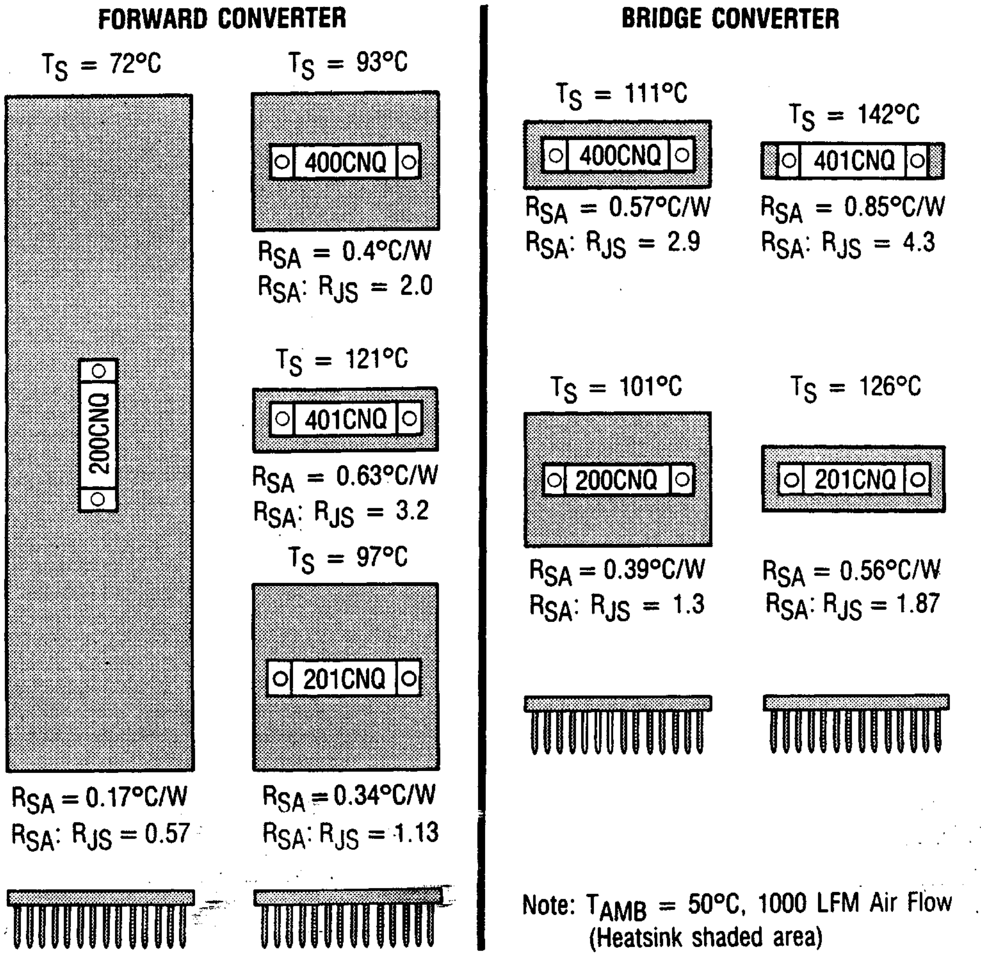


Figure 43. Various possible Schottky/heatsink choices for a 200A, 5V power supply, where heatsink temperature is determined by Schottky temperature capability only.

The following conclusions can be drawn:

(a) The 200 CNQ, in the Forward converter, requires an impractically large heatsink. The corresponding R_{SA}: R_{JS} ratio is less than 1.0.

(b) The 400A rated Schottkys generally require substantially less heatsink than the 200A rated Schottkys.

(c) The 175°C rated Schottkys (201 and 401CNQ) require significantly smaller heatsinks than the 150°C rated Schottkys (200 and 400CNQ) in any given situation. Heatsink temperatures, though, are consistently higher for the 175°C Schottkys.

(d) The Bridge circuit requires a significantly smaller heatsink than the Forward Converter for any given design situation. This is because of the symmetrical operation of the Bridge versus the asymmetrical operation of the Forward converter.

2. Heatsink temperature restricted

Figure 44 illustrates various examples of Schottky and heatsink combinations, for a 200A, 5V Bridge converter, where the overriding design criterion is that the heatsink temperature must not exceed 100°C.

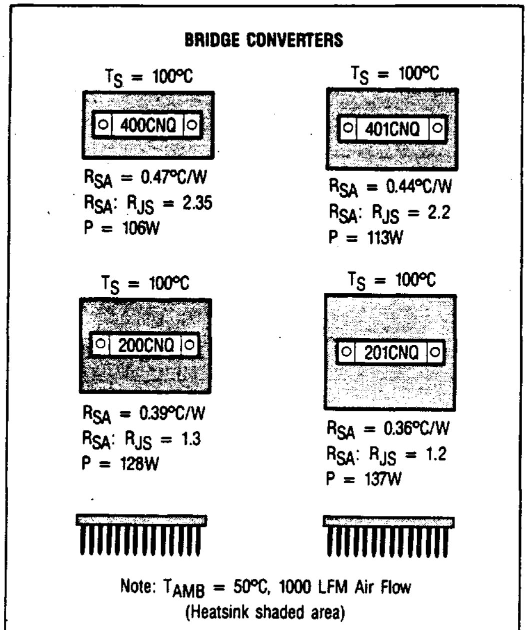


Figure 44. Comparison of various Schottky/heatsink choices for a 200A, 5V power supply where heatsink temperature is restricted to 100°C.

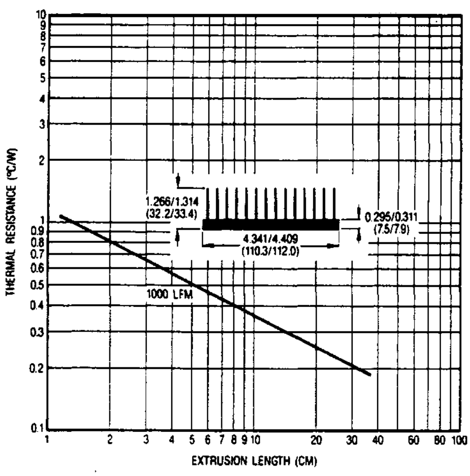


Figure 45. Typical relationship between length of heatsink extrusion and thermal resistance.

The following conclusions can be drawn:

(a) The heatsink size required for a given Schottky type is larger than that needed for the "minimum heatsink" design represented in Figure 43.

(b) The more "silicon intensive" 400/401CNQ modules require smaller heatsinks than their 200/201CNQ counterparts.

(c) The 150°C T_{Jmax} class Schottkys, with their lower losses, require smaller heatsinks than the less efficient 175°C T_{Jmax} class Schottkys.

This is a reversal of the "roles", depicted in Figure 43, for a "minimum heatsink, unrestricted sink temperature" design. In that case, the less efficient 175°C class Schottkys require smaller heatsinks, because their operating temperatures are higher.

VII. "OR-ING" SCHOTTKY

A. What It Is

Critical loads often employ parallel-connected power supplies, with redundant power capability, to enhance system reliability. In the event of failure of one or more power supplies, the healthy ones continue to supply uninterrupted power to the load.

In these situations, an OR-ING[6] rectifier is connected in series with the output of each power supply, as illustrated in Figure 46. When all power supplies operate normally, each "OR-ING" diode carries the output current of its power supply and has no reverse voltage applied. Failure of any power supply results in that OR-ING diode ceasing to carry current; instead it blocks the system output voltage, preventing current from flowing back into the faulty supply from the others.

It is critically important that the voltage drop of an OR-ING diode is low, in order to maintain the best possible system efficiency. The OR-ING diode's voltage rating need be compatible only with the system voltage, which typically will be 5V. A continuous voltage rating of 15V is therefore more than adequate for an OR-ING diode in a 5V system.

The required characteristics of an OR-ING diode lend themselves well to a low V_{RRM} class, low T_{Jmax} class Schottky. International Rectifier 15V, 100°C process Schottkys are ideally suited to this duty; in fact, they were developed specially for this purpose.

Their forward voltage drop is about 350mV, and their continuous reverse dc voltage rating is 15V. Peak transient working voltages of 25V are permissible. This allows for short-lived overvoltages that might occur, for example, during "hot" replacement of a failed power supply.

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[6]The term "OR-ING" derives from the logic "OR" function, provided by a logic "OR-ING" diode. In the logic context, the function of a group of OR-ING diodes is to accept two or more input signals and deliver an output "1" signal whenever one or more inputs has a "1" value. If any input has a "0" value, that does not effect the output signal, so long as at least one signal has a "1" value.

In the power supply context, the "OR-ING" diode allows power to flow to the load whenever one or more supplies delivers normal voltage. If one or more supplies fail, or are not functional, this does not effect or load the "OR-ED" system output.

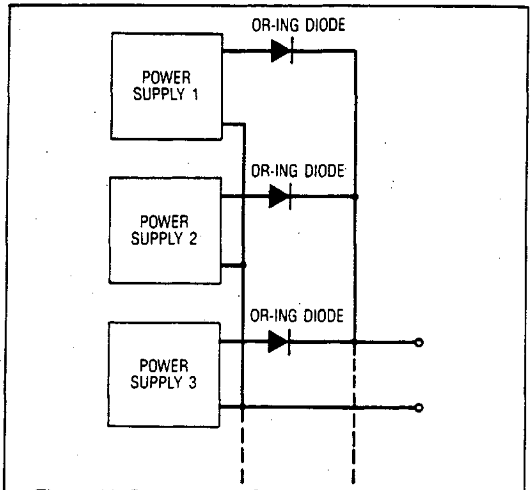


Figure 46. Connection of OR-ing diodes in the outputs of individual power supplies to provide redundancy.

B. Designing In The OR-ING Schottky

In common with other Schottkys, the forward voltage drop of International Rectifier's OR-ING Schottky decreases as operating junction temperature increases. Best efficiency is therefore obtained by allowing the OR-ING diode to operate close to its rated T_{Jmax}.

The following examples illustrate that a heatsink sized for the forward conduction losses will be more than adequate to handle the reverse power losses when the OR-ING diode switches from forward conduction to reverse blocking.

Example

Figure 47 shows the relationship between forward conduction losses and junction temperature for the International Rectifier 19TQ015 OR-ING Schottky, for continuous forward currents of 15 and 25A. The relationship between continuous reverse power and junction temperature, for an applied reverse voltage of 5V, is also shown.

Loci of junction to ambient thermal resistance are shown, for an ambient temperature of 50°C and a junction operating temperature of 90°C. Corresponding loci of junction to case thermal resistance (1.5°C/W) show that for 25A operating current, the operating case temperature will be 77°C, and for 15A, 83.5°C.

In the event of a power supply failure, the Schottky's case temperature will momentarily stay unchanged, and operation will move to point A, for the 25A design, and to point B, for the 15A design, on the reverse power loss characteristic. In either case, a solid "non-tangential" intersection point, between the locus of junction to case thermal resistance and the reverse power loss characteristic is obtained, ensuring that the operation will be stable.

As the Schottky cools down — the reverse power loss being significantly less than the previous forward conduction loss — the operating points on the reverse power characteristics will move to A' and B', for the 25A and 15A heatsink designs respectively, assuming that the Schottky is mounted on its own heatsink. If all OR-ING diodes are mounted on a common heatsink, then the operating points would stay close to A and B, for the 25A and 15A designs respectively.

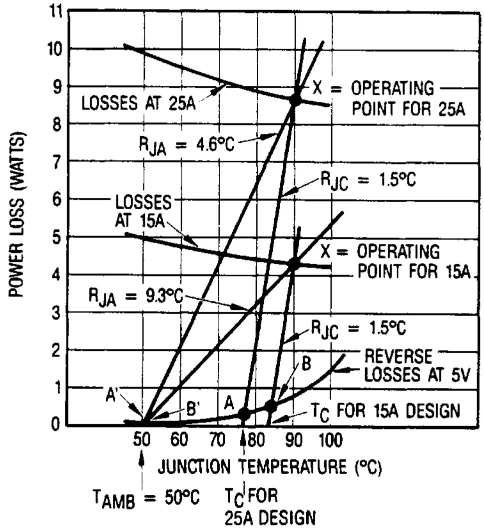


Figure 47. Characteristics and design operating points for 19TQ015 Schottky in 15A and 25A "OR-ing" application.

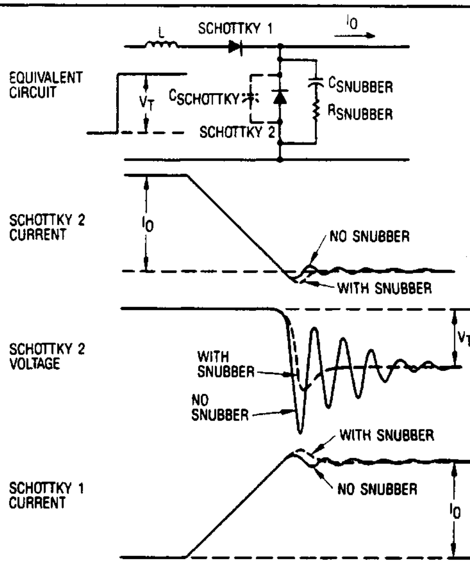


Figure 48. Equivalent circuit and operating waveforms during commutation with and without a snubber.

VIII. SWITCHING TRANSIENTS

When current in the Schottky is rapidly switched, a voltage transient is generated, due to interaction between circuit inductance and the Schottky's self-capacitance. This happens, for example, in a Forward or Bridge Converter, whenever the output transformer voltage changes polarity. The transformer's leakage inductance, as well as "stray" circuit inductance, forms a resonant circuit with the Schottky's self-capacitance. Figure 48 shows an equivalent circuit and idealized current and voltage waveforms during commutation.

With no snubber, the reverse voltage across the outgoing Schottky overshoots, to about twice the transformer voltage; this is followed by an underdamped oscillation, at the resonant frequency of the circuit inductance with the Schottky's capacitance.[7]

A snubber serves the dual purpose of reducing the Schottky's peak reverse voltage and of damping the high frequency oscillation.

IR's Schottkys are rated to absorb avalanche energy, at voltage above the normal working voltage. This will not stop oscillation from occuring below the Schottky's avalanche voltage, which will typically be about 1.5x the Schottky's rated working voltage. The switching oscillations typically have a frequency in the range of 1 to 15 MHz and may be undesirable, because of the electrical interference they create. A snubber will usually be needed, if only to dampen the oscillation.

Thus the Schottky avalanche property will generally not eliminate the need for a snubber. What is does do is provide a valuable "insurance" against abnormal voltage transients; it also eliminates the need for a generous operating voltage margin, which allows the size and losses of the damping snubber to be minimized.

A. Snubber Circuit Design

The R-C snubber circuit requires careful dimensioning. Energy equal to $1/2\ C_{SNUBBER}\ V^2$ is dissipated each time the snubber capacitor is charged or discharged.[8] Thus total energy equal to $C_{SNUBBER}\ V^2$ is lost in each snubber during each switching cycle. ($1/2\ C_{SNUBBER}\ V^2$ when the Schottky turns ON, and $1/2\ C_{SNUBBER}\ V^2$ when it turns OFF). The snubber capacitance must be kept as small as possible, consistent with achieving the required damping of the switching oscillation, in order to minimize the snubber losses.

Though, for a given capacitance, the value of the snubber resistance has no effect upon the net energy dissipation, it does have a major effect upon the amplitude of the voltage oscillation.

If the snubber resistance is too small, then the snubber capacitance, in effect, is connected almost directly in parallel with the Schottky capacitance. The circuit will be underdamped and resonate at a frequency of $1/[2\pi \bullet \sqrt{L \bullet (C_{SCHOTTKY} + C_{SNUBBER})}]$.

If the snubber resistance is too large, it will not damp the oscillations caused by the Schottky capacitance. The circuit will now have an underdamped oscillation at a frequency of $1/[2\pi \bullet \sqrt{(L \bullet C_{SCHOTTKY})}]$.

Figures 49 through 53 show switching voltage and current waveforms, based on a linear approximation of the Schottky self-capacitance. A value of 1nF is assumed; this would be representative, for example, of a 50HQ Schottky.

Figure 49 illustrates the effect of the choice of snubber resistance, with a fixed snubber capacitance, equal to 6x the Schottky capacitance. (N = 6, where N is the ratio of snubber to Schottky capacitance). These waveforms confirm that a snubber resistance that is either too large or too small results in an oscillation that is underdamped and has substantial voltage overshoot. With the "correct" value of snubber resistance, effective damping of the oscillation is achieved; the peak voltage is kept to about 45V, for a 34V transformer voltage.

Figure 50 illustrates the effect of increasing the snubber capacitance, to 10x Schottky capacitance. The peak Schottky voltage is now just over 40V, for a 34V transformer voltage. These waveforms show virtually "perfect" damping.

Figures 51 and 52 show the effect of higher circuit inductance — 300nH and 1μH respectively-compared with 100nH in Figures 49 and 50. These waveforms demonstrate that with proper choice of the snubber resistance, the size of the snubber capacitance, for a given voltage overshoot, stays about the same with increasing circuit inductance. Of course, a larger inductance means a slower voltage rise time, and a lower amplitude snubber current.

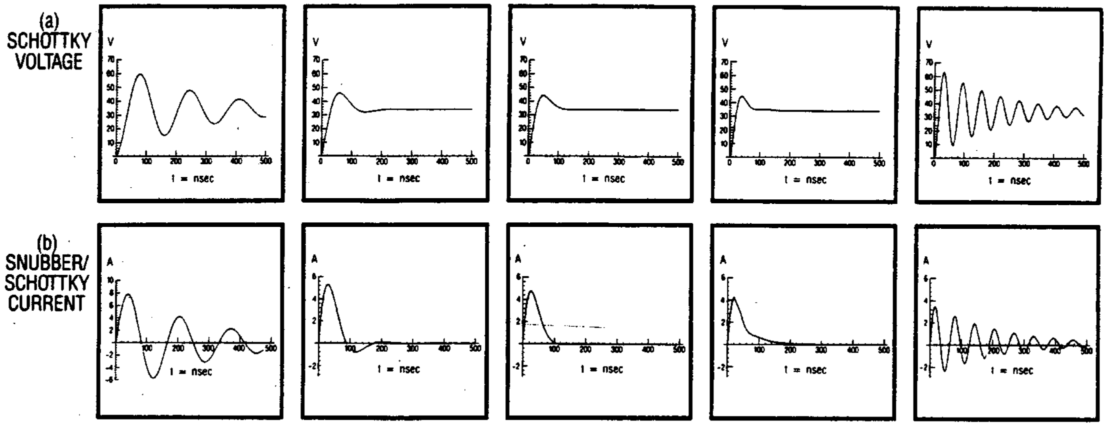
The waveforms in Figure 53 are for a reduced transformer voltage, of 28V. The snubber capacitance values range from 6 to 2x the Schottky capacitance. The value of snubber resistance in each case is chosen to maximize the damping.

These waveforms demonstrate the trade-off between voltage overshoot and snubber capacitance. A snubber capacitance of 6x the Schottky's capacitance is needed to limit the peak Schottky voltage to 36V. The snubber capacitance can be reduced to just 2x the Schottky's capacitance, if the voltage is allowed to rise to 43V.

Thus, by taking advantage of the ruggedness of IR's Schottkys and paring down the operating voltage margin, the size and losses of the snubber can be significantly reduced.

[7] The Schottky's capacitance is non-linear and is a function of the applied voltage. The circuit operation can be approximated by assuming a linear capacitance of about the value obtained at the full circuit operating voltage.

[8] This is fundamental, and independent of the value of circuit inductance or snubber resistance. V is the level to which the capacitor voltage settles when the oscillation is completed, i.e. it is the operating voltage delivered by the output transformer, not the peak voltage to which the capacitor voltage may overshoot.

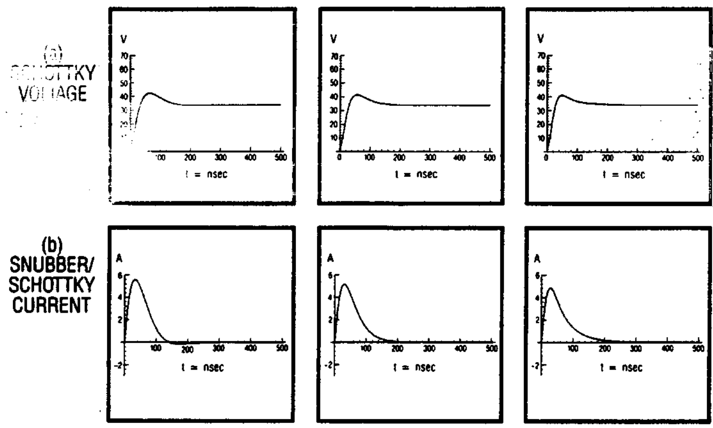


1. R = 1 Ω 2. R = 5 Ω 3. R = 7 Ω 4. R = 10 Ω 5. R = 100 Ω

Figure 49. Waveforms of (a) commutating voltage across Schottky and (b) combined current in snubber and self-capacitance of Schottky, for various values of snubber resistance. $N = C_{Snubber}/C_{Schottky} = 6$.

$C_{Schottky} = 1nF$ $C_{Snubber} = 6nF$ $L = 100nH$ $V_T = 34V$

(Reference Figure 48)



1. R = 5 Ω 2. R = 6 Ω 3. R = 7 Ω

Figure 50. Waveforms of (a) commutating voltage across Schottky and (b) combined current in snubber and self-capacitance of Schottky, for various values of snubber resistance. $N = C_{Snubber}/C_{Schottky} = 10$.

$C_{Schottky} = 1nF$ $C_{Snubber} = 10nF$ $L = 100nH$ $V_T = 34V$

(Reference Figure 48)

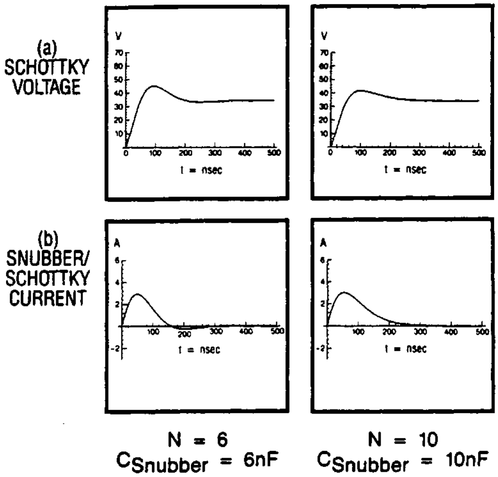


Figure 51. Waveforms of (a) commutating voltage across Schottky and (b) combined current in snubber and self-capacitance of Schottky, for different values of snubber capacitance. (= N x Schottky Capacitance).

$C_{Schottky}$ = 1nF $R_{Snubber}$ = 10 Ohms L = 300nH V_T = 34V

(Reference Figure 48)

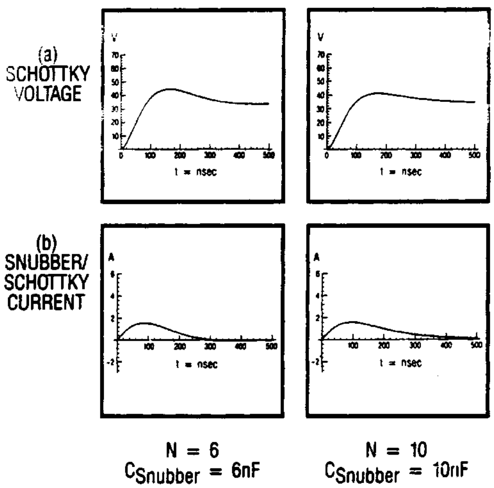


Figure 52. Waveforms of (a) commutating voltage across Schottky and (b) combined current in snubber and self-capacitance of Schottky, for different values of snubber capacitance. (= N x Schottky Capacitance).

$C_{Schottky}$ = 1nF $R_{Snubber}$ = 20 Ohms L = 1μH V_T = 34V

(Reference Figure 48)

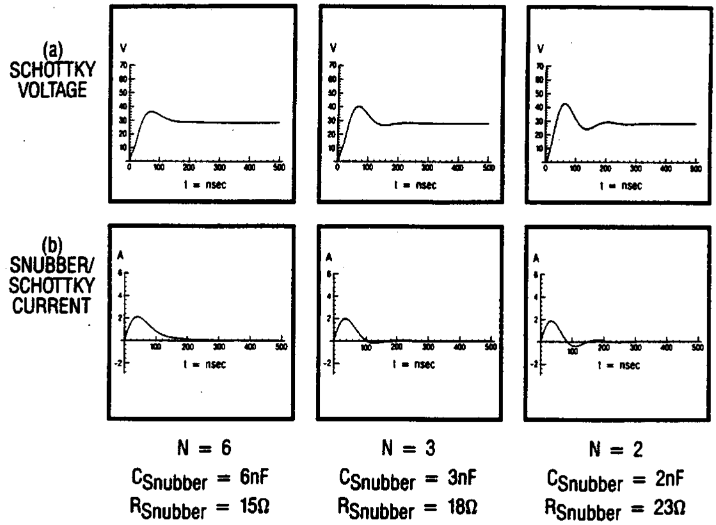


Figure 53. Waveforms of (a) commutating voltage across Schottky and (b) combined current in snubber and self-capacitance of Schottky, for various values of snubber resistance.

$C_{Schottky}$ = 1nF L = 300nH V_T = 34V

(Reference Figure 48)

IX. SCHOTTKY RECTIFIER SELECTION GUIDES FOR SWITCHING POWER SUPPLIES

Tables 16 through 18 show Schottky Rectifier Selection Guides for "Forward," "Bridge" and "Flyback" converters for a range of output currents and output voltages.

The following explanations will help in using these Tables:

- Tables 16(a) through (g) cover Forward Converters, with output currents from 5 to 30A. These Tables apply to the "single-ended" and "double-ended" Forward Converter circuits shown in Figure 27.
- Bridge Converters are not covered below output current of 50A, because they are generally not used at lower current levels.
- Tables 17(a) through 17(i) cover Forward and Bridge Converters, with Output Currents from 50 to 400A. Forward Converters can be "single" or "double-ended," as shown in Figure 27. Bridge Converters can be "half-bridge" or "full bridge," as shown in Figure 29.
- Tables 18(a) through 18(f) cover Flyback Converters, with output currents from 5 - 150A. These Tables apply to a Flyback converter operating in the "total energy transfer" mode, with a fixed conduction duty cycle of 50%, as depicted in Figure 32.
- For each power supply specification, the possible Schottky choices are grouped first by package type. For each package type, several choices of specific Schottky type may generally be possible. These choices show how "Schottky silicon" (within the given package) can be traded against the heatsink thermal resistance and losses.
- For each Schottky type, two selections of heatsink thermal resistance — R_{SA} and $R_{SA(100)}$ — are shown.

  R_{SA} represents the "minimum heatsink" design (i.e. the largest possible value of thermal resistance). This value is based on a design safety margin which allows the ambient temperature to rise 10°C above the design maximum, before the Schottky operating junction temperature will reach T_{Jmax}.

  The second value of heatsink thermal resistance, $R_{SA(100)}$, is needed to keep the heatsink temperature to 100°C — even though the Schottkys themselves can be safely operated at higher heatsink temperature.

  This gives a point of reference for design situations where system constraints, other than the capabilities of the Schottkys themselves, dictate the heatsink

  The Schottky losses obtained with $R_{SA(100)}$ are generally higher than those for the "minimum" heatsink, because conduction losses are higher at lower operating temperature.

- The maximum range of input voltage specified in the selection Guides is the maximum range permitted by the voltage rating of the Schottky; it corresponds to a 33% margin between the peak transformer voltage (exclusive of the switching transient) and the Schottky's rated working voltage.

  Heatsink thermal resistance required for a lower input voltage range will generally be higher (i.e. the heatsink will be smaller). This is particularly so for the Forward Converters, for which the greater the range of input voltage, the greater the asymmetry of conduction between the Schottkys.

- The Selection Guides are based on a maximum design ambient temperature of 50°C.

  The heatsink thermal resistance required for a higher maximum design ambient temperature can be estimated using the formula in the footnote of the Table. This formula assumes that the heatsink has the same temperature (and therefore the Schottky has the same operating junction temperature) as at 50°C ambient. This is conservative for the "minimum heatsink" (R_{SA}) value, because for a given margin of 10°C in the design *ambient* temperature, the greater "temperature stability" of the larger heatsink for higher *ambient* actually would allow a somewhat higher Schottky operating *junction* temperature.

  Conversely, the formula applied to a lower ambient temperature will yield a slightly optimistic value for R_{SA}, and should be used as a guideline only, recognizing that the actual value for R_{SA} will be rather lower than that calculated. □