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FINAL REPORT

BYPASS DIODE INTEGRATION

PREPARED UNDER JPL CONTRACT 955894

REPORT DATE: DECEMBER 11, 1981

ENERGY SYSTEMS AND TECHNOLOGY DIVISION

GENERAL ELECTRIC

DOE/JPL 955894-5
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The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of flat-plate solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

GENERAL ELECTRIC
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The following individuals, within the General Electric Company, Advanced Energy Programs Department, have made significant contributions to the content of this study:

N. F. Shepard, Jr.	Program Manager and Principal Investigator
R. Landes	Task Leader of Bypass Diode Integration Study
J. Parker	Thermal Analysis of Bypass Diode Mounting Concepts
R. Drummond	Design of Bypass Diode Mounting Configurations

Mr. R. S. Sugimura was the JPL Project Manager.

ABSTRACT

This report summarizes the results of a bypass diode integration study which was conducted as part of the "Integrated Residential Photovoltaic Array Development" effort (JPL Contract No. 955894). The study involved research into protective bypass diodes and mounting configurations which are applicable for use with photovoltaic modules having power dissipation requirements in the 5 to 50 watt range. Using PN silicon and Schottky diode characterization data on packaged diodes and diode chips, typical diodes were selected as representative for each range of current carrying capacity, an appropriate heat dissipating mounting concept along with its environmental enclosure was defined, and a thermal analysis relating junction temperature as a function of power dissipation was performed. In addition, the heat dissipating mounting device dimensions were varied to determine the effect on junction temperature. The results of the analysis are presented as a set of curves indicating junction temperature as a function of power dissipation for each diode package.

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SUMMARY

SECTION 1
SUMMARY

Diodes, which are suitable for use in bypass applications within photovoltaic modules, are available from 15 manufacturers as listed in Table 1-1. Two basic rectifying diode types have been considered in this study: (1) the silicon PN junction device which is characterized by a 0.9 to 1.2 volt forward drop and a reverse blocking voltage exceeding 50 volts, and (2) the Schottky device with a 0.5 to 0.6 volt forward drop and a reverse blocking voltage of approximately 20 volts. Diodes of either of these types are available in packaged form as one of the case configurations illustrated in Figure 1-1 or in chip form as typified by the configurations shown in Figure 1-2.

Typical diode/heat sink configurations were researched for each of the available package designs for mounting on the rear surface of the module or for attachment to the module frame. In each case the diode mounting hardware, including the electrical insulating washers and bushings required to isolate the case from the heat sink, is specified along with representative methods for the attachment of the heat sink to the module. The thermal analysis of these packaged diode mounting configurations is summarized in Figures 1-3 and 1-4 in terms of the square heat spreader plate area required for a rear side mounting configuration and the diode junction temperature resulting from a frame mounted package of various configurations and power dissipations. It should be noted that the selection of case configuration has a large impact on the power dissipation capability of a given diode installation.

The mounting of diode chips directly to copper sheet heat spreaders for lamination within the module encapsulant offers many advantages which include: (1) a low junction-to-heat sink thermal resistance, (2) a thin profile which permits mounting within the laminate, (3) environmental protection and electrical insulation provided by the module encapsulant, and (4) use of copper foil strips used for diode lead wiring and contained within the module laminate. The thermal dissipation capability of such a diode chip mounting approach is shown in Figure 1-5 for a diode junction temperature limit of 120°C which is dictated by the high temperature endurance limitation of the EVA encapsulant.

Table 1-1. Potential Suppliers of Suitable Diodes

Manufacturer	Forward Current Range (A)	Packaged Diodes		Diode Chips	
		Silicon PN Junction	Schottky Barrier	Silicon PN Junction	Schottky Barrier
1. EDAL East Haven, CT	5-45	X			
2. General Electric Electronic Components Sales Auburn, NY	5-40	X			
3. General Instrument Hicksville, NY	5-25	X	X	X	
4. NAE Lynn, MA	3-60	X	X		
5. International Rectifier El Segundo, CA	6-60	X	X	X	X
6. Motorola Semiconductor Phoenix, AZ	6-60	X	X		X
7. Microwave Associates Burlington, MA	30-60		X		X
8. Seimans Colorado Components Broomfield, CO	12-60	X	X		
9. Semicon Burlington, MA	5-75	X	X	X	X
10. Solitron San Diego CA (PN) Riviera Beach, FL (Schottky)	5-40	X	X		
11. ST- Semicon Bloomington, IN	6-50	X			
12. TRW Semiconductor Lawndale, CA	25-60		X		X
13. Unitrode Lexington, MA	7-60	X	X	X	X
14. Varo Garland, TX	5-60		X		X
15. Westinghouse Semiconductor Youngwood, PA	5-60	X			

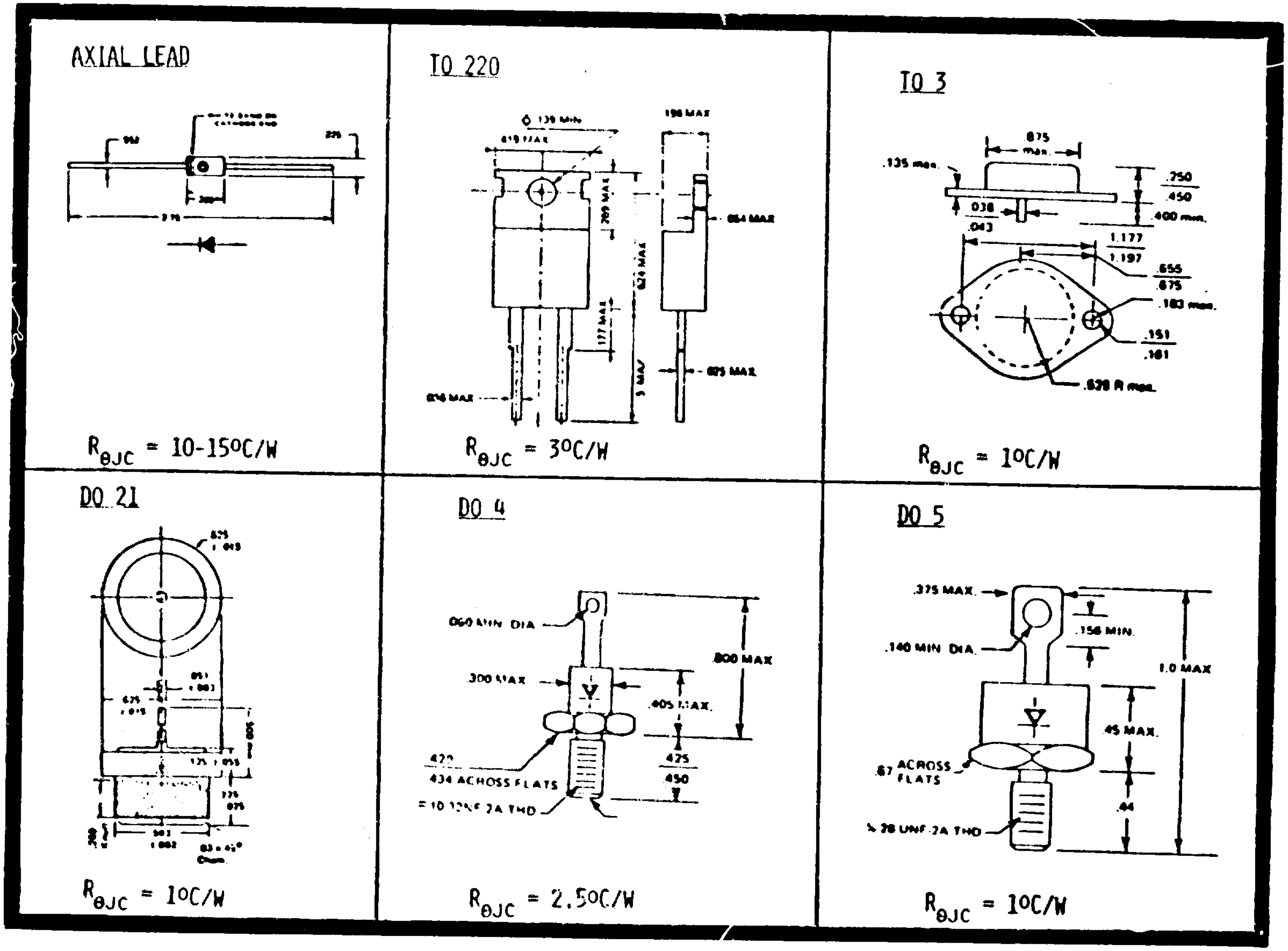
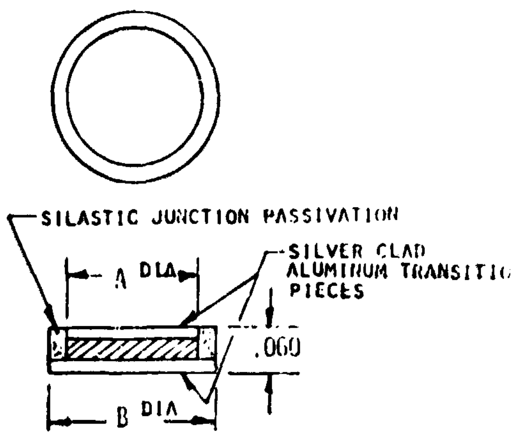


Figure 1-1. Applicable Packaged Diodes

PN JUNCTION

- MAX JUNCTION TEMP ($T_{J\ MAX}$) = 175°C (ZERO CURRENT CARRYING CAPACITY)
- MAX. REVERSE VOLTAGE (V_R) = 50V
- MAXIMUM REVERSE CURRENT (I_R) = 1 μA TO 10 MA
- TYPICAL FORWARD VOLTAGE DROP (I_F) = 0.9 TO 1.2V

APPROXIMATE CURRENT CARRYING CAPACITY (I_F) (AMPS)	APPROXIMATE THERMAL RESISTANCE JUNCTION TO SINK (°C/W)	CHIP DIMENSIONS (INCHES)	
		A	B
12	2.5	.120	.140
20	1.0	.140	.160
25	1.0	.200 (SQUARE)	.220
35-50	1.0	.200	.220



SCHOTTKY

- MAX JUNCTION TEMP ($T_{J\ MAX}$) = 150°C (ZERO CURRENT CARRYING CAPACITY)
- MAX REVERSE VOLTAGE (V_R) = 20V
- MAXIMUM REVERSE CURRENT (I_R) = 400 μA TO 400 MA
- TYPICAL FORWARD VOLTAGE DROP (I_F) = 0.5 TO 0.6V

AVG. FORWARD CURRENT RATING (I_F) (AMPS)	APPROXIMATE THERMAL RESISTANCE JUNCTION TO SINK (°C/W)	CHIP DIMENSIONS (INCHES)		
		A	B	C
15	2.5	.125	.100	.180
30	2.0	.160	.140	.230
50	1.0	.200	.175	.250

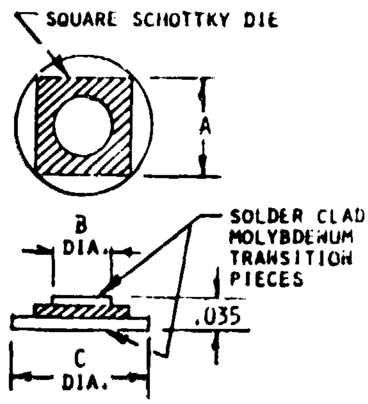


Figure 1-2. Typical Diode Chip Configurations

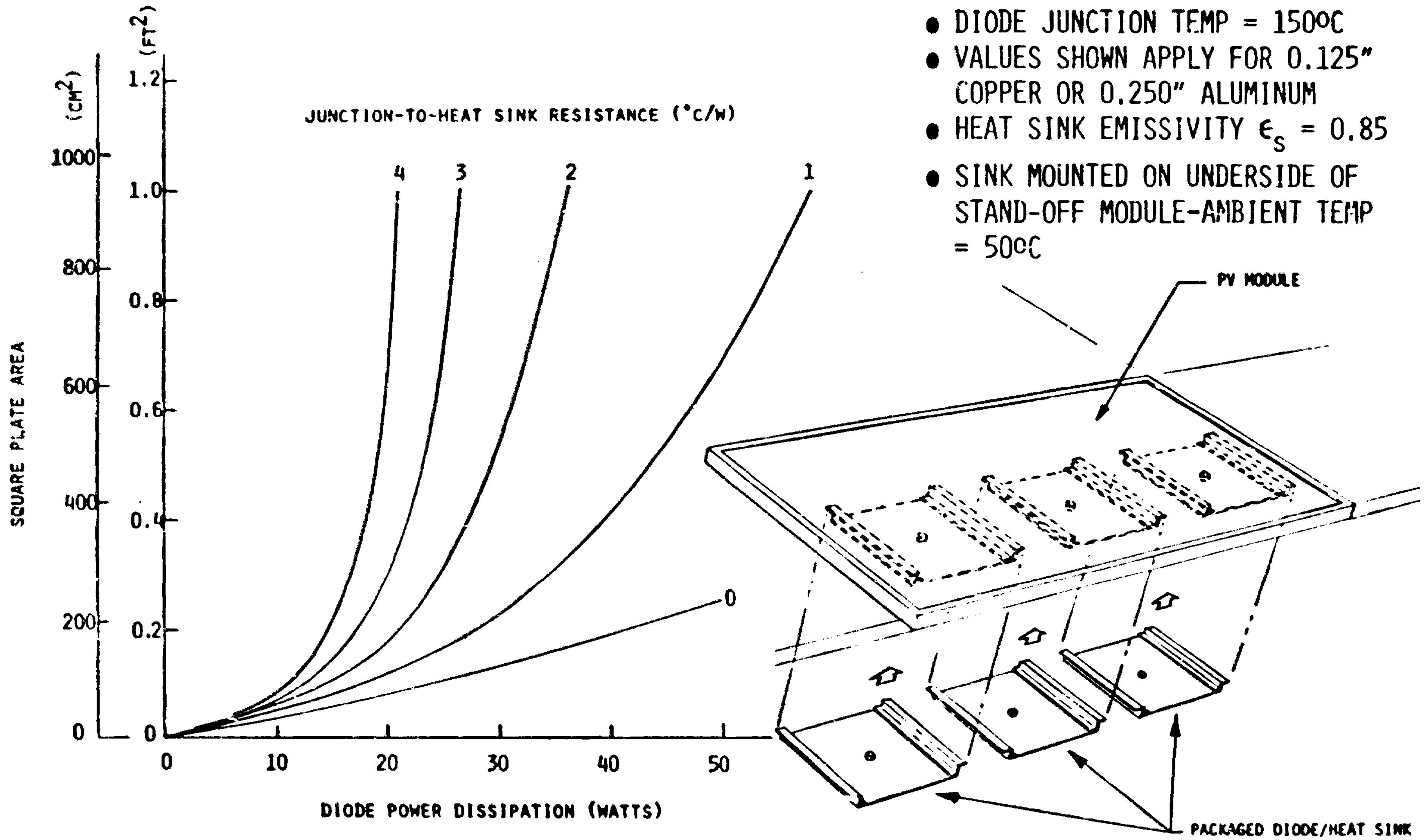
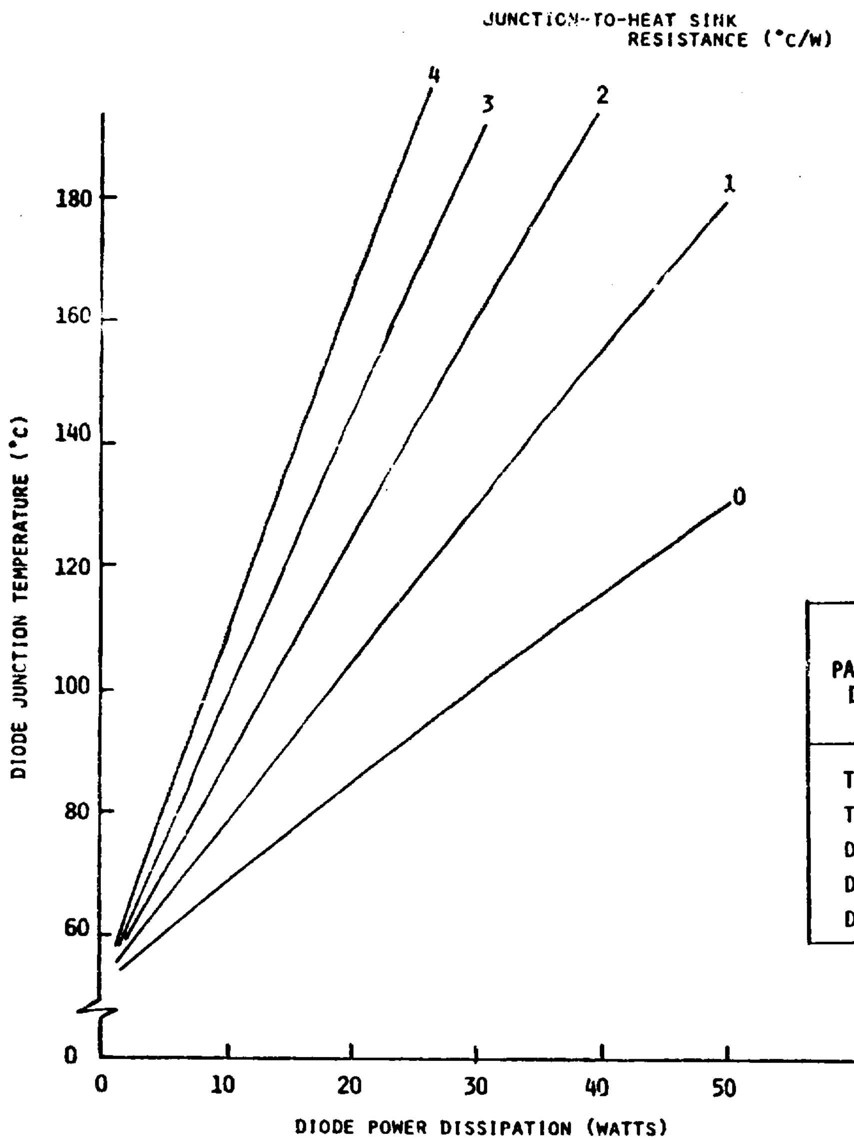
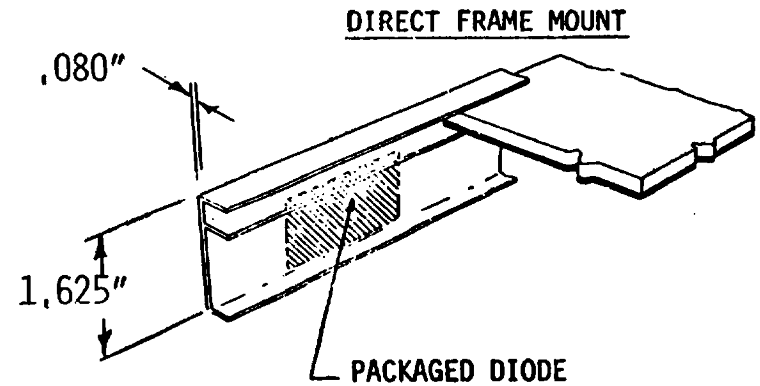


Figure 1-3. Thermal Analysis of Back Mounted Packaged Diode/Heat Sink Configurations





PACKAGED DIODE TYPE	TYPICAL MAXIMUM POWER LEVEL W	ESTIMATED THERMAL RESISTANCE, °C/W		
		JUNCTION TO CASE (MFG. SPEC. DATA)	CASE TO HEAT SINK (ESTIMATED)	JUNCTION TO HEAT SINK
T03	30	1.0	0.14	1.14
T0220	15	3.0	0.20	3.20
D04	20	2.0	0.10	2.10
D05	40	1.0	0.10	1.10
D021	30	1.0	1.5	2.5

Figure 1-4. Thermal Analysis of Frame Mounted Packaged Diode/Heat Sink Configurations

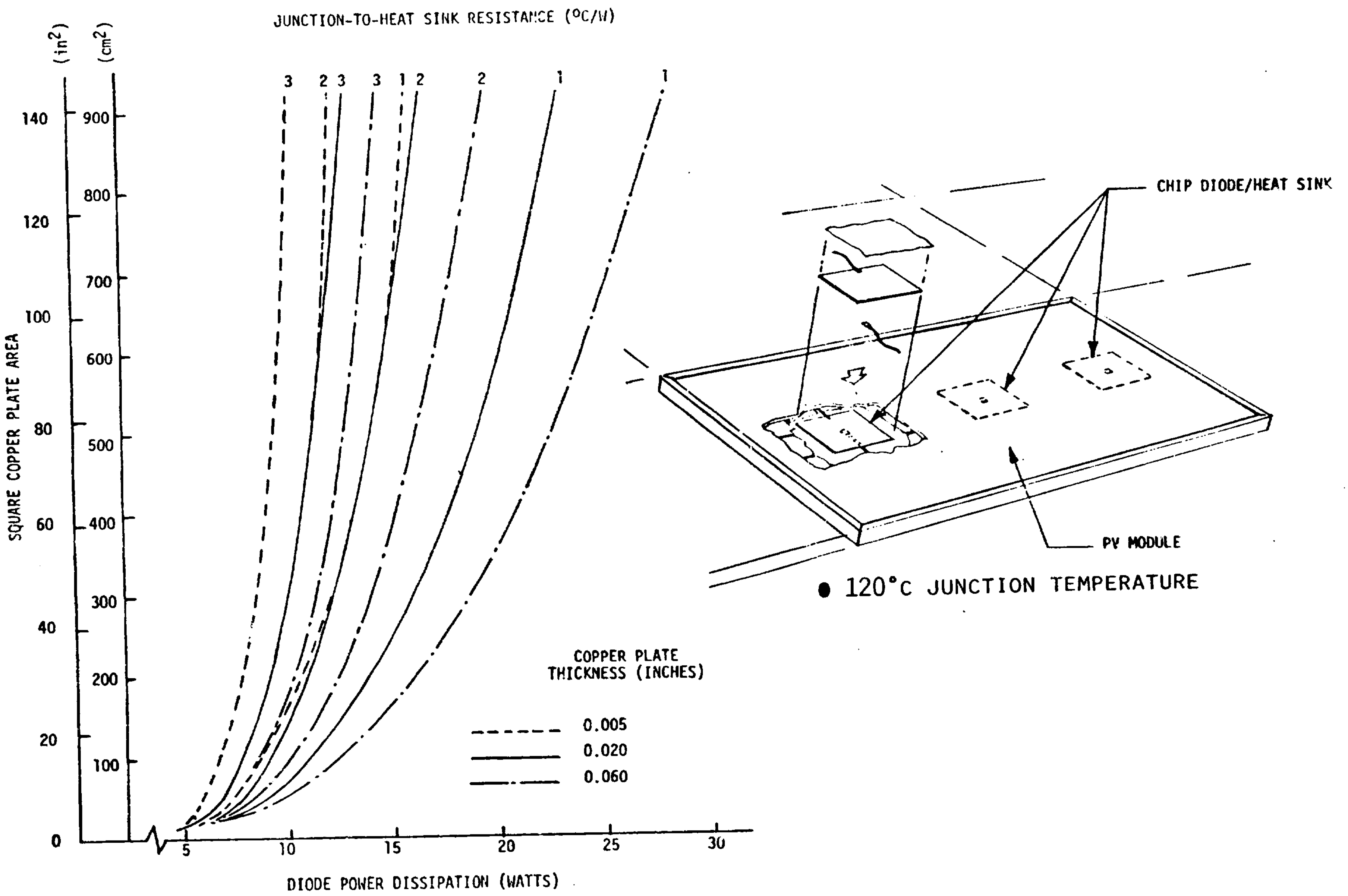


Figure 1-5. Thermal Analysis of Diode Chips Mounted Within the Module Encapsulant

SECTION 2

INTRODUCTION

SECTION 2

INTRODUCTION

The Bypass Diode Integration Study, reported herein, was conducted as part of JPL Contract 955894 entitled "Integrated Residential Photovoltaic Array Development." This task activity, which encompassed an analysis of bypass diode integration into residential photovoltaic modules, consisted of the following specific elements:

1. Establishment of bypass diode requirements for photovoltaic modules
2. Determination of commercially available packaged and chip form devices which are suitable for use as solar cell circuit bypass diodes
3. Definition of the physical and operational characteristics of typical packaged and chip diodes
4. Development of diode/heat sink mounting concepts integrated into the stand-off, direct and integral residential photovoltaic module types.
5. Thermal analysis of each mounting concept to establish typical flat plate heat sink size requirements
6. Evaluation of factors affecting the reliability of diodes.

SECTION 3

TECHNICAL DISCUSSION

SECTION 3
TECHNICAL DISCUSSION

3.1 BYPASS DIODE APPLICATION AND REQUIREMENTS

Bypass diodes are often used within photovoltaic modules as shown in Figure 3-1. In this application, the diode functions to bypass or shunt module current which would otherwise be reduced or eliminated by the open-circuit failure or shadowing of the solar cells within the bypassed group. Under normal solar cell operating conditions, the bypassed circuit element is generating power with the voltage polarity indicated on the figure and the bypass diode is reverse biased and blocking the flow of current. A reduction in the short-circuit current generating capability of any of the solar cells within the bypassed group, which can result from complete or partial open circuit failures or shadowing, will cause the excess current from the unaffected portions of a shorted module to flow through the bypass diode. Under these circumstances, the voltage polarity across the bypassed element is reversed and limited to the forward voltage drop across the diode.

Thus, when used in this application, the diode serves the following functions:

- Provides a parallel path for current flow around module circuit elements so that the module short-circuit current capability is not limited by a reduction in the capability of elements within the bypassed group.
- Limits the reverse voltage that can be developed across the group to the forward voltage drop of the forward conducting bypass diode. This limits the amount of reverse voltage "hot-spot" heating that can occur within an affected solar cell of the bypassed group.

The number of series-connected solar cells within a bypassed group should not exceed 15 if acceptably low hot-spot temperatures are to be assured. The open-circuit voltage of a series string of this length at 100 mW/cm^2 and -20^o is 11 volts and can be considered as a realistic upper limit on the reverse voltage imposed across the bypass diode under normal circuit operating conditions.

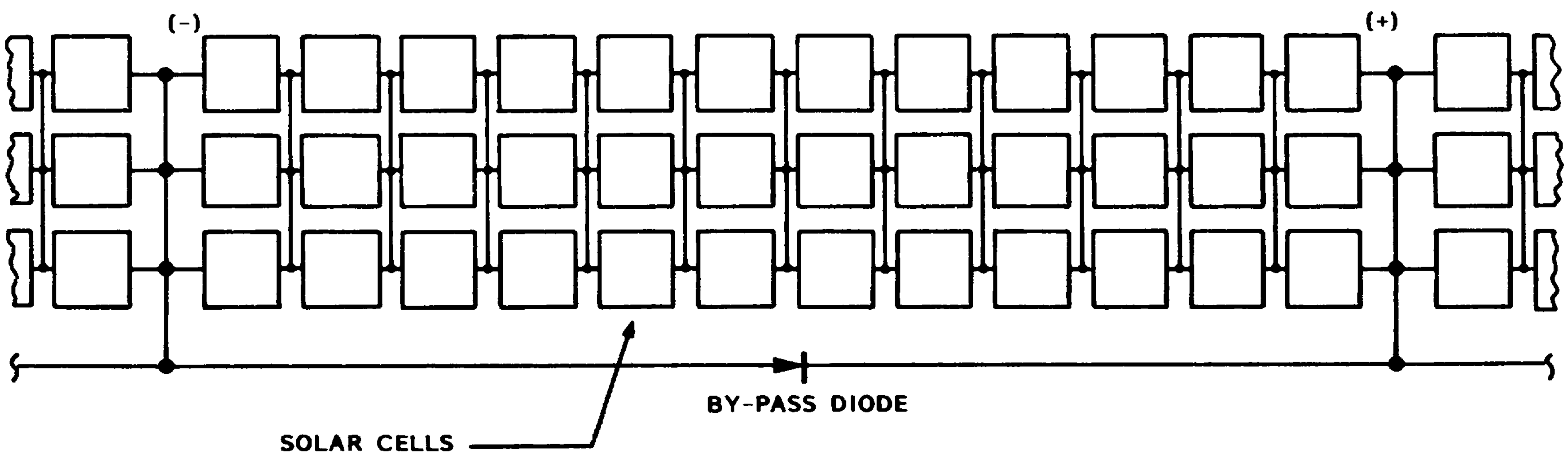


Figure 3-1. Typical Bypass Diode Placement Within A Photovoltaic Module

The solar cell area connected in parallel within the module determines the current which could be forced through the bypass diode in the forward direction since it must be assumed that an entire parallel group within the bypassed element could be shadowed or failed as a complete open-circuit. Under either of these two conditions, the bypass diode could be required to pass the rated short-circuit current of the module.

The analysis of various module sizes, which was performed as part of the Integrated Residential Array Study and reported in the final report (DOE/JPL 955894-4), has revealed that the majority of circuit design options for module sizes ranging from 2' x 4' to 4' x 8' can be accommodated with bypass diodes with forward current carrying capacities of 36 amperes or lower.

3.2 SURVEY OF DIODE MANUFACTURERS

An evaluation of diode types indicated that both the PN junction silicon diode and Schottky barrier diode are applicable as solar cell bypass devices. Though higher priced, the Schottky diode provides a lower forward voltage drop (i.e., approximately one-half that of the PN junction diode) and consequently lower power dissipation requirements for a given current carrying capacity.

The diode manufacturers listed in Table 3-1 were canvassed to obtain information regarding the availability of specific types of PN junction and Schottky diodes. Inputs obtained from this survey indicated that a large number of diode manufacturers only supply the communications market with high frequency tuning diodes in the forward current range up to approximately 1 ampere. Power type rectifier diodes more closely match the requirements for photovoltaic cell bypass diodes. However, most power diode manufacturers are engaged in producing high frequency, fast recovery units, many with high reverse voltage (blocking) capability for use in switching power supplies where a very large market presently exists. Other manufacturers specialize in packaging groups of rectifiers in bridge configurations for full cycle/full power AC rectification. From both a cost and requirements standpoint, the more mundane general purpose rectifier diode is most applicable for solar cell bypass applications in either PN junction or Schottky form.

Table 3-1. Diode Manufacturers Canvassed

- Alpha Industries
- American Power Devices
- Amperex Electronic
- Baytron
- Collmer Semiconductors/Fuji Electric
- Cherry Semiconductor
- Crimson Semiconductor
- Diode Transistors
- EDAL Industries
- EDI Electronic Devices
- Eaton Corp - Addington Semiconductor
- Ferranti Electric
- Fairchild Semiconductor Products
- FMC - Semiconductor Products
- GE - Electronic Component Sales
- General Instruments Discrete Semiconductors
- General Semiconductors
- GTE/Sylvania Semiconductor Products
- Hitachi America
- International Diode
- International Rectifier
- ITT Semiconductors
- Microwave Associates
- Motorola Semiconductor Products
- NAE
- NEC Electron
- PPC Products
- Parametric Industries
- RCA - Solid State
- Semicon
- Semitronics
- Solitron Devices
- Solid State Devices
- ST - Semicon
- Schauer
- Siemens - Colorado Components
- Sprague Electric
- Shigoto Far East
- Teledyne - Crystalonics
- Texas Instruments - Semiconductor Products
- Thompson CSF Components - Semiconductors
- Toshiba Semiconductors
- TRW - Power Semiconductor
- Unitrode
- Varo Semiconductor
- Westinghouse - Semiconductor

3.3 APPLICABLE PACKAGED DIODES

3.3.1 PACKAGED DIODE MANUFACTURERS

Of the diode manufacturers surveyed, those producing packaged PN junction and Schottky diodes applicable as solar cell bypass devices are presented in Table 3-2. In addition to the manufacturer's name and location, the diode rating, its standard enclosure (i.e., package or case type) and designation are provided.

Diodes are rated at their maximum permissible forward current (I_F), generally at an upper limit of case temperature (Note: above which the diode must be derated), and their reverse or blocking voltage (V_R) capability. The forward current rating is based on AC operation; when DC is applied, its current rating for the same case temperature, can generally be increased by approximately 25 percent. Reverse voltage ratings for a PN junction diode can exceed 1,000 V with the lowest ratings set at 50 V. Schottky diodes presently have an upper limit of 45 V and 20 V for the low end of the scale. Lower reverse voltage rated diodes are generally lower priced. The reverse or blocking voltage level required for bypass devices based on 15 solar cells in series is 11 V (i.e., 0.75 V/cell x 15 cells). Applying a conservative safety factor, a diode rated at 20 V blocking voltage should be more than adequate. Though PN junction diodes rated below 50 V do not appear in manufacturer's offerings, they are available and probably at reduced costs. Diode manufacturing processes are set up for obtaining the desired higher reverse voltage devices; however, the yield provides units across the full voltage spectrum. The output of a production lot is run through a test/selection procedure that segregates units by reverse voltage capability. PN junction devices below 50 V may very well be discarded by the manufacturer.

3.3.2 PACKAGED DIODE CHARACTERIZATION AND COSTS

Typical characteristics of packaged PN junction and Schottky diodes are presented in Table 3-3. The operational values indicated are typical of the group of diodes previously identified in Table 3-2 as applicable for solar cell bypass devices.

Table 3-2. Packaged Diode Manufacturers
Forward Current Range: 5 to 60 Amperes

MANUFACTURER (LOCATION)	FORWARD CURRENT (I_F); REVERSE VOLTAGE (V_R); PACKAGE TYPE; IDENT. NO.							
	SILICON PN JUNCTION GENERAL PURPOSE DIODES				SCHOTTKY BARRIER DIODES			
	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.
EDAL (East Haven, CT)	5	50	Axial-Plastic	MA5A5				
	6	50	"	MA7A5				
	16	50	D04	E4A3				
	22	50	D04	E7A3				
	30	50	D05	F3A3				
	37	50	D05	F4A3				
	45	50	D05	F5A3				
General Electric - Electronic Component Sales (Auburn, NY)	5	50	D04	1N1612				
	6	50	D04	1N1341A				
	12	50	D04	1N1199A				
	10	50	D05	1N248				
	20	50	D05	1N248A				
	20	50	D05	1N1191A				
	35	50	D05	1N2154				
	40	50	D05	1N1183A				
General Instrument (Hicksville, NY)	6	50	Axial-Plastic	P600A	5	20	D021AD	SB520
	25	50	Button-Plastic	AR25A	8	20	T0220	SB820
NAE (Lynn, MA)	12	50	D04	1N1199	30	20	D04	NSD3020
	3	50	D05	1N1183	35	30	D04	1N6095
					60	20	D05	NSD6020
					60	30	D05	1N6097

Table 3-2. Packaged Diode Manufacturers
Forward Current Range: 5 to 60 Amperes (Cont)

MANUFACTURER (LOCATION)	FORWARD CURRENT (I_F); REVERSE VOLTAGE (V_R); PACKAGE TYPE; IDENT. NO.							
	SILICON PN JUNCTION GENERAL PURPOSE DIODES				SCHOTTKY BARRIER DIODES			
	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.
International Rectifier (El Segundo, CA)	6	50	Axial	60S05	8	30	Axial	80SQ030
	12	50	D04	12F5	10	30	T0220	10TQ030
	12	50	D04	1N1199A				
	15	50	D04	1N3208	27.5	30	D04	1N6095
	16	50	D04	16F5	30	20	D04	21FQ030
	35	50	D04	1N1183	30	30	D04	20FQ020
	40	50	D05	40HF5	30	30	D04	30FQ030
	40	50	D05	1N1183A	55.5	30	D05	1N6097
					60	30	D05	52HQ030
					60	20	D05	50HQ020
Motorola Semiconductor (Phoenix, AZ)	6	50	Axial-Plastic	MR750	5	20	Case 60	1N5823
	12	50	D04	1N1199	15	20	D04	1N5826
	12	50	D04-Plastic	1N1199C	15	20	D04	MBR1520
	15	50	D05	1N3208	25	20	D04	1N5829
	20	50	D05	1N1191	25	20	D04	MBR2520
	20	50	D05-Plastic	MR2000S	25	30	D04	1N6095
	25	50	Button-Plas.	MR2500	35	20	D04	MBR3520
	25	50	D021	1N3491	40	20	D05	1N5832
	30	50	D021-Plastic	1N3659	40	20	D05	MBR4020
	40	50	D05	1N1183	40	20	D021	MBR2020A
	50	50	Case 43-04	MR5005	50	30	D05	1N6097
					60	20	D05	MBR6020
Microwave Associates (Burlington, MA)					30	45	D04	SD41
					60	45	D05	SD51

Table 3-2. Packaged Diode Manufacturers
Forward Current Range: 5 to 60 Amperes (Cont)

MANUFACTURER (LOCATION)	FORWARD CURRENT (I_F); REVERSE VOLTAGE (V_R); PACKAGE TYPE; IDENT. NO.							
	SILICON PN JUNCTION GENERAL PURPOSE DIODES				SCHOTTKY BARRIER DIODES			
	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.
Seimans-Colorado Components (Broomfield, CO)	12	50	D04	S20405	30	30	D04	1N6095
	16	50	D04	S2005	60	30	D05	1N6097
	22	50	D04	S2105				
	30	50	D05	S3105				
	37	50	D05	S3205				
	40	50	D05	S30405				
	45	50	D05	S3405				
Semicon (Burlington, MA)	5	50	D04	1N1612&A	5	30	Body C-Axial	SSH5A20
	5	50	D04	1N2228	30	20	D04	SSH30A020S
	6	50	D04	1N2491	30	20	T03	SSH30A020D
	12	50	D04	1N1199	75	20	D05	SSH75A020
	10	50	D04	1N2246A	75	20	D021	SSH75A020V
	16	50	D04	1N3615				
	20	50	D05	1N2488				
	35	50	D05	1N1183				
	18	50	D05	1N1191				
	22	50	D05	1N1191A				
	37	50	D05	1N2128				
	25	50	D05	1N2154				
	45	50	D05	1N2446				
	15	50	D05	1N3208				
	25	50	D05	S25A05				
	40	50	D05	S40A05				
	18	50	D021	1N3491				
	25	50	D021	1N3659				
	50	60	D021	SR5005				

Table 3-2. Packaged Diode Manufacturers
Forward Current Range: 5 to 60 Amperes (Cont)

MANUFACTURER (LOCATION)	FORWARD CURRENT (I_F); REVERSE VOLTAGE (V_R); PACKAGE TYPE; IDENT. NO.							
	SILICON PN JUNCTION GENERAL PURPOSE DIODES				SCHOTTKY BARRIER DIODES			
	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.
Solitron	5	50	Body C-Axial	5A50	8	10	D04	SSP810
(San Diego, CA) - PN	5	50	Body D-Axial	5C50	8	20	D04	SSP820
(Riviera Beach, FL) -	12	50	D04	1N1199A7B	15	10	D04	SS1510
Schottky	6	50	D04	1N1341	15	20	D04	SS1522
	5	50	D04	1N2228	20	10	D04	SS2010
	6	50	D04	1N2491	20	20	D04	SS2020
	20	50	D05	1N2488	30	5	D04	SS3005
	35	50	D05	1N1183	30	10	D04	SS3010
	40	50	D05	1N1183A	30	20	D04	SS3020
	18	50	D05	1N1191				
	37	50	D05	1N1301				
	30	50	D05	1N1434				
	25	50	D05	1N2154				
	15	50	D05	1N3208				
ST-Semicon	6	100	Al-Axial	6AL1				
(Bloomington, IN)	6	100	QD-Quick Connect	6QD1				
	6	100	D04	10H3P				
	12	100	D04	ST210P				
	16	100	D05	ST210E				
	25	100	D05	ST310P				
	40	100	D05	ST410P				
	50	100	D05	ST5A10P				

Table 3-2. Packaged Diode Manufacturers Forward Current Range: 5 to 60 Amperes (Cont)

MANUFACTURER (LOCATION)	FORWARD CURRENT (I_F); REVERSE VOLTAGE (V_R); PACKAGE TYPE; IDENT. NO.							
	SILICON PN JUNCTION GENERAL PURPOSE DIODES				SCHOTTKY BARRIER DIODES			
	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.
TRW Semiconductor (Lawndale, CA)					30 30 25 50 60	50 45 30 30 45	D04 D04 D05 D05 D05	SD32 SD41 1N6095 1N6097 SD51
Unitrode (Lexington, MA)	7.5 9 12	50V 50V 50V	Body C-Stud Body C-Stud Body C-Stud	UT5105 UT6105 UT8105	12 16 25 30 40 50 60	20 20 30 45 20 30 45	T0220 T0220 D04 D04 D04 D05 D05	USD820 USD920 1N6095 SD41 USD420 1N6097 SD51
Varo (Garland, TX)					5 15 30 40 60	20 20 20 20 45	Axial D0203AA D0203AA D05 D05	VSK520 VSK1520 VSK3020 VSK4020 VSK6020

Table 3-2. Packaged Diode Manufacturers
Forward Current Range: 5 to 60 Amperes (Cont)

MANUFACTURER (LOCATION)	FORWARD CURRENT (I_F); REVERSE VOLTAGE (V_R); PACKAGE TYPE; IDENT. NO.							
	SILICON PN JUNCTION GENERAL PURPOSE DIODES				SCHOTTKY BARRIER DIODES			
	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.	I_F(A)	V_R(V)	PACKAGE TYPE	IDENT. NO.
Westinghouse - Semiconductor (Youngwood, PA)	5	50	D04	1N1612				
	6	50	D04	1N1341				
	6	50	D027-Axial	R340				
	12	50	"	1N1199				
	15	50	D05	1N3208				
	16	50	D04	1N3615				
	18	50	D05	1N1191				
	20	50	D05	1N248				
	22	50	D05	1N1191A				
	25	50	D05	1N2154				
	35	50	D05	1N1183				
	40	50	D05	1N1183A				
	60	50	D05	R404				

Table 3-3. Typical Characteristics of PN Junction and Schottky Diodes

PN JUNCTION DIODES[1]

- MAX. JUNCTION TEMP. = 175°C (ZERO CURRENT CARRYING CAPACITY)
- REVERSE BLOCKING VOLTAGE = 50 V
- REVERSE CURRENT = 1 μa TO 10 ma
- FORWARD VOLTAGE DROP = 0.9 TO 1.2 V

SCHOTTKY DIODES[1]

- MAX. JUNCTION TEMP. = 150°C (ZERO CURRENT CARRYING CAPACITY)[2]
- REVERSE BLOCKING VOLTAGE = 20 V
- REVERSE CURRENT = 400 μa TO 400 ma
- FORWARD VOLTAGE DROP = 0.5 TO 0.6 V

TYPICAL THERMAL RESISTANCE JUNCTION TO CASE ($R_{\theta JC}$)
(FUNCTION OF PACKAGE TYPE)

PACKAGE TYPE	$R_{\theta JC}$ (°C/W)
AXIAL	10-15[3]
TO 220	3
TO 3	1
DO 4	2.5
DO 5	1
DO 21	1

(1) FORWARD AND REVERSE CURRENT AND VOLTAGE CHARACTERISTICS VARY WITH THE SPECIFIC DIODE SELECTED.

(2) SOME MANUFACTURERS HAVE DEVELOPED PROCESSES THAT HAVE RAISED THIS LIMIT TO 175°C.

(3) A FUNCTION OF LEAD LENGTH USED.

The typical maximum junction temperature of the PN junction diode is 175°C. At this level, the diode exhibits zero current carrying capability. Full rated forward current operation is possible up to approximately 150°C, with a rapid drop-off in current capability as the junction temperature rises to the 175°C limit. A number of manufacturers provide diodes that have a somewhat higher maximum junction temperature rating, with the zero current carrying limit reached at 200°C as opposed to the typical value of 175°C indicated. Schottky diode maximum junction temperature is somewhat lower, typically rated at 150°C at which point zero current can be passed. Recent manufacturing process developments have raised the Schottky junction temperature limit to 175°C. A limited number of manufacturers presently produce the 175°C maximum junction temperature Schottky diode (e.g., International Rectifiers "830" Process Schottkys).

As discussed in Section 3.2.2.1, the lowest specified reverse blocking voltages of 50 V for the PN junction and 20 V for the Schottky are typically applicable for bypass devices. Though a lower than 50 V rated PN junction diode blocking voltage would suffice, it cannot presently be ordered by standard part number. It should also be pointed out that higher reverse voltage capability in a diode is obtained at the expense of a somewhat greater forward voltage drop and consequent higher forward power losses.

Reverse current and forward voltage drop characteristics of diodes vary with junction temperature and the specific standard diode specified. Values indicated for these parameters in Table 3-3 represent a range of applicable values at the higher junction operating temperature (e.g., 125°C). Reverse leakage current values presented are at the specified reverse voltage rating of the diode. At either lower reverse voltage or lower junction temperatures, reverse leakage current is considerably reduced. The forward voltage drops indicated correspond to values at rated forward current levels. At current levels below rated value, forward voltage drop is reduced somewhat. A reduction in junction temperature, however, increases forward voltage drop due to a negative temperature coefficient in forward mode operation.

Schottky reverse leakage current is generally higher than that experienced with PN junction diodes, though still within tolerable levels for the bypass application under consideration. On the other hand, Schottky diodes exhibit forward voltage drops on the order of one-half that of the PN junction diode. This results in lower power losses and reduced heat dissipation requirements to maintain acceptable junction temperatures. Diodes that fall within the lower end of the reverse leakage current or forward voltage drop bands indicated in Table 3-3 are readily available, but usually at a somewhat higher price.

Typical junction-to-case thermal resistance (in °C/W) for the standard package types used with these diodes is also provided in Table 3-3. For the lower current diodes of interest (i.e., 5 to 8 amperes) where axial leaded packaging is used, the junction-to-lead thermal resistance varies as a function of the lead length to heat sink (e.g., 3/8" lead length = ~ 15°C/W). The higher current carrying diode chips are packaged in larger case types with improved heat dissipation capability that results in thermal resistance as low as 1°C/W. It should be noted that the diode chip size, the associated case heat dissipation capacity and the quality of the bond determine the thermal resistance level.

The values presented in Table 3-3 represent a composite picture of many diodes in a particular class at a specified operational point (i.e., diode junction temperature or rated forward current). Specific values for each of the parameters indicated are a function of the particular operating conditions. Appendix A presents detail operating characteristics of a number of typical packaged PN junction and Schottky diodes with forward current ratings of 6 to 50 amperes. For each diode type, in addition to a tabular listing of rated values at specific operating points, the following curves, which show the variation of critical parameters with temperature, are presented in Appendix A.

- Forward current versus forward voltage drop as a function of junction temperature.
- Reverse current versus reverse voltage as a function of junction temperature.
- Forward current derating as a function of package case temperature or lead temperature (for axial leaded diodes).

Tables 3-4 through 3-9 provide pictorial presentations of each of the diode package configurations, the JEDEC standard dimensions, and the 1981 price range of both PN junction and

Schottky diodes. Pricing is indicated for quantities of one thousand, fifty thousand, two hundred thousand and two million. The price range presented for a particular class of packaged diode represents the lowest and highest budgetary quotation obtained from the diode manufacturers listed in Table 3-2.

As indicated in Tables 3-4 through 3-9, for any given package type, the Schottky diodes are higher current rated because of their lower forward voltage drop and consequent lower heat dissipation requirements. It should also be pointed out, that the same diode wafer or chip when encased in a larger package type (i.e., greater heat sink capacity) can carry a higher current rating. There is however, a limit to extending a wafer's current carrying capacity based on its physical size. Progressively larger wafers are generally used to obtain higher current carrying capacities.

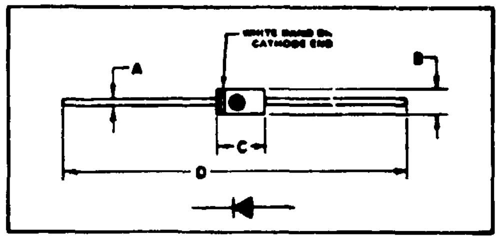
The low current carrying capacity diodes (i.e., up to 6 amp PN junction and 8 amp Schottky) are usually axial leaded plastic encased units (see Table 3-4) and are generally the lowest priced diodes.

T0220 type flat plastic packages (see Table 3-5) with an external copper heat sink are presently sold only with Schottkys and encompass the 10 to 20 ampere current range. By far, the majority of T0220 diode packages on the market today carry two diodes for full wave AC rectification. These contain three output leads, the center common lead used for connection to a transformer secondary center tap. For solar cell bypass devices, only a single diode in a T0220 package is needed and should be specified accordingly.

The T03 metal cap type package (see Table 3-6) is selectively used, and almost exclusively carries Schottky diodes at about the 30 amp rating. For this current rating, it is somewhat higher priced than other packages (e.g., the D04), but its two point tie-down provides a lower thermal resistance as previously indicated in Table 3-3. As in the case of the T0220, it usually contains two diodes for full wave rectification. Here again, if a T03 case is desired it must be specified as a single diode unit.

Table 3-4. Typical Axial Type Packaged Diode

LTR.	INCHES
A	.040 — .052
B	.190 — .225
C	.370 — .380
D	2.75



PN JUNCTION DIODES (V_R=50V)

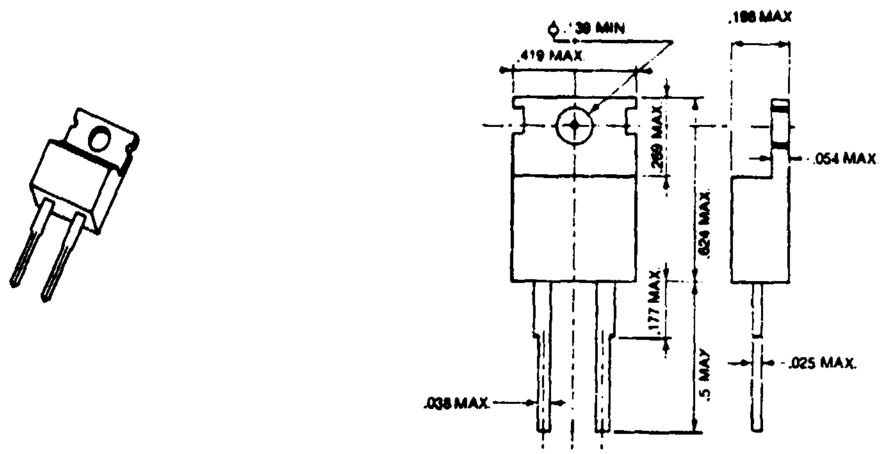
DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD(1) CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	5-6	.38 - .78	.19 - .40	.17 - .32	.16 - .30

SCHOTTKY DIODES (V_R=20V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD(1) CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	5-8	1.33-2.15	.85-1.41	.80 - 1.27	.69 - 1.02

(1) BASED ON DIODE USED FOR AC RECTIFICATION; IN DC APPLICATION HIGHER RATING (~25%) POSSIBLE.

Table 3-5. T0220 Type Packaged Diode

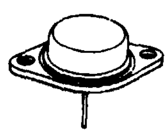


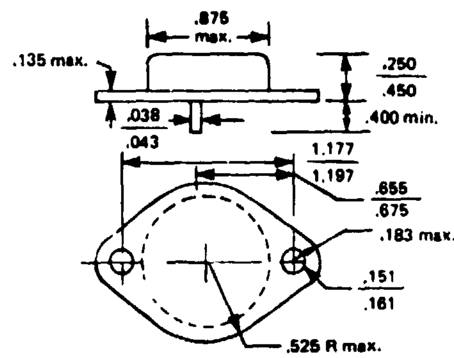
SCHOTTKY DIODES (V_R=20V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[1] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	8-16	.95-1.95	.62-1.15	.56 - 1.05	.48 - 1.00

(1) BASED ON DIODE USED FOR AC RECTIFICATION; IN DC APPLICATION HIGHER RATING (~25%) POSSIBLE.

Table 3-6. T03 Type Packaged Diode



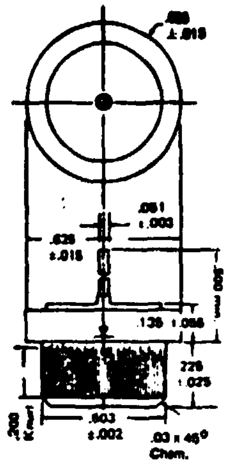


SCHOTTKY DIODES (V_R=20V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[1] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	30	3.50-3.93	2.30-3.25	2.07-3.10	1.80-2.48

(1) BASED ON DIODE USED FOR AC RECTIFICATION; IN DC APPLICATION HIGHER RATING (~25%) POSSIBLE.

Table 3-7. D021 Type Packaged Diode



PN JUNCTION DIODES (V_R=50V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[1] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
1N 3491	18	.59-.75	.46-.69	.45-.66	.44-.63
1N 3659	25	.83-.88	.63-.80	.60-.76	.57-.72
R5005[2]	50	1.20-1.42	1.08-1.15	.96-1.10	[illegible]-1.05

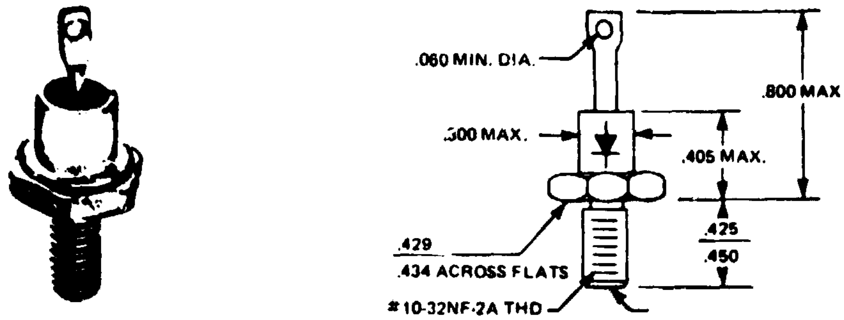
SCHOTTKY DIODES (V_R=20V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[1] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	40-75	3.80-4.18	3.30-3.45	3.00-3.28	2.62-2.80

(1) BASED ON DIODE USED FOR AC RECTIFICATION; IN DC APPLICATION HIGHER RATING (~25%) POSSIBLE.

(2) REVERSE BLOCKING VOLTAGE (V_R) = 75 TO 80V.

Table 3-8. D04 Type Packaged Diode



PN JUNCTION DIODES (V_R=50V)

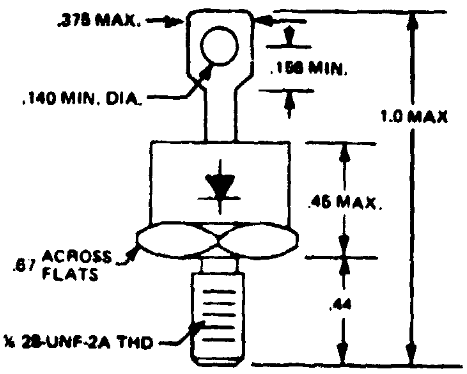
DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[(1)] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
1N1612	5	.99-1.15	.90-.95	.70-.91	.60-.88
1N2228	5	.95-1.15	.70-.92	.65-.89	.65-.86
1N2491	6	.97-1.15	.70-.94	.65-.93	.65-.89
1N1341	6	.79-1.15	.39-.90	.35-.70	.35-.60
1N2246A	10	1.14	1.02	1.00	.96
1N1199	12	.65-1.19	.51-1.07	.50-1.04	.48-1.01
1N3208	15	1.24-2.10	1.09-1.70	1.01-1.40	.91-1.29
1N3615	16	.81-1.55	.75-1.40	.72-1.15	.70-1.11

SCHOTTKY DIODES(V_R=20V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[(1)] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	15	2.40-3.75	1.55-3.55	1.47-3.38	1.40-3.38
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	20-30	2.50-4.90	1.86-4.65	1.76-4.42	1.68-4.42
1N6095[(2)]	25	2.50-4.20	1.83-3.26	1.63-3.26	1.57-3.26
SD 41[(3)]	30	2.80-4.20	2.05-3.10	1.85-3.00	1.65-3.00

(1) BASED ON DIODE USED FOR AC RECTIFICATION: IN DC APPLICATION HIGHER RATING (~25%) POSSIBLE.
(2) REVERSE BLOCKING VOLTAGE (V_R) = 30V.
(3) REVERSE BLOCKING VOLTAGE (V_R) = 45V.

Table 3-9. D05 Type Packaged Diode



PN JUNCTION DIODES (V_R=50V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[(1)] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
1N1191	19	1.12-1.89	1.06-1.76	.87-1.76	.85-1.76
1N2488	20	2.05-2.10	1.70-1.78	1.40-1.78	1.29-1.78
1N2154	25	1.31-2.10	1.18-1.70	1.15-1.50	1.11-1.29
1N1434	30	1.35	1.30	1.20	1.05
1N1183	35	1.06-2.10	.85-1.70	.83-1.41	.80-1.40
1N2128	37	1.93	1.76	1.59	1.33
1N1301	37	1.50	1.24	1.15	1.00
1N1183A	40	2.16-3.70	1.80-2.00	1.50-1.80	1.27-1.80
1N2446	45	1.81	1.65	1.49	1.24

SCHOTTKY DIODES (V_R=20V)

DIODE IDENTIFICATION NUMBER (JEDEC)	AVERAGE FORWARD[(1)] CURRENT RATING (I_f)	PRICE RANGE ($/UNIT) - 1981			
		1K	50K	200K	2M
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	40	3.80-4.48	3.30-4.00	3.00-3.60	2.40-3.12
1N6097[(2)]	50	3.50-5.05	2.50-4.20	2.40-4.20	2.30-4.20
MFG'S. INDIVIDUAL IDENTIFICATION NOS.	60	3.00-4.48	2.45-3.45	2.40-3.29	2.30-3.12
SD61[(3)]	60	3.80-5.06	3.10-3.70	2.70-3.28	2.40-3.28

(1) BASED ON DIODE USED FOR AC RECTIFICATION; IN DC APPLICATION HIGHER RATING (≈25%) POSSIBLE.
(2) REVERSE BLOCKING VOLTAGE (V_R) = 30V.
(3) REVERSE BLOCKING VOLTAGE (V_R) = 45V.

D021 press fit type packages (see Table 3-7) are extensively used for both PN junction and Schottky diodes in current carry capacities from approximately 20 to 70 amperes, the Schottky being the higher current rated units because of their lower heat dissipation requirements. For comparable current carrying capacity, the D021 packaged diode is competitively priced with other package types.

The D04 and D05 (See Tables 3-8 and 3-9) stud mount diode packages are the most popular and are available in a broad range of current carrying capacities. D04 packages generally encompass diodes in the 10 to 20 ampere range for the PN junction and 15 to 30 amperes for the Schottky. The D05 package, with its larger case dimensions, provides a much lower junction-to-case thermal resistance and, therefore, for the same diode wafer, permits higher current loads. D05 current ratings include 20 to 40 ampere units for PN junction diodes and 40 to 60 amperes for the Schottky devices.

Packaged PN junction diodes, priced at the 1,000 quantity level range from $0.40 for low current units to as high as $2.00 for higher current rated devices. Corresponding Schottky packaged diodes are priced from $1.00 to $5.00. At the 2 million quantity level, the axial leaded, T0220 and T03 packaged unit prices are reduced by approximately 50 percent. The D021, D04 and D05 packaged diode prices are reduced only about 30 to 40 percent at the larger quantity level, possibly attributable to the fact that these diode units are presently in higher volume production and therefore somewhat lower priced.

3.4 APPLICABLE DIODE CHIPS

3.4.1 DIODE CHIP MANUFACTURERS

Packaged diode manufacturers were canvassed to determine whether they presently sell or would be interested in supplying diode chips (Note: commonly referred to as dies in the industry). Most refused and some hesitated to sell PN junction diode chips for the following reasons: (1) they are very thin devices that are hard to handle, fragile and easily cracked; (2) difficult to test in chip form; and (3) experience has indicated that most purchasers have difficulty in properly bonding the chip to another surface. Over the years, diode manufacturers have developed in-house techniques for properly handling and mounting these thin devices in standard packages and, therefore, to avoid problems, prefer to sell only packaged PN junction diodes. The few manufacturers that presently sell unmounted PN junction chips, usually are providing one or two types in large quantities to a purchaser who has developed processes for properly incorporating the chips in their particular product.

Table 3-10 presents a list of potential diode chip suppliers. Some presently supply chips; others expressed an interest if quantities ordered are substantial.

Table 3-10. Potential Diode Chip Suppliers

• Unitrode	PN Junction (limited unmounted types) and Schottky
• International Rectifier	PN Junction (limited unmounted types) and Schottky
• Semicon	PN Junction (mounted types) and Schottky
• General Instruments - Discrete Semiconductors	PN Junction (one mounted type)
• Microwave Associates	Schottky
• TRW - Power Semiconductor	Schottky
• Motorola Semiconductor	Schottky
• Varo Semiconductor	Schottky

3.4.2 DIODE CHIP CHARACTERIZATION AND COSTS

Characterization and costs of mounted PN junction diode chips are presented in Table 3-11. These chips represent the offerings of a single supplier who mounts the PN junction chips between silver clad aluminum transition pieces which are used in a packaged diode line as well as being sold separately in mounted chip form. These mounted PN junction chips can readily be handled and bonded to a heat sink without damaging the diode device. Prices indicated are based on the chip meeting a maximum reverse blocking voltage of 50 V and a reverse leakage current no greater than 10 ma at the 50 V reverse voltage level. Prices of chips ordered to standard packaged diode number (i.e., standard specification), most of

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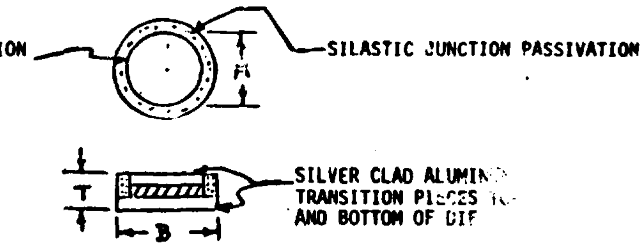
Table 3-11. PN Junction (Silicon) Diode Chip Characterization



TYPICAL CHARACTERISTICS(1)

- MAX JUNCTION TEMP ($T_{J\ MAX}$) = 175°C (ZERO CURRENT CARRYING CAPACITY)
- MAX. REVERSE VOLTAGE (V_R) = 50V
- MAXIMUM REVERSE CURRENT (I_R) = 1 μa TO 10 ma(2)
- TYPICAL FORWARD VOLTAGE DROP (I_F) = 0.9 TO 1.2V(2)

SIZE AND PRICING(1)

APPROXIMATE(3) CURRENT CARRYING CAPACITY (I_F) (AMPS)	TYPICAL ASSOCIATED PACKAGED DIODE DESIGNATION (AND CASE STYLE)	APPROXIMATE(4) THERMAL RESISTANCE JUNCTION TO SINK (°C/W)	CHIP DIMENSIONS (INCHES)			PRICE ($/UNIT)(5) - 1981			
			A	B	T	1K	50K	200K	2M
12	1N1199, 1N2246A (DO4)	2.5	.120	.140	.060	.69	.59	.45	.39
20	1N3615 (DO4); 1N2488, 1N1191, 1N1191A, 1N3208 (DO5); 1N3491 (DO21)	1.0	.140	.160	.060	.84	.69	.61	.44
25	1N2154 (DO5); 1N3659 (DO21)	1.0	.200 (SQUARE)	.220	.060	1.05	.80	.65	.55
35-50	1N1183, 1N2446, 1N2128 (DO5)	1.0	.200	.220	.050	1.20	1.05	.80	.66

(1) OFFERING OF A SINGLE SUPPLIER WHO PROVIDES COMPLETE LINE OF MOUNTED PN JUNCTION CHIPS USED IN HIS PACKAGED DIODES. VERY FEW SUPPLIERS WILL PROVIDE PN CHIPS SINCE THEY ARE EXTREMELY FRAGILE, DIFFICULT TO TEST, ETC. IN UNMOUNTED FORM.
(2) WHEN CHIP ORDERED BY STANDARD PACKAGED DIODE NUMBER, IT WILL MEET SPECS. ASSOCIATED WITH THAT PARTICULAR UNIT.
(3) BASED ON DIODE USED FOR AC RECTIFICATION; IN DC APPLICATION HIGHER RATINGS (~25%) POSSIBLE.
(4) BASED ON USE OF LOWEST THERMAL RESISTANCE TO CASE, WHEN PACKAGED IN LARGEST CASE USUALLY USED.
(5) PRICES INDICATED BASED ON CHIP MEETING MAX. REVERSE BLOCKING VOLTAGE LIMIT OF 50V AND REVERSE (LEAKAGE) CURRENT NO GREATER THAN 10 ma @ V_R=50V. PRICES OF CHIPS ORDERED BY STANDARD PACKAGED DIODE NUMBER WHICH MEETS MORE STRINGENT REVERSE CURRENT LEAKAGE SPECS. ARE PRICED 20 TO 30% HIGHER.

which meet more stringent reverse current requirements, are priced 20 to 30 percent higher than the prices indicated in Table 3-11. The chip prices indicated in the table are not substantially lower than the corresponding packaged unit, since the chip mounting and Silastic junction passivation processes add to the cost of the basic chip.

Thermal resistance to sink values presented in the table match the typical resistance to case values for the particular diode chip in its largest standard package. The resistance of these chips bonded to flat plate heat sinks should prove somewhat lower than the values indicated.

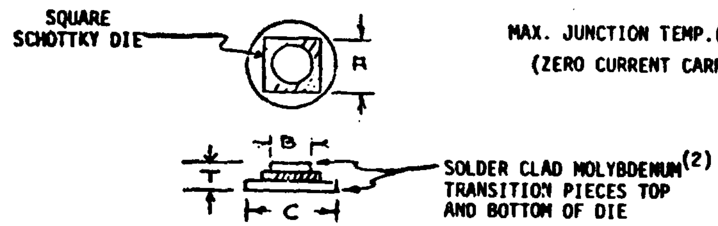
Table 3-12 presents Schottky chip characterization and costs. The chips indicated represent the typical size, operating characteristics and costs of the offerings of a number of Schottky chip suppliers. Schottky chips are considerably thinner and more fragile than mounted PN junction chips, and are mounted between two solder clad molybdenum transition pieces. Chip thickness, as well as plate heat sink thickness, are important parameters to be considered when encapsulating these devices within a PV module. As in the case of the PN junction diode, the junction-to-sink thermal resistance indicated has been conservatively estimated based on the typical resistance-to-case values for the chip in its largest standard package. Schottky chip prices are substantially lower than their corresponding packaged unit costs, since the chips used in packaged units are all initially mounted. Compared to mounted PN junction chips, the Schottky devices are on the order of 50-75 percent higher priced.

3.5 DIODE/HEAT SINK MOUNTING CONCEPTS

3.5.1 POTENTIAL MOUNTING LOCATIONS

A bypass diode can be mechanically and thermally integrated within a module by any one of several methods, some of which are illustrated in Figure 3-2. The details of the module design and the module attachment provisions will determine which method is best suited to a particular application. The methods depicted in Figure 3-2 include: (1) the diode chip soldered to a heat sink plate which is embedded within the module encapsulant; (2) a packaged diode mounted to a heat sink plate which is, in turn, attached to the back of the module; and (3) a packaged diode mounted to the frame of the module.

Table 3-12. Schottky Diode Chip Characterization



MAX. JUNCTION TEMP. ($T_{J\,MAX.}$) = 150°C(3)
(ZERO CURRENT CARRYING CAPACITY)

TYPICAL CHARACTERISTICS SIZE AND PRICING(1)

AVERAGE(4) FORWARD CURRENT RATING (I_F) (AMPS)	FORWARD VOLTAGE DROP	MAX. REVERSE VOLTAGE (V_R) AND REVERSE CURRENT LEAKAGE (I_R)	CHIP DIMENSIONS (IN.)				APPROX.(6) THERMAL RESISTANCE JUNCTION TO SINK (°C/W)	PRICE RANGE ($/UNIT) - 1981			
			A	B	C	T		1K	50K	200K	2M
15	.6V @ T_J=150°C .67V @ T_J=25°C	20V I_R<15 ma to 200 ma @ T_J=125°C I_R=2 ma to 9 ma @ T_J=25°C	.125	.100	.180	.035	2.5	.86 TO 1.20	.38 TO .88	.30 TO .81	.25 TO .75
30	.53V @ T_J=125°C .62V @ T_J=25°C	20V I_R=.4 ma(5) to 400 ma @ T_J=125°C I_R=.1 ma(5) to 10 ma @ T_J=25°C	.160	.140	.230	.035	2.0	1.44 TO 2.65	.64 TO 1.86	.55 TO 1.80	.50 TO 1.80
50	.53V @ T_J=125°C .62V @ T_J=25°C	20V I_R=13 ma(5) to 250 ma @ T_J=125°C I_R=.05 ma(5) to 75 ma @ T_J=25°C	.200	.175	.250	.035	1.0	1.43 TO 3.52	.71 TO 3.17	.64 TO 2.91	.60 TO 2.67

(1) BASED ON COMPOSITE OF AVAILABLE SCHOTTKY CHIPS.
(2) ALTERNATE: NICKEL PLATED, GOLD FLASHED MOLYBDENUM TRANSITION PIECES.
(3) SPECIAL MFG. PROCESSES RECENTLY DEVELOPED THAT HAVE RAISED THIS LIMIT TO 175°C.
(4) BASED ON DIODE USED FOR AC RECTIFICATION; IN DC APPLICATION HIGHER RATINGS (~25%) POSSIBLE.
(5) LOWER VALUES REFLECT USE OF PLATINUM BARRIER METAL (IN PLACE OF CHROME OR TUNGSTEN).
(6) BASED ON USE OF LOWEST THERMAL RESISTANCE TO CASE, WHEN PACKAGED IN LARGEST CASE USUALLY USED.

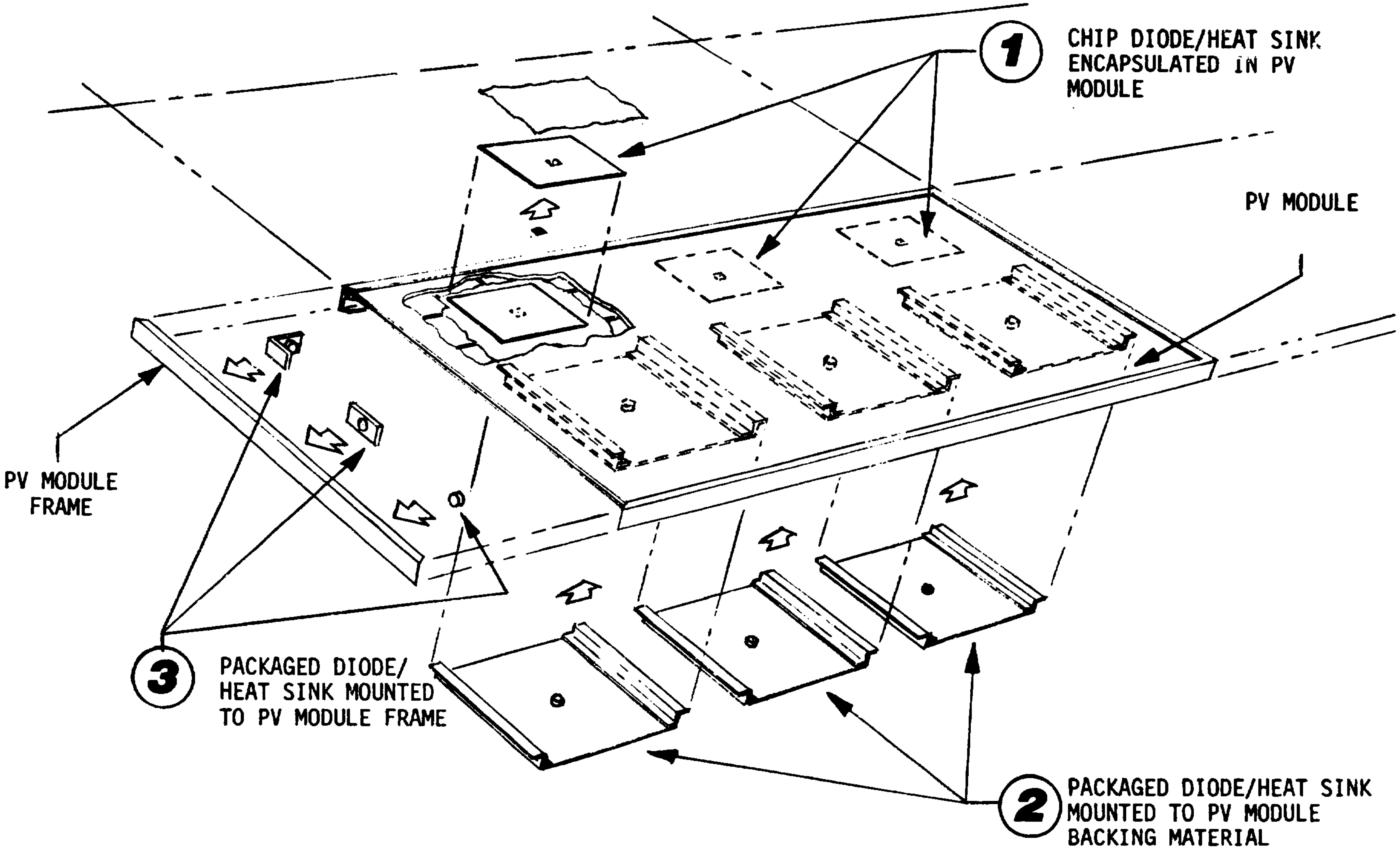


Figure 3-2. Concepts of Diode/Heat Sink Mounting to PV Module Assembly

The details of each of these mounting approaches are discussed in the following sections.

3.5.2 MODULE BACK MOUNTING

The mounting of a packaged diode/heat sink directly to the rear surface of a module can be accomplished in a variety of ways depending upon the nature of the diode package selected. For relatively low power dissipations, it may be adequate to use an axial lead diode in an existing AMP Solarlok enclosure as illustrated in Figure 3-3. In this case, the mounting pads of the plastic enclosure are bonded directly to the rear cover material of the module. This enclosure is sealed for outdoor exposure conditions and provides for the entrance and exit of insulated wiring.

For higher power dissipation capabilities, it will generally be necessary to mount the diode package to a separate heat spreader or heat sink as shown in Figures 3-4 through 3-7. In all of these illustrations, the diode is shown mounted to a planar aluminum heat spreader plate which is, in turn, bonded to the rear cover material of the module. For the vast majority of residential array installations, it is expected that air flow stagnation will occur over the rear surface of the module. Under these conditions there would be no advantage associated with the use of an extruded aluminum finned heat sink as the diode mounting substrate. However, the use of such a finned heat sink should be considered for a rack mounted module installation or for an integral mounting with forced air flow. Heat sink design guides supplied by Wakefield Engineering, Thermalloy, IERC and WEI are valuable sources of information in this area.

The heat spreader attachment to the back of the module will generally require stand-off brackets to allow space for the diode mounting hardware. Since it is customary for these packaged diodes to be supplied with the cathode lead as the case of the device, it will be necessary to attach an electrical lead to the case and to electrically isolate the case from the metallic heat sink which will be grounded as part of the array electrical safety procedure. A thermally conductive compound is used at all bolted interface surfaces to reduce the thermal resistance between the heat sink and the diode case.

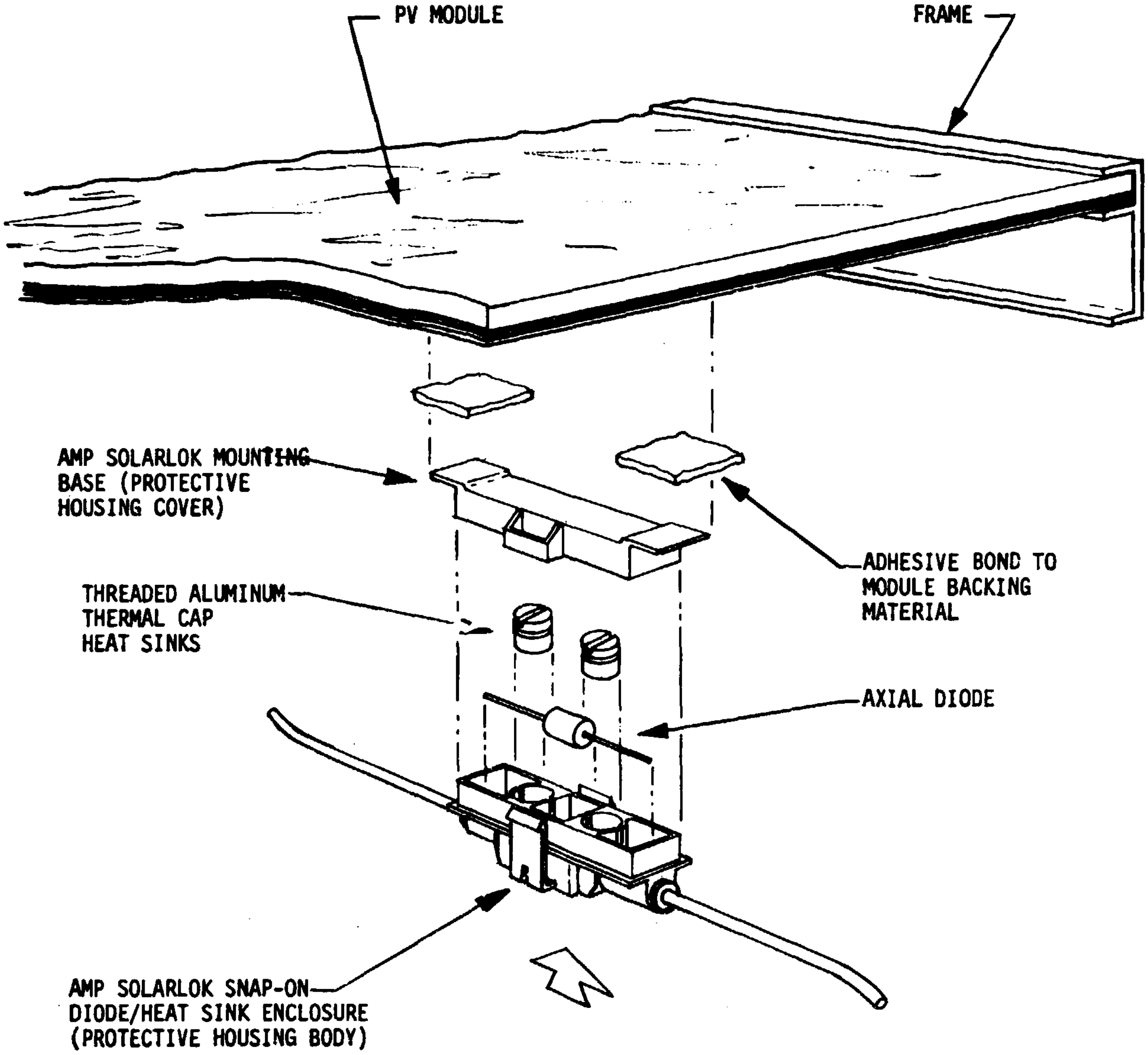


Figure 3-3. Axial Diode Package Mounted to Back of PV Module

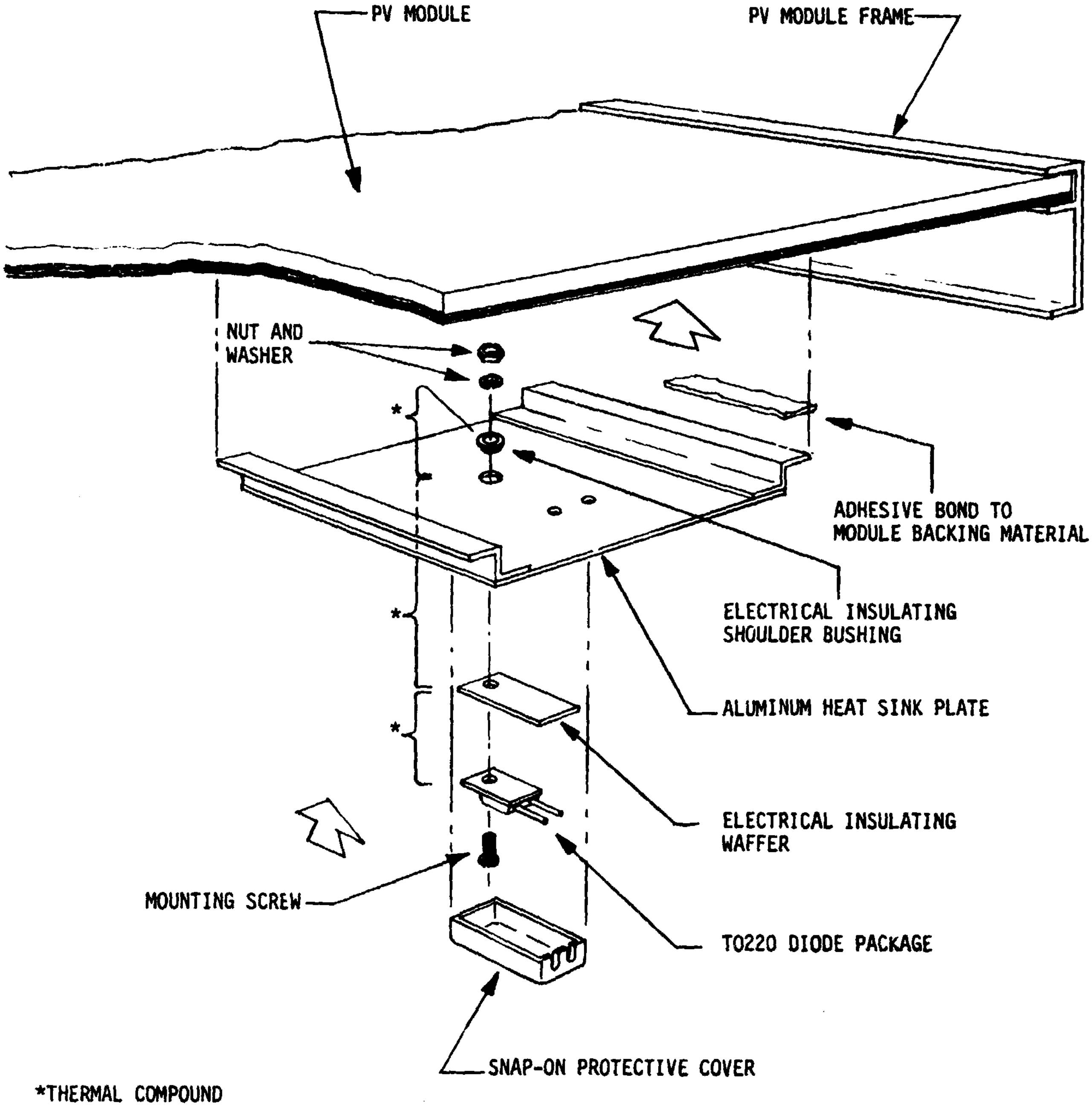


Figure 3-4. T0220 Diode Package Mounted to Back of PV Module

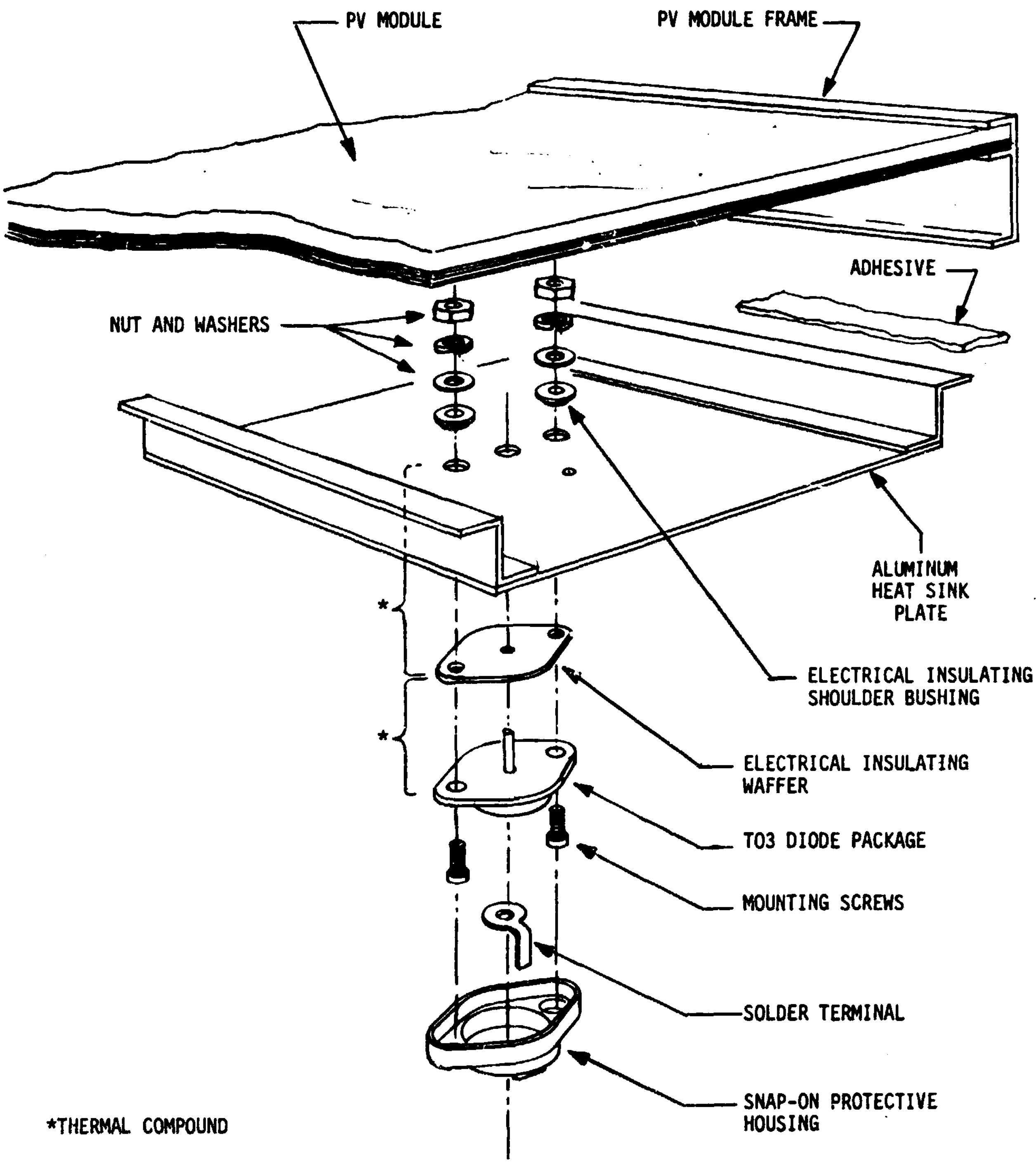


Figure 3-5. T03 Diode Package Mounted to Back of PV Module

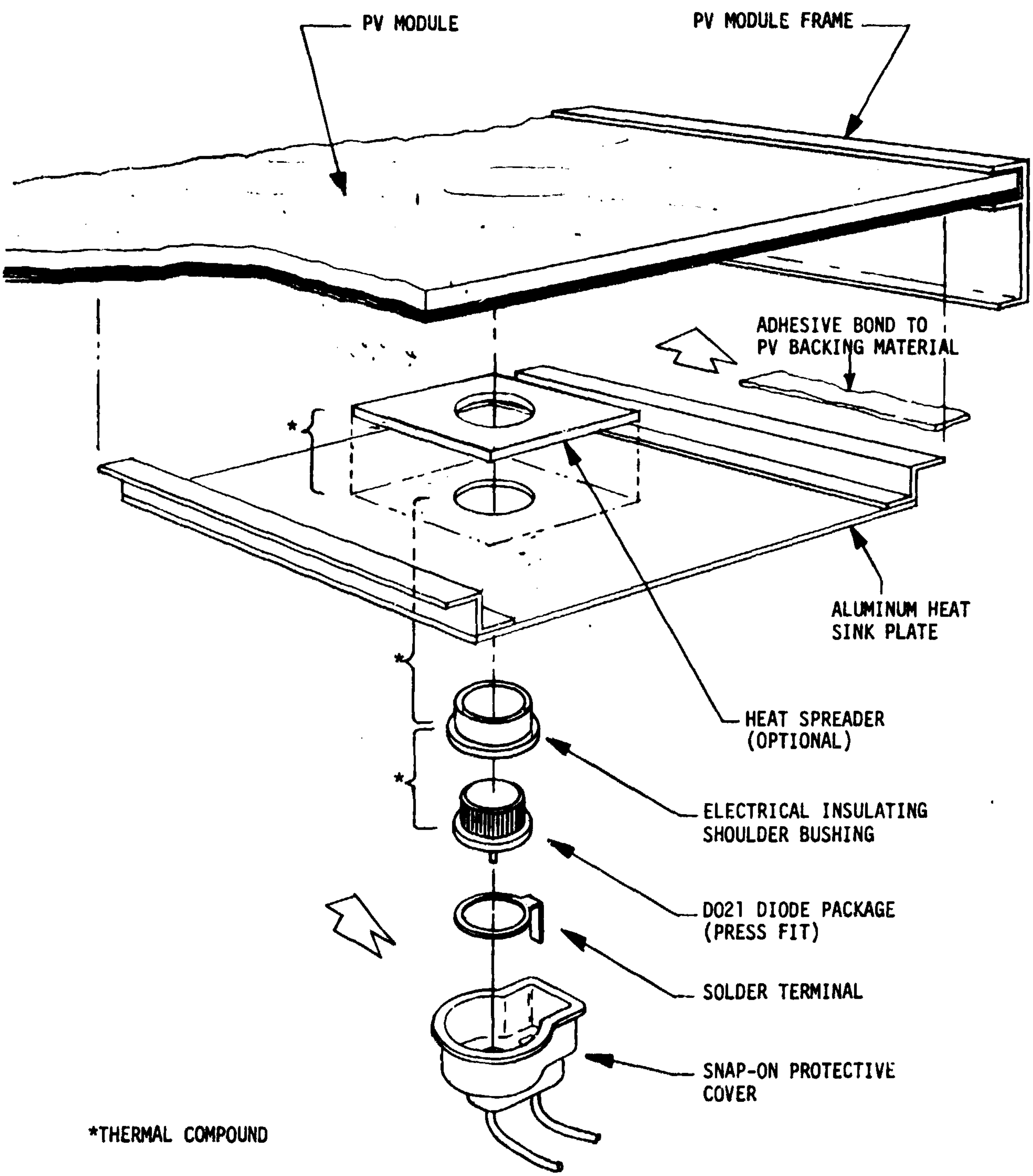


Figure 3-6. D021 Diode Package Mounted to Back of PV Module

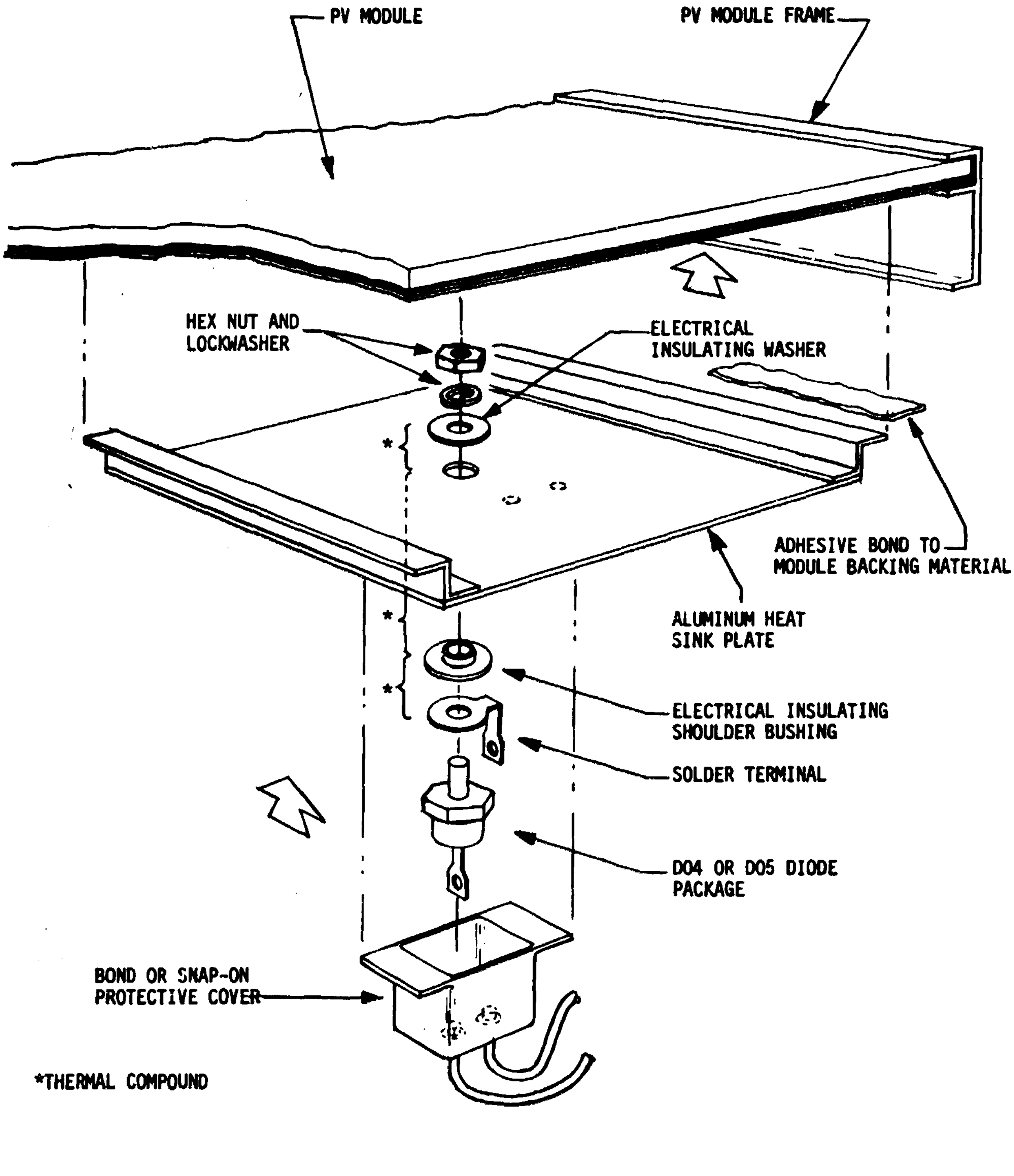


Figure 3-7. D04 or D05 Diode Package Mounted to Back of PV Module

A plastic cover will be required over the exposed diode case for electrical safety and to provide environmental protection. Special wiring provisions will be required to secure the diode leads with the proper strain relief and weather sealing.

3.5.3 MODULE FRAME MOUNTING

The mounting of packaged diodes on the module frame is depicted in Figures 3-8 through 3-12. The proximity of an adjacent module may dictate that the diode be mounted to a transition angle as shown in Figures 3-10 and 3-12. In all cases, where it is possible to physically touch the diode mounting hardware, as in Figure 3-12, it will be necessary to provide a plastic protective cap.

3.5.4 MOUNTING WITHIN ENCAPSULANT

Figure 3-13 illustrates a method for use in the mounting of diode chips on heat spreader plates which are laminated within the module encapsulant. The diode chip is soldered to a heat spreader which is fabricated from copper sheet material of the required thickness and size. This heat spreader also functions as one of the diode electrical leads. This thin sheet with the diode chip attached can then be positioned on the rear side of the solar cell circuit with suitable insulating layers and laminated within the encapsulated cell assembly as part of the same process step used to laminate the cells to the glass superstrate and rear cover sheet. Thus, the diode is environmentally protected by the same materials which encapsulate the solar cells. All diode leads and wiring are copper foil strips which are laminated within the cell stack-up.

3.6 DIODE/HEAT SINK THERMAL ANALYSIS

Thermal analysis evaluated diode junction temperatures parametrically as a function of diode parameters (i.e., power dissipation and thermal resistance from junction to the heat sink mounting surface) and diode mounting concept for both packaged and chip type diodes. Each of the diode mounting concepts incorporated a high thermal conductivity mounting surface (block, plate, frame, etc.) which served to promote the flow of heat from the diode to the surrounding thermal environment.

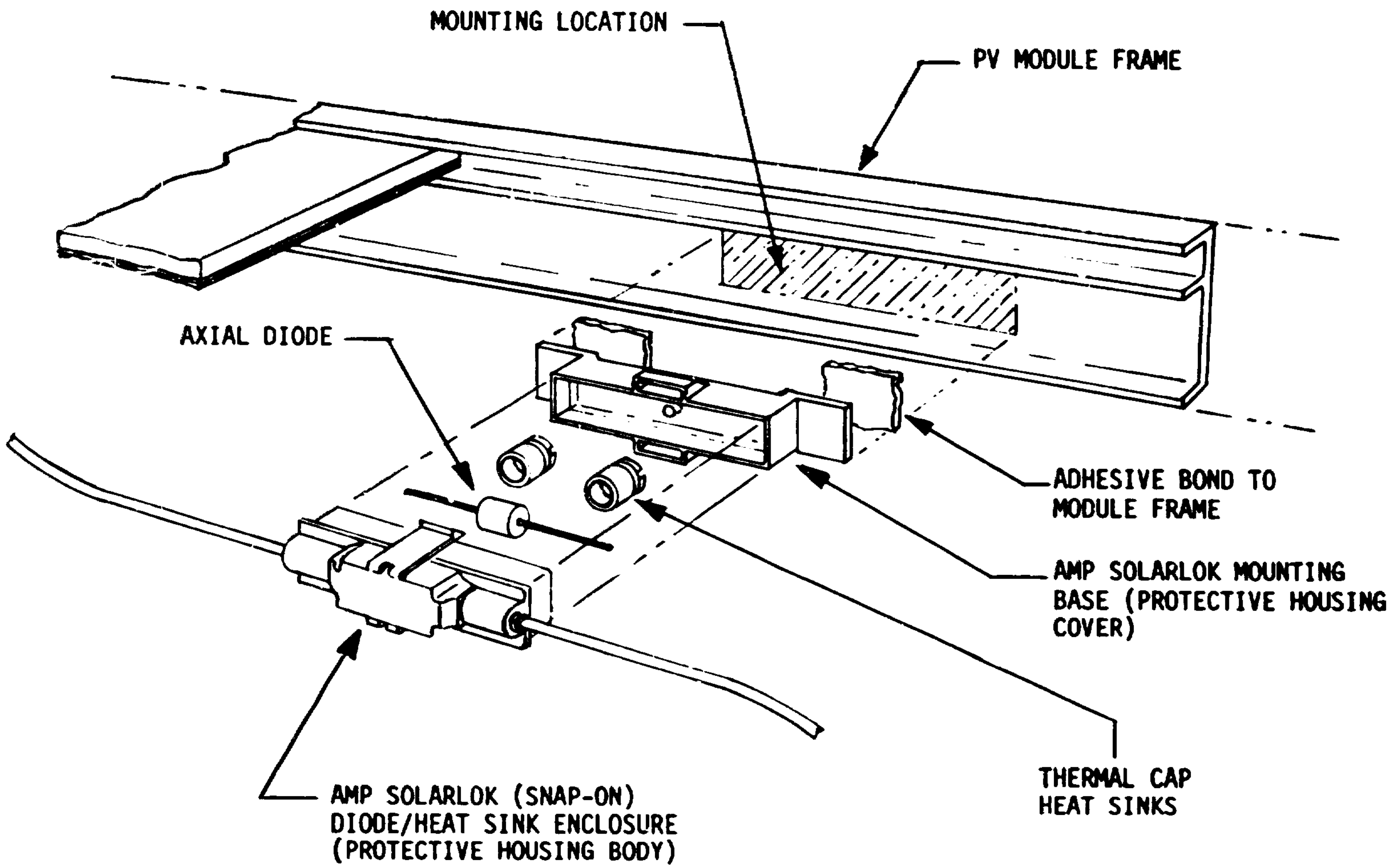


Figure 3-8. Axial Diode Package Mounted to PV Module Frame

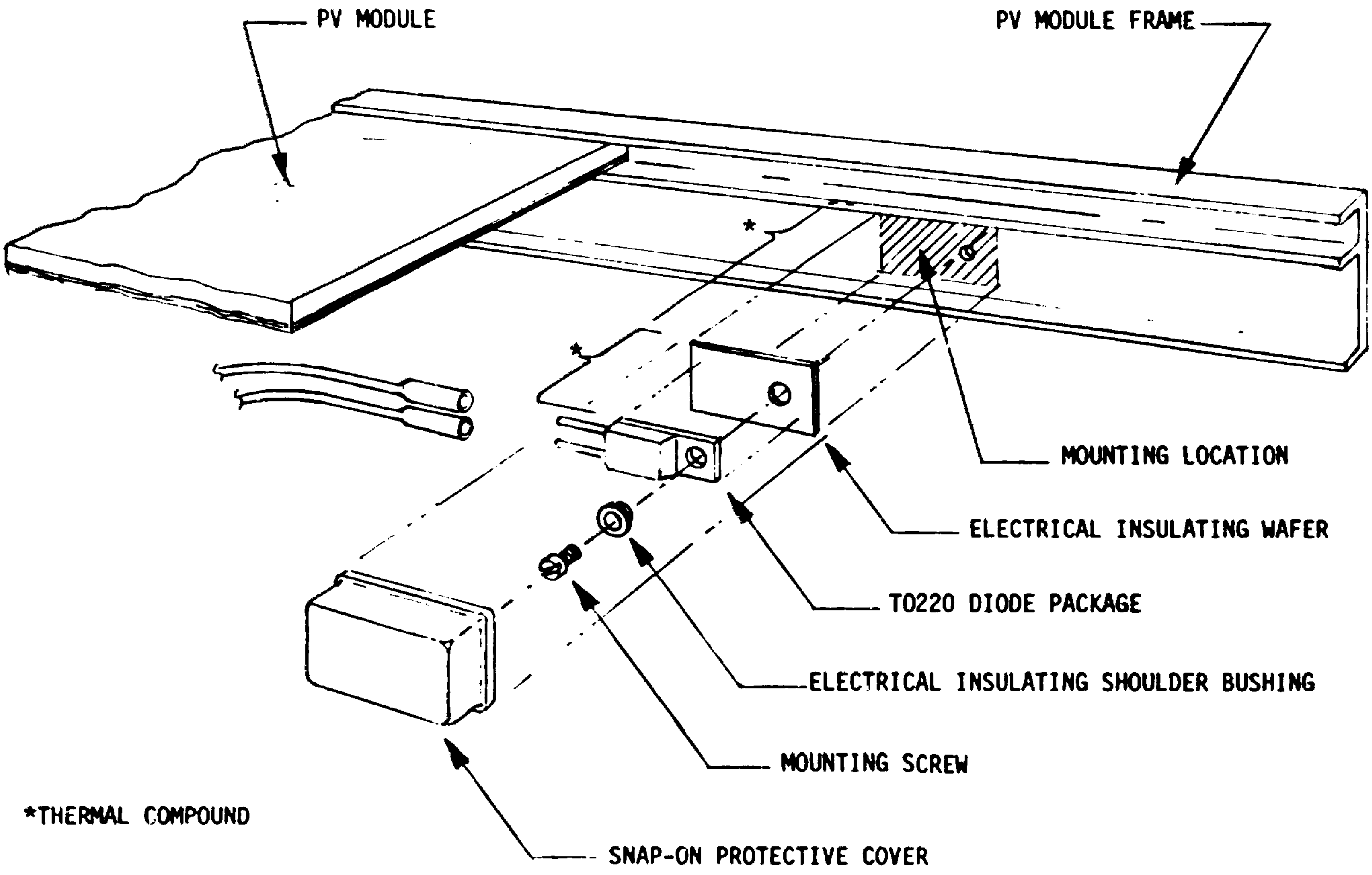


Figure 3-9. T0220 Diode Package Mounted to PV Module Frame

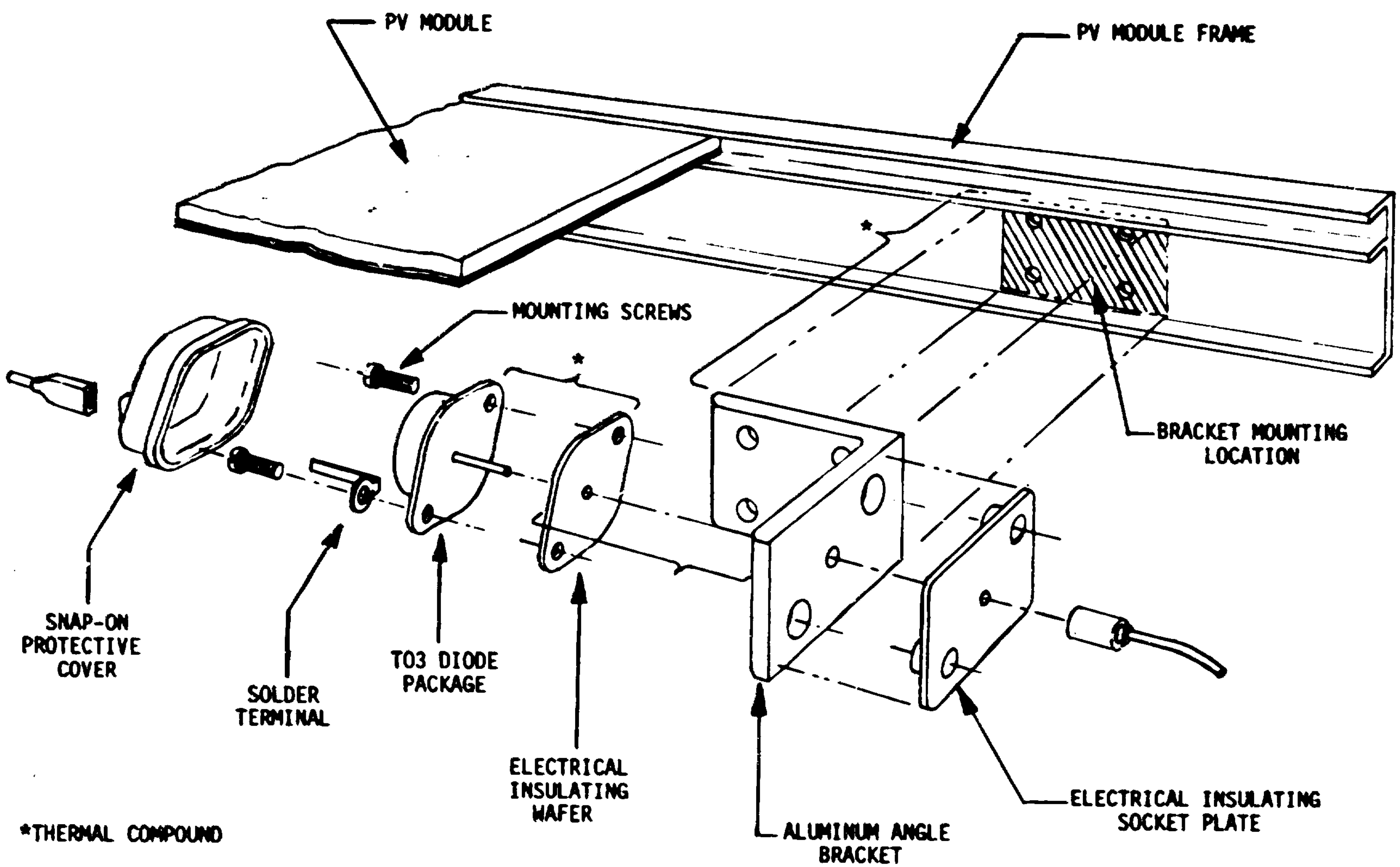


Figure 3-10. T03 Diode Package Mounted to PV Module Frame

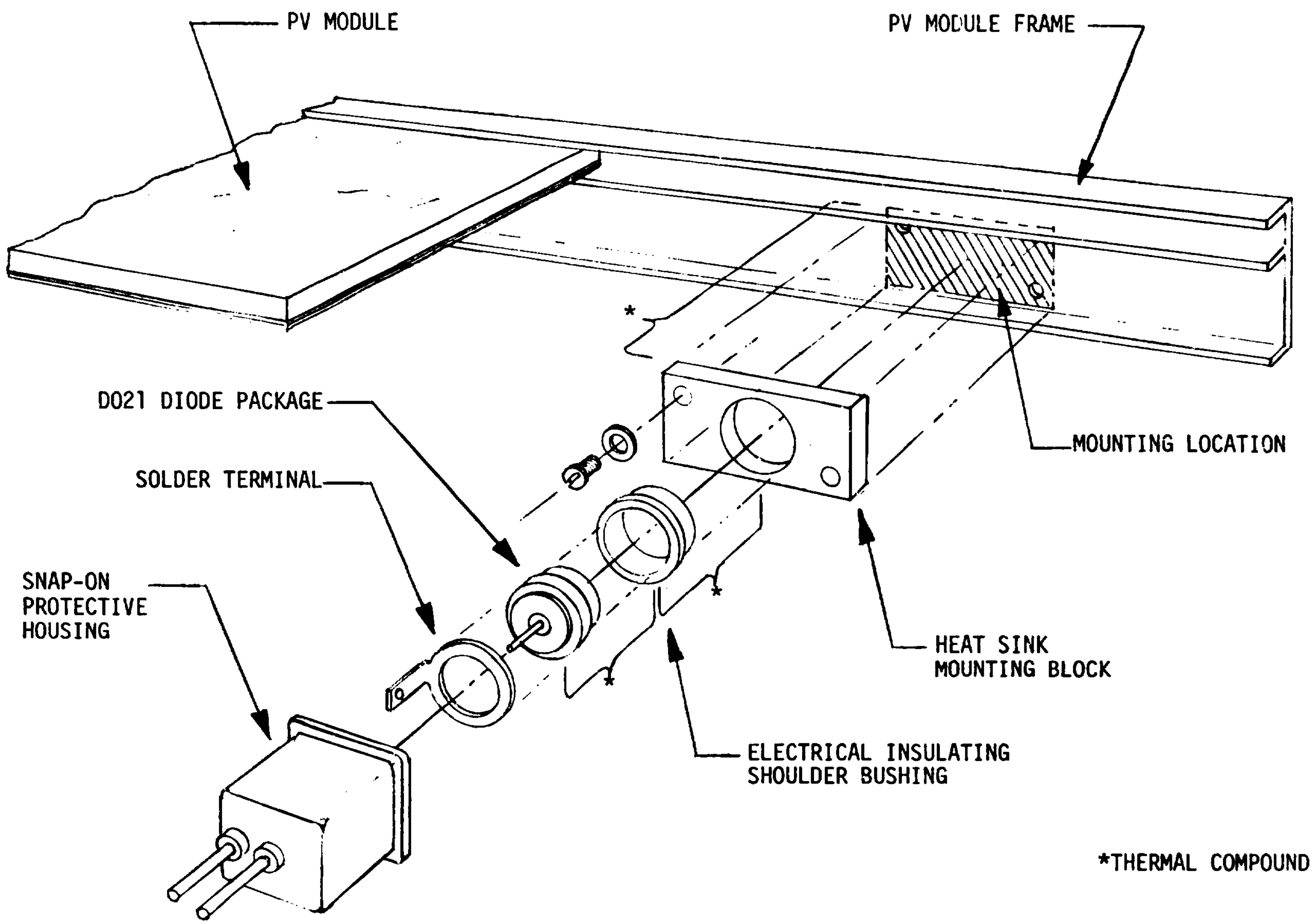


Figure 3-11. D021 Diode Package Mounted to PV Module Frame

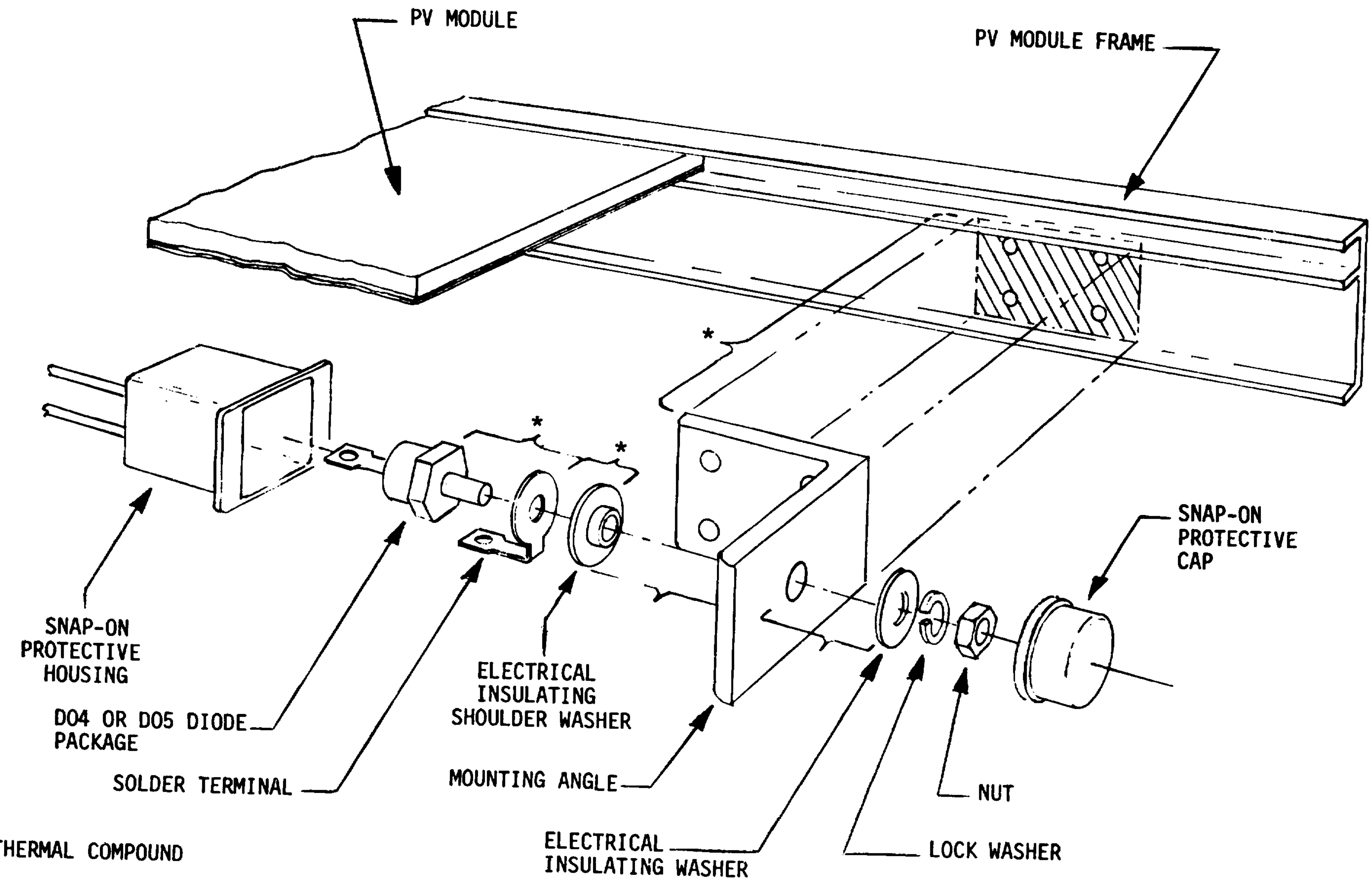


Figure 3-12. D04 or D05 Diode Package Mounted to PV Module Frame

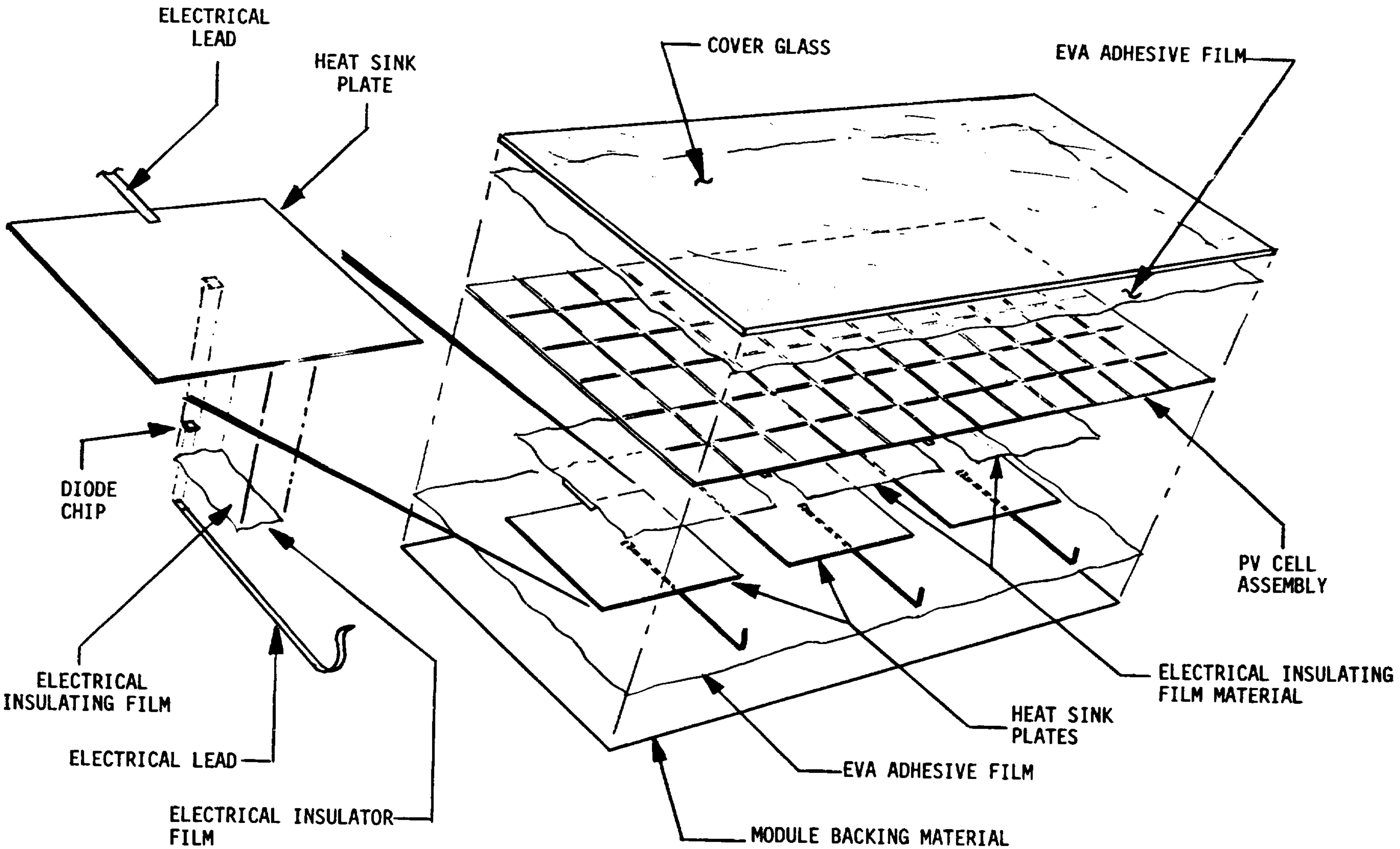


Figure 3-13. Chip Diode/Heat Sink Encapsulated within the PV Module Assembly

3.6.1 THERMAL ENVIRONMENT

Since the surrounding thermal environment is the ultimate sink for the energy dissipated by the diode, the exact condition of the environment is an important factor in determining the temperature response of the diode.

As indicated in Figure 3-14, the top side of the PV module was assumed to be exposed to a thermal environment consistent with the NOCT conditions (i.e., insolation = 0.8 kW/m^2; ambient temperature = 20°C; wind speed = 1 m/s). The condition of the environment under the PV module also must be considered in the analysis of diode temperatures for mounting concepts located on the underside of the PV module. For these underside mounting concepts, which could be applied only to stand-off and integral roof mounted PV modules, the underside thermal environment was assumed to be 50°C. For concepts involving diode encapsulation within the PV module, the effect of the environment under the module on diode temperature is insignificant due to the high thermal resistance of the PV module backface.

3.6.2 THERMAL MODEL

Thermal models were developed for each of the diode mounting concepts discussed in Section 3.5, and reflect a variety of diode power dissipation and junction to heat sink (mounting surface) thermal resistance. Each model consists of a multi-nodal, multi-dimensional thermal network which represents the significant heat flow paths from the diode junction to adjacent module components and the surrounding thermal environment. The models also account for heat dissipation from the diode as well as insolation absorbed at the front surface of the PV module. The models are structured to accommodate conductive, convective, and radiative modes of heat transfer.

3.6.3 PACKAGED DIODE MOUNTING CONFIGURATIONS

Packaged diodes, representative of the type that could be used for this application, have been characterized by power dissipation and thermal resistance from the junction to the heat sink mounting surface in Table 3-13.

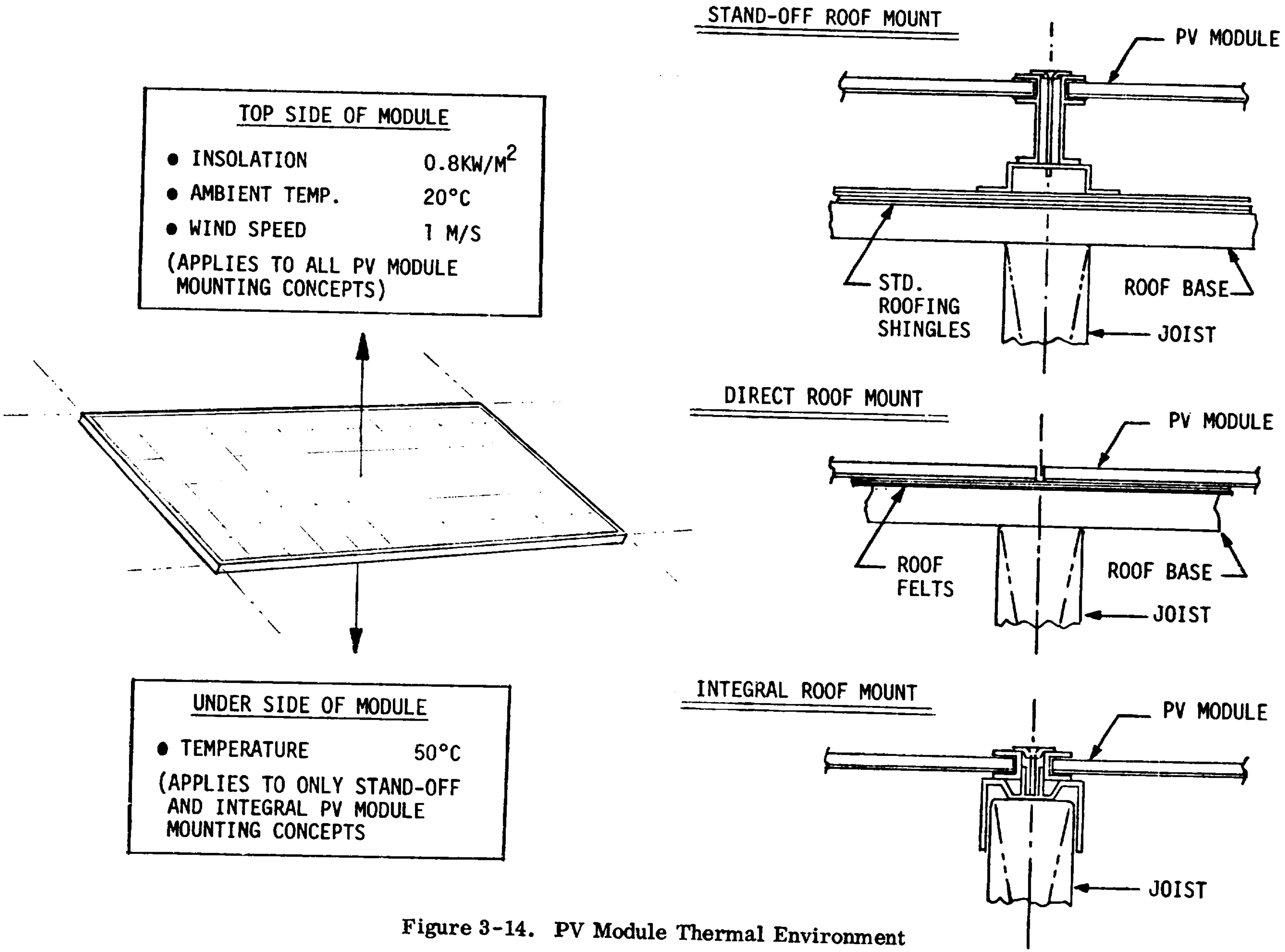


Figure 3-14. PV Module Thermal Environment

Table 3-13. Typical Packaged Diode Characteristics

PACKAGED DIODE TYPE	TYPICAL MAXIMUM POWER LEVEL W	ESTIMATED THERMAL RESISTANCE, °C/W		
		JUNCTION TO CASE (MFG. SPEC. DATA)	CASE TO HEAT SINK (ESTIMATED)	JUNCTION TO HEAT SINK
T03	30	1.0	0.14	1.14
T0220	15	3.0	0.20	3.20
D04	20	2.0	0.10	2.10
D05	40	1.0	0.10	1.10
D021	30	1.0	1.5	2.5

The junction-to-heat sink thermal resistance is comprised of the sum of the junction-to-case and case-to-heat sink resistance. The junction-to-case resistance is a strong function of the type of diode case used; whereas, the case-to-heat sink resistance reflects the nature of the interface between the case and the heat sink. In all cases, it was assumed that a thermal joint compound (e.g., EG&G Wakefield Engineering Type 120 or 121 joint compound) would be used at all interfaces to minimize the contact resistance. For diodes with electrically hot cases, it was assumed that an insulating beryllium oxide washer (or shoulder bushing) was incorporated between the diode and the heat sink. The values shown in Table 3-13 reflect these assumptions.

In order to encompass the range of diode characteristics indicated in Table 3-13, the thermal analysis was performed in a parametric manner with diode power dissipation ranging from 1 to 50 W, and thermal resistance ranging from 0 to 4°C/W. Since most diodes experience performance deterioration as junction temperatures increase above 150°C, the 150°C junction temperature limit was used as the criterion for defining acceptable characteristics of packaged diode mounting concepts.

3.6.3.1 Module Back Mounting

This mounting concept is depicted in Figure 3-15 and consists of a thermally conductive mounting plate (heat sink) located on the underside of the PV module. This concept could be used with stand-off or integral mount PV modules. Heat dissipated from the diode would be transferred by conduction to the mounting heat sink, and then by radiation and natural convection from the mounting heat sink to the underside thermal environment.

The mounting heat sink area required to maintain the diode junction temperature at or below 150°C is shown in Figure 3-16 for heat sinks of 0.125 inch thick copper or 0.25 inch thick aluminum.

Using Figure 3-16, flat plate heat sink area requirements can be established for the various packaged diode types based on the estimated thermal resistance and the typical power level presented in Table 3-13. The required heat sink areas are indicated in Table 3-14 below.

Table 3-14. Heat Sink Size Versus Packaged Type Diode for PV Module Back Mounting

PACKAGED DIODE TYPE	TYPICAL MAX POWER LEVEL (W)	ESTIMATED THERMAL RESISTANCE - JUNCTION TO SINK (°C/W)	FLAT PLATE HEAT SINK AREA* (FT^2)
T03	30	1.14	.25
T0220	15	3.20	.18
D04	20	2.10	.20
D05	40	1.10	.42
D021	30	2.5	.90

* 0.125 inch thick copper or 0.25 inch thick aluminum plate

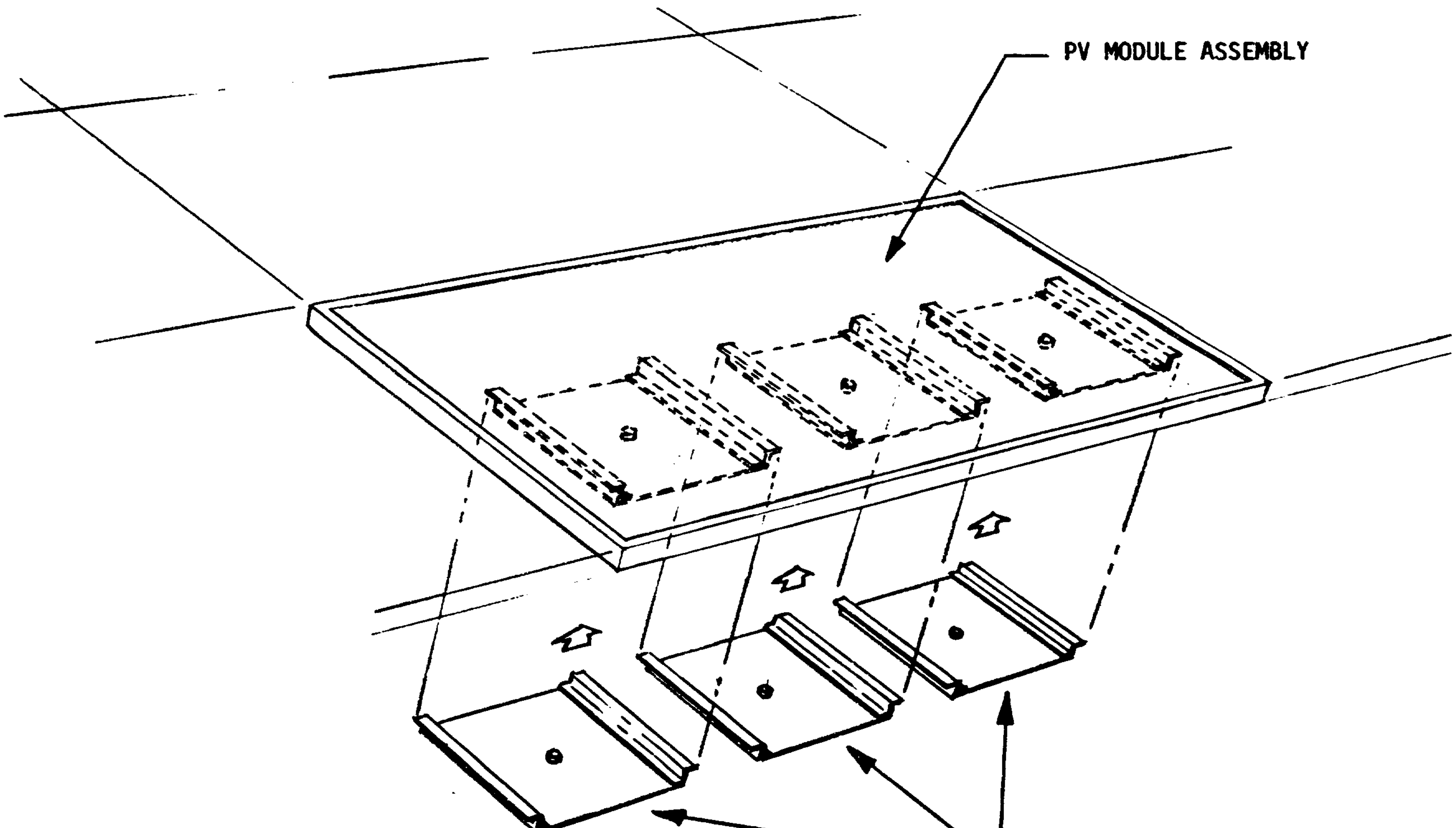


Figure 3-15. Diode/Heat Sink Mounted on the Back of the PV Module

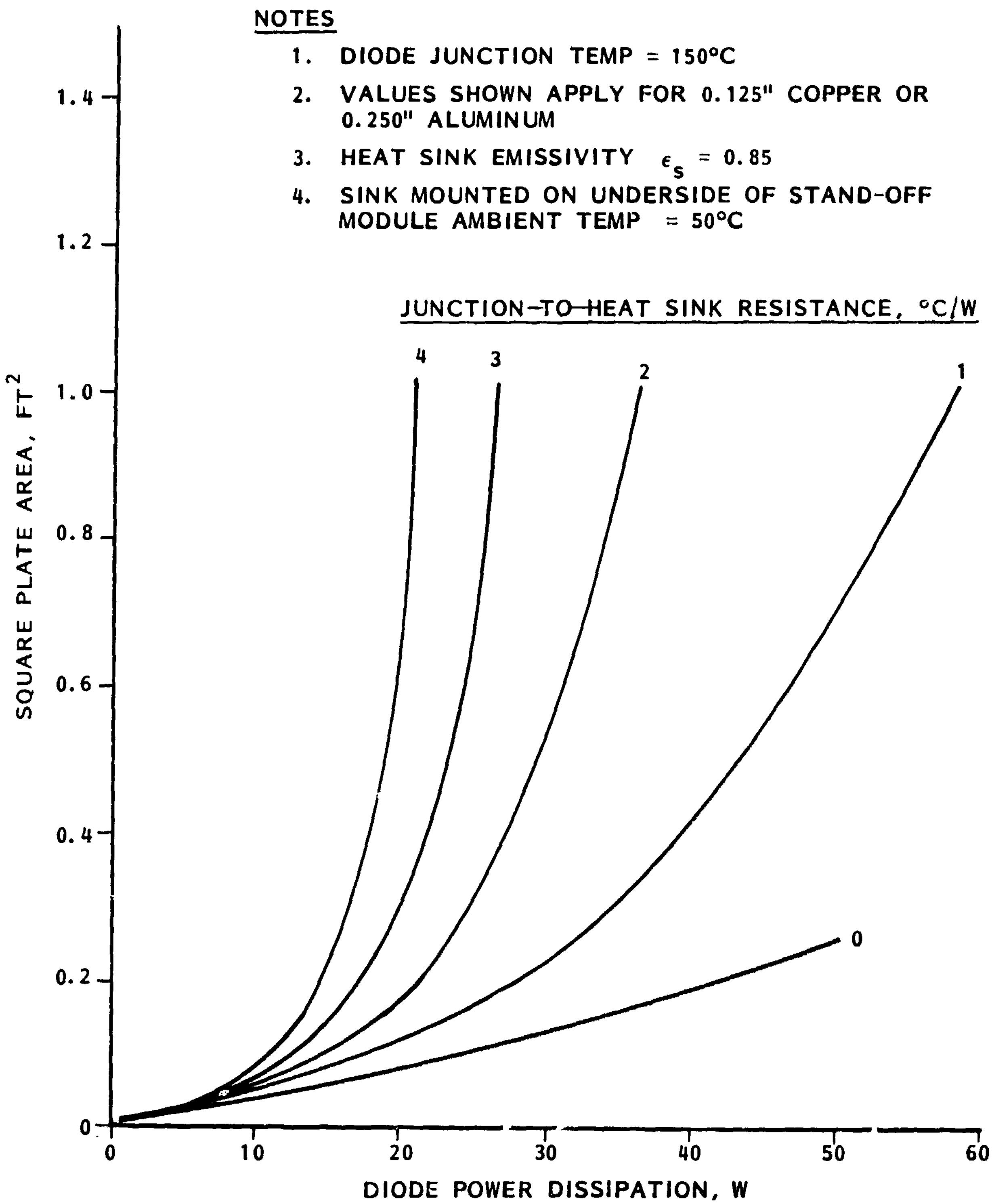


Figure 3-16. Heat Sink Area Required for Module Backing Material Mounting Concept

It should be pointed out that these heat sink areas relate to a typical near maximum power level, that is, a high current level and the forward voltage drop of a PN junction diode. For lower current capacity diodes using the same package type with Schottky diodes, that exhibit approximately half the forward voltage drop, the heat sink area requirements are considerably reduced.

3.6.3.2 Module Frame Mounting

Three different frame mounting concepts shown in Figure 3-17 were evaluated and include:

- Block-to-frame mount
- Angle-to-frame mount
- Direct frame mount

In the block-to-frame mount concept, the diode is mounted on an aluminum block which is configured to fit within the webs of the frame. The main purpose of the frame is to provide additional thickness required for the press fit diodes (e.g., D021). It was originally thought that the block would also improve the lateral conduction of heat away from the diode by providing a greater cross-section for heat flow than is available with the 0.08 inch thick frame. As the results later show, this advantage is offset by the added resistance across the block/frame interface, even though thermal joint compound is used. The diode junction temperature is shown in Figure 3-18 as a function of power dissipated and junction-to-heat sink thermal resistance for the block-to-frame mount concept with a 2 x 1 x 0.25 inch block of aluminum. Results were also obtained for aluminum blocks with dimensions of 4 x 1 x 0.25 inches and 8 x 1 x 0.25 inches. The block length required to maintain the diode junction temperature at 150°C is correlated to the diode characteristics of power dissipated and junction-to-heat resistance in Figure 3-19. The steepness of the curves indicates that little benefit is obtained by increasing the heat sink length beyond 2 inches.

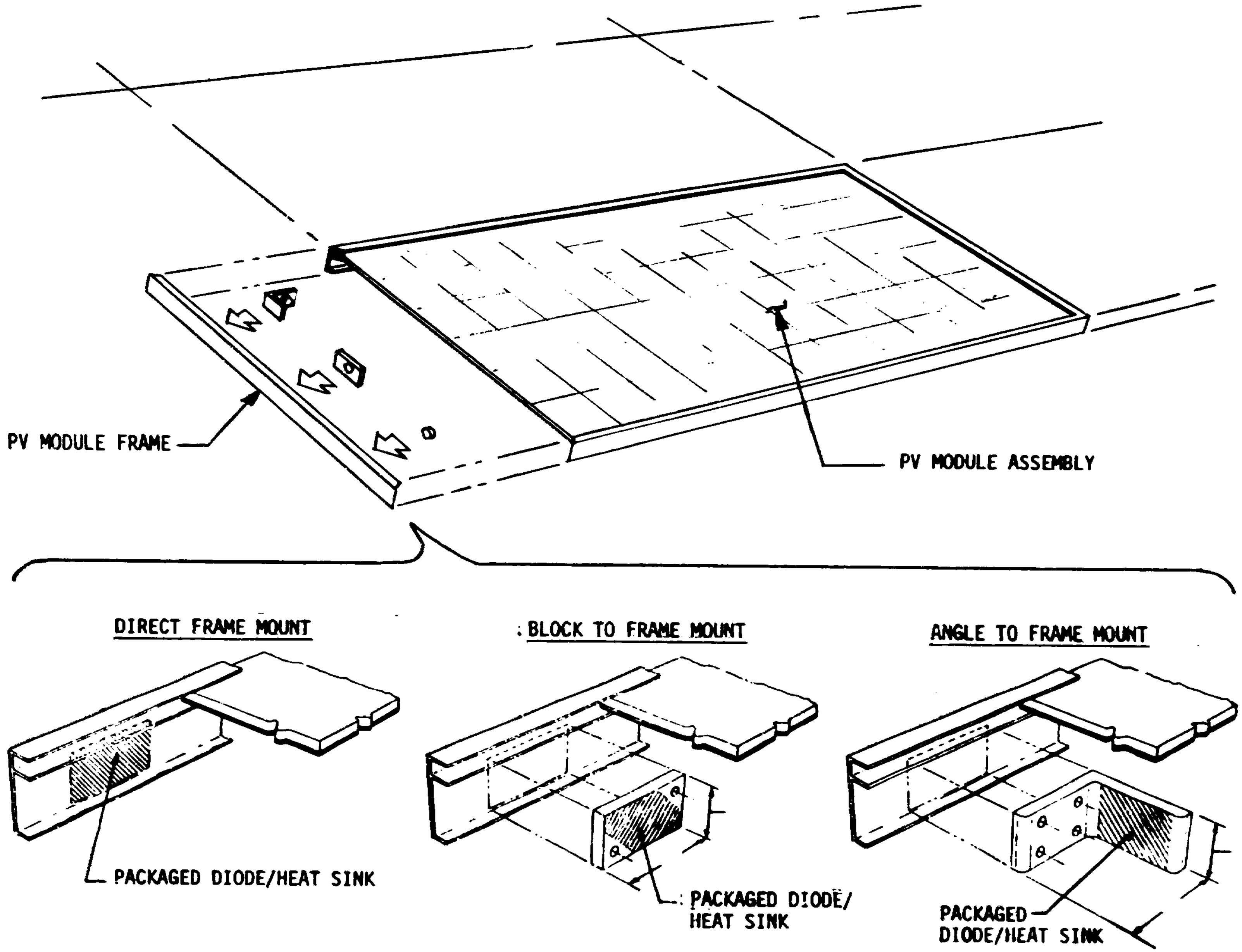


Figure 3-17. Packaged Diode/Heat Sink Mounted on PV Module Frame

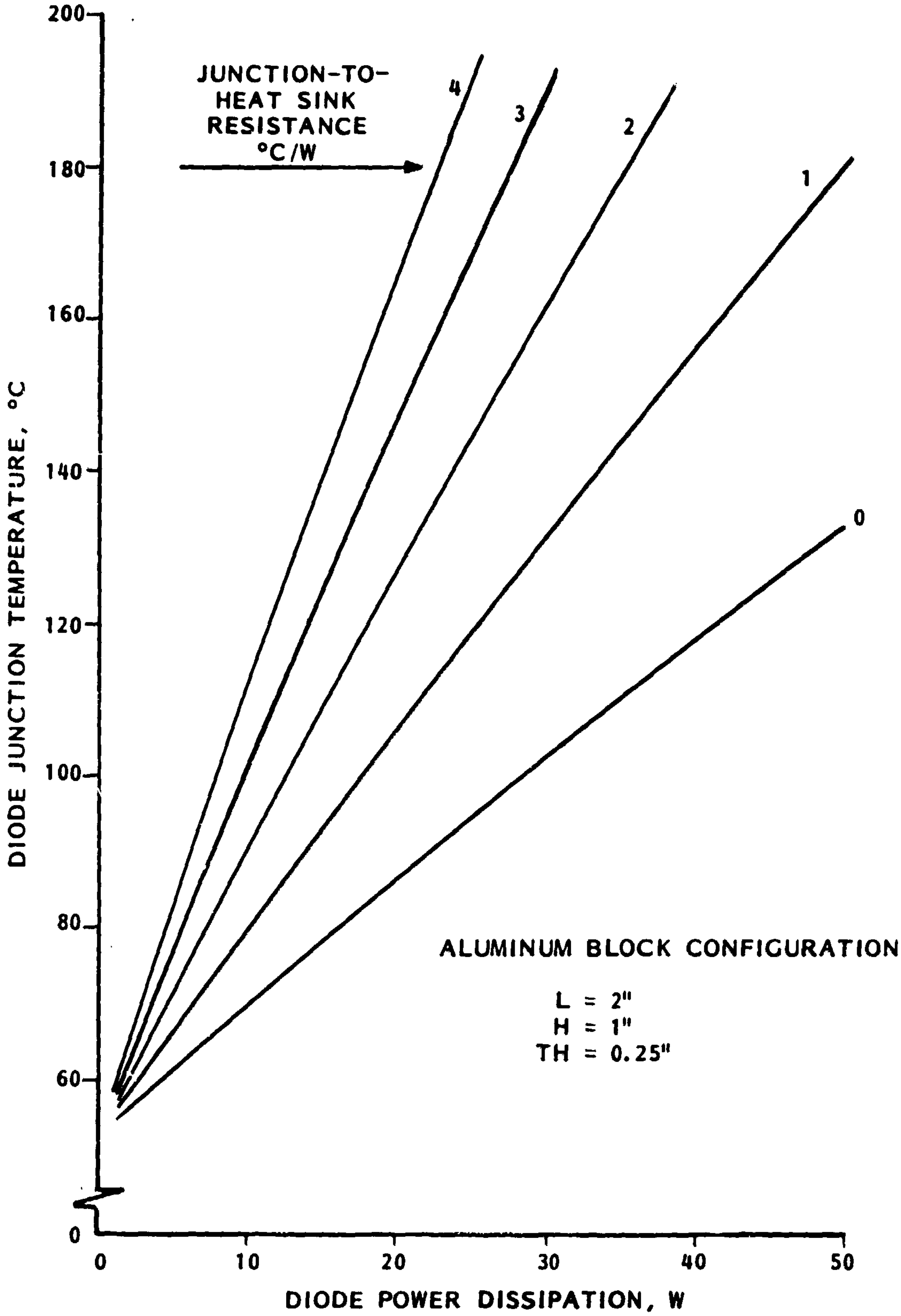


Figure 3-18. Diode Temperature as a Function of Power Output and Junction-to-Heat Sink Resistance for Block to Frame Mount Concept

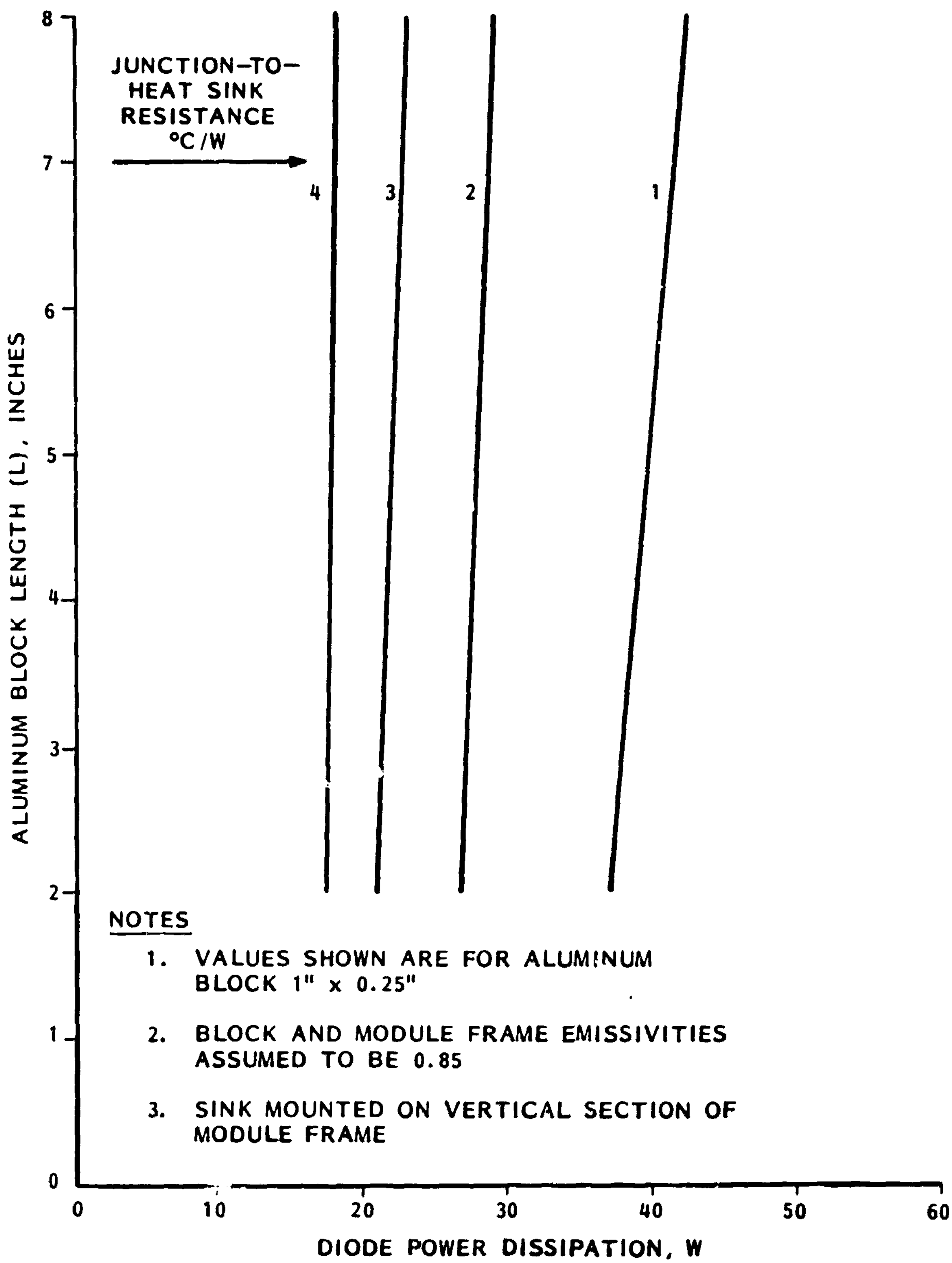


Figure 3-19. Mounting Block Length Required to Maintain Diode Junction Temperature at or Below 150°C

The aluminum angle-to-frame mount, designed to facilitate the mounting of diodes having electrical lead terminations on opposite ends of the diodes (e.g., T03) is shown in Figure 3-17. This concept mounts to the frame in the same way as the block concept; however, the diode is located on the leg extended away from the frame. Consequently, the angle-to-frame concept has a somewhat longer heat flow path and results in higher diode temperatures than would occur with the block-to-frame concept. A comparison of diode junction temperatures for the angle and block mounting concepts is shown in Figure 3-20.

The direct-to-frame mount concept can be used for diodes that do not have the special mounting requirements (e.g., the T0220 package or the AMP Solarlok package for axial leaded diodes) satisfied by the block or angle mount concepts. This concept is simple in that it utilizes the frame directly for diode mounting and has the shortest heat flow path of the module frame mounting concepts. As a result, the diode operates slightly cooler when mounted directly to the frame. This fact is demonstrated in the comparison between diode temperature for the direct-to-frame mount and the block-to-frame mount concepts shown in Figure 3-21. The capability of the direct-to-frame mount concept to maintain specific diode junction temperatures is defined in Figure 3-21 as a function of diode power dissipation and junction-to-heat sink thermal resistance. For example, with this mounting concept, the diode junction temperatures can be limited to 150°C for diodes dissipating 20 W of power if the thermal resistance from the junction-to-heat sink is 3°C/W or less. If the thermal resistance from the junction-to-heat sink is 1°C/W, this concept can satisfy the 150°C junction temperature limit for diodes dissipating as much as 40 W.

3.6.3.3 Axial Leaded Enclosure Mounting

Axial leaded diode enclosures containing screw-down heat sink mounts are amenable to either mounting on the back or frame of the module. Typical of this type of axial leaded enclosure is the AMP SOLARLOK Diode Connector which has self-contained heat sinks (see Figures 3-3 and 3-8). The results of an AMP thermal analysis for PN junction and Schottky barrier diodes housed in the SOLARLOK connector are shown in Figure 3-22. The diode junction temperature is indicated as a function of ambient temperature for diodes having forward current ratings in the 4 to 8 ampere range. At an ambient temperature of 50°C (the underside of module), the diode junction temperature can be maintained at or below 150°C when the diode forward current is limited to approximately 7 amperes for the Schottky barrier diode or 5 amperes for the PN junction diode.

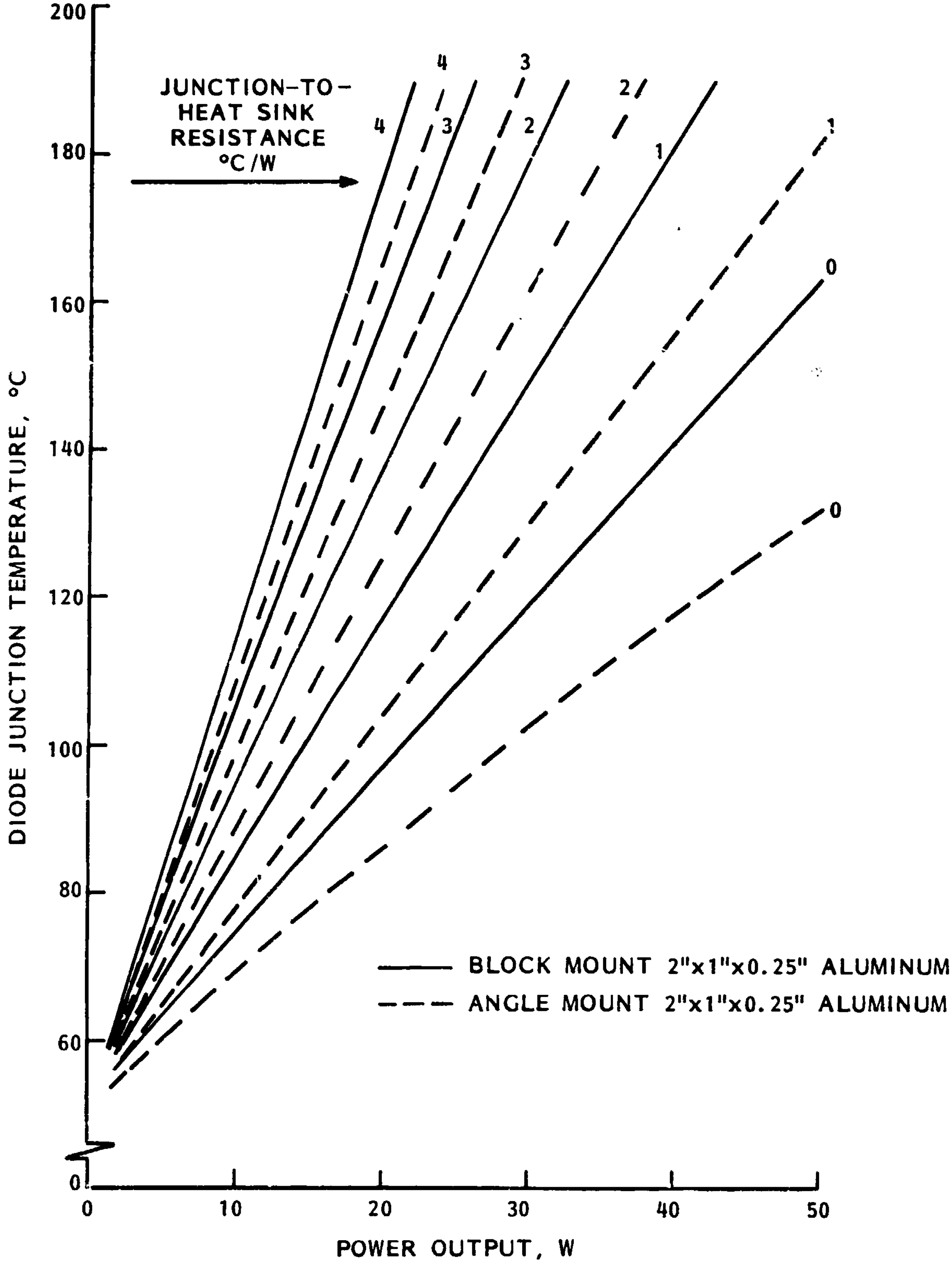


Figure 3-20. Diode Temperature as a Function of Power Output and Junction-to-Heat Sink Resistance for Angle to Frame

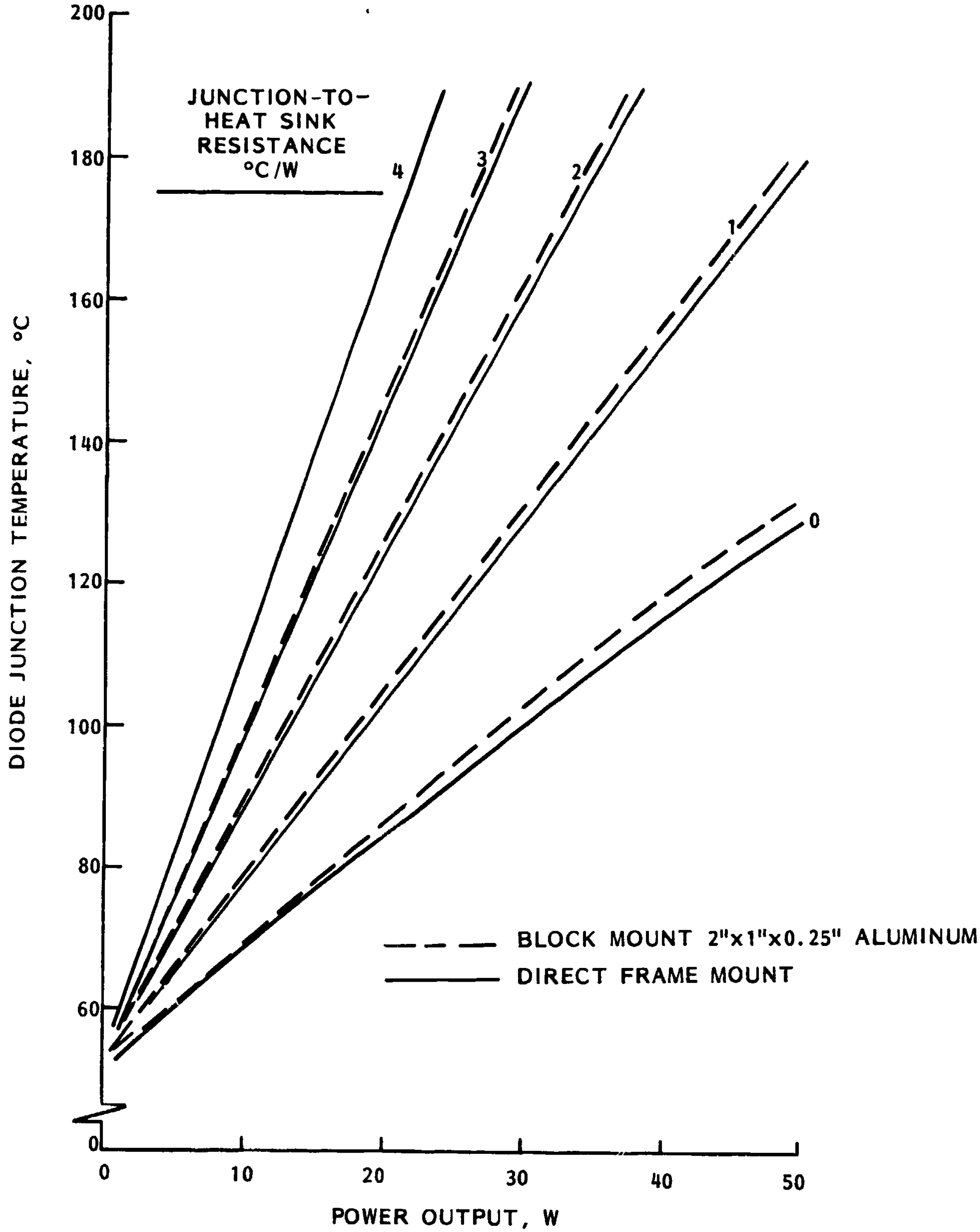


Figure 3-21. Diode Temperature as a Function of Power Output and Junction-to-Heat Sink Resistance for Direct-to-Frame Mount Concept

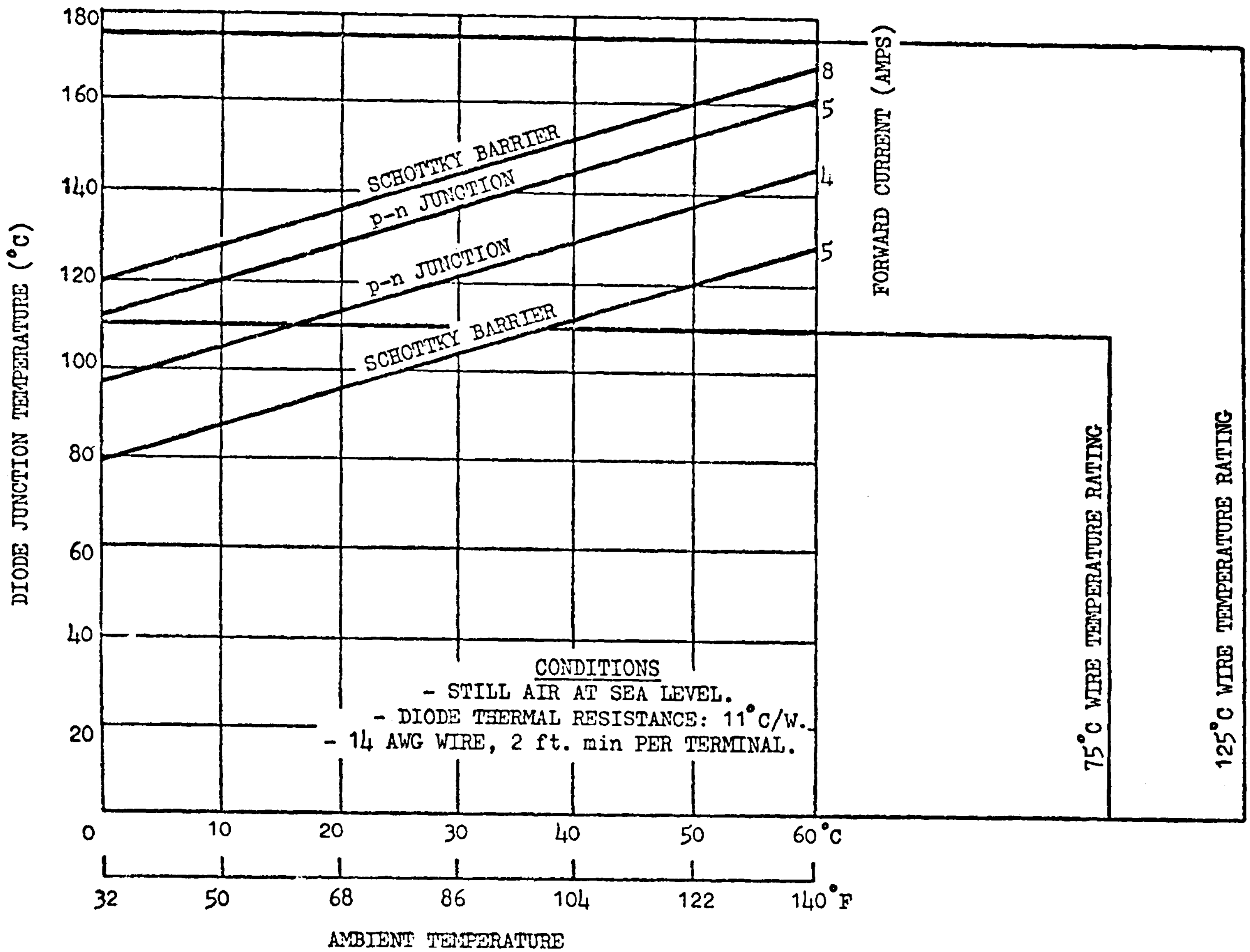


Figure 3-22. Thermal Characteristics of Axial Leaded Diode in AMP SOLARLOK Diode Connector

3.6.4 MOUNTING WITHIN ENCAPSULANT

This concept involves the encapsulation of the diode chip/heat sink within the module as illustrated in Figure 3-23. The diode chip is attached to a copper sheet heat sink and is sandwiched between the back side of the solar cell circuit and the rear cover sheet of the module. The cell circuit is electrically isolated from the diode by a thin insulator film.

The primary heat flow path from the diode is through the front of the module. Heat conducted in other directions is insignificant due to the relatively high thermal resistance of the EVA and module backing material. The high thermal conductivity of the copper plate provides excellent lateral conduction of heat away from the diode. The size of the copper plate essentially dictates the extent of lateral conduction and defines the effective area for heat transfer through the front of the module.

The copper plate is sized to maintain the diode junction temperature at or below 120°C. This temperature reflects the adjacent EVA adhesive limit and not the diode junction temperature limit. The copper plate area required to satisfy the 120°C temperature limit is shown in Figure 3-24 as a function of diode power dissipated, junction-to-heat sink thermal resistance, and copper plate thickness. Note that a decrease in copper plate thickness or an increase in junction-to-heat sink thermal resistance tends to reduce the effectiveness of the copper plate and increase the plate area required for a given power dissipation. Junction-to-sink thermal resistance, which cannot be specifically defined until chip/flat plate heat sink assemblies are tested, should range between 0.8 to 2°C/W depending on the chip size used and the bond quality obtained.

A diode power dissipation of up to 28.5 W can be accommodated on a 1 square foot (144 in^2) plate when the plate thickness is 0.06 inches and the diode junction-to-heat sink resistance is 1°C/W. If the diode power were reduced to 10 W, the plate area requirements would decrease dramatically. For example, for a plate thickness of 0.06 inches and a junction-to-heat sink resistance of 1°C/W, the plate area required is only 7.5 in^2; whereas, if the junction-to-heat resistance were 2°C/W, a plate area of 14 in^2 would be required.

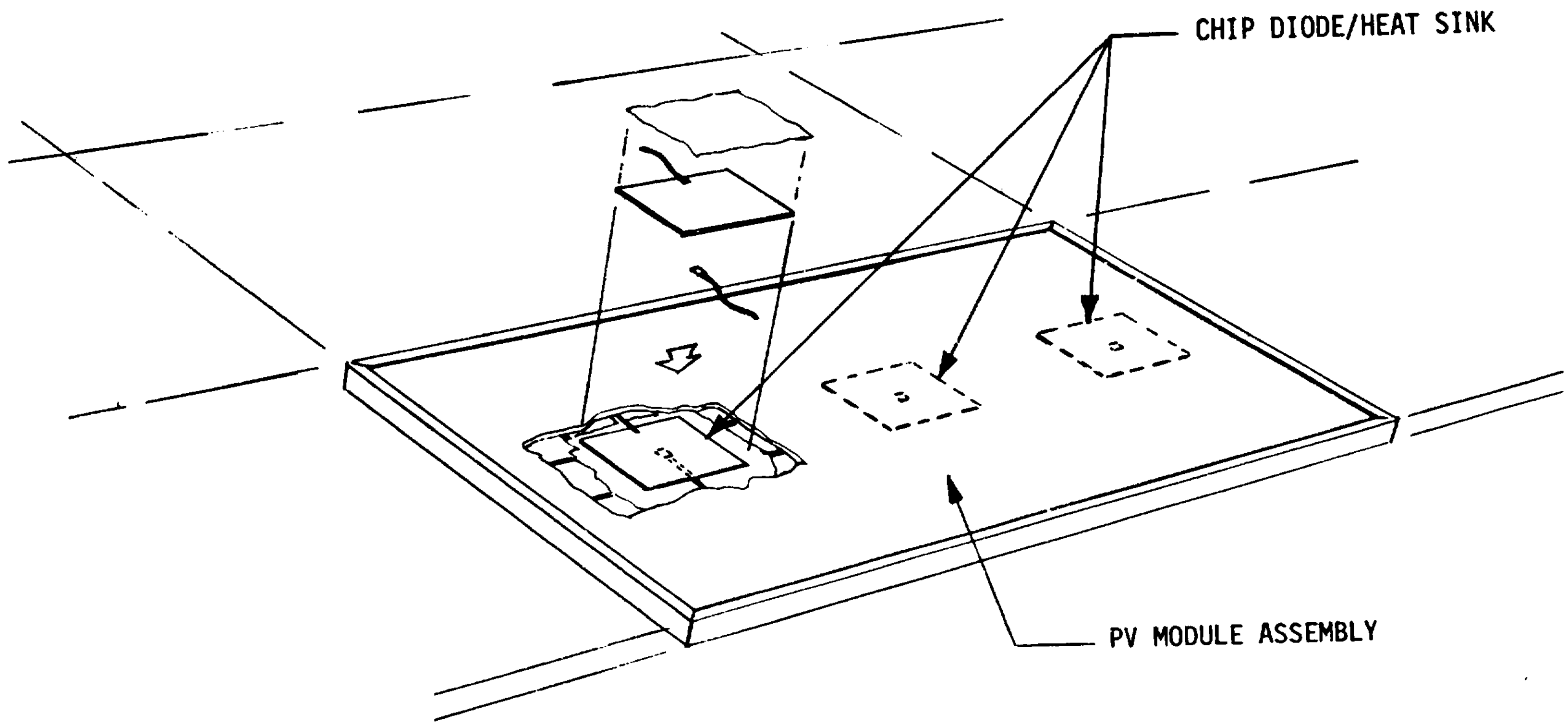


Figure 3-23. Chip Diode/Heat Sink Encapsulated in Module

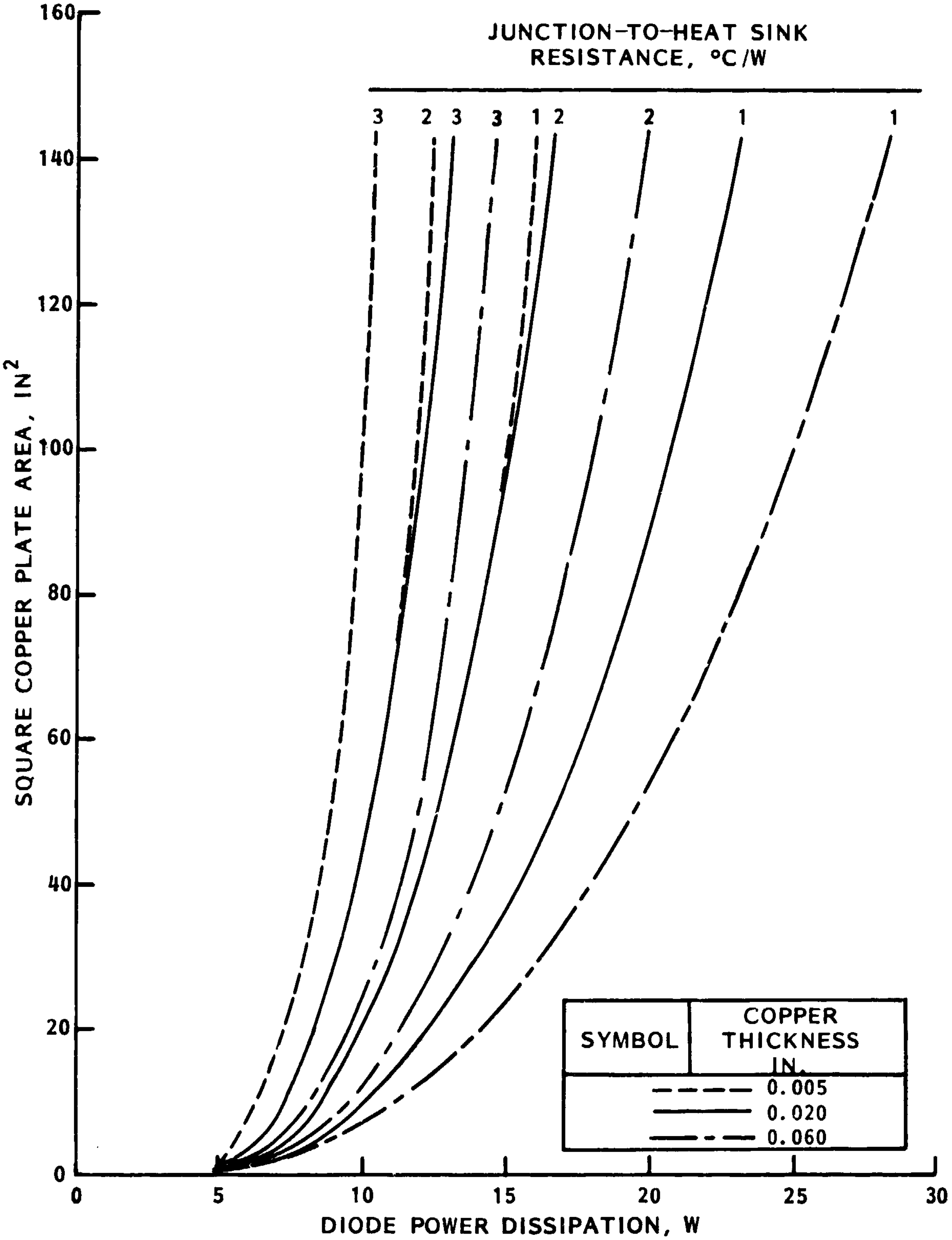


Figure 3-24. Area Requirements for the Encapsulated Copper Mounting Plate to Maintain Diode Junction at or Below 120°C

The thickness required to maintain the junction diode temperature at 120°C is shown in Figure 3-25 as a function of diode power dissipated and junction-to-heat sink resistance for a 6 x 6 inch plate size. Relatively small variations in diode characteristics produce relatively large changes in thickness requirements. If the copper plate configuration is fixed at 6 x 6 x 0.020 inches, the acceptable diode power dissipation would range from 9.5 W for a junction-to-heat sink resistance of 3°C/W, to 14.75 W for 1°C/W.

3.7 DIODE RELIABILITY FACTORS

The reliability of a diode used in a bypass application within a photovoltaic module can be defined as its ability to continue to perform its intended design function under the electrical loading conditions and environmental influences. The failure of a diode used in this application could manifest itself as one or more of the following anomalous conditions:

1. A short-circuit resulting in the loss of the power generated by the cells within the bypassed group and a reduction of the branch circuit voltage which is proportional to the number of series-connected cells within the bypassed group;

2. An open-curcuit failure resulting in the removal of the bypass function which could lead to increased "hot-spot" heating under cell shadowing or open-circuit failure conditions;

3. An increase in the reverse leakage current resulting in an increase in the shunt power loss during normal circuit operation; or

4. An increase in forward voltage drop at a given current level and temperature which results in increased bypass diode power dissipation under solar cell circuit shadowing or failure conditions.

The first of these possible anomalous conditions is of the most concern since it has an immediate and lasting effect on the circuit output power.

Diode failure mechanisms can be broadly grouped into defect categories related to surface condition, mechanical assembly, and bulk material. The most prevalent cause of poor reliability is failure due to the condition of the semiconductor surface due to imperfections within the encapsulated diode itself, or due to the failure of the package which causes the

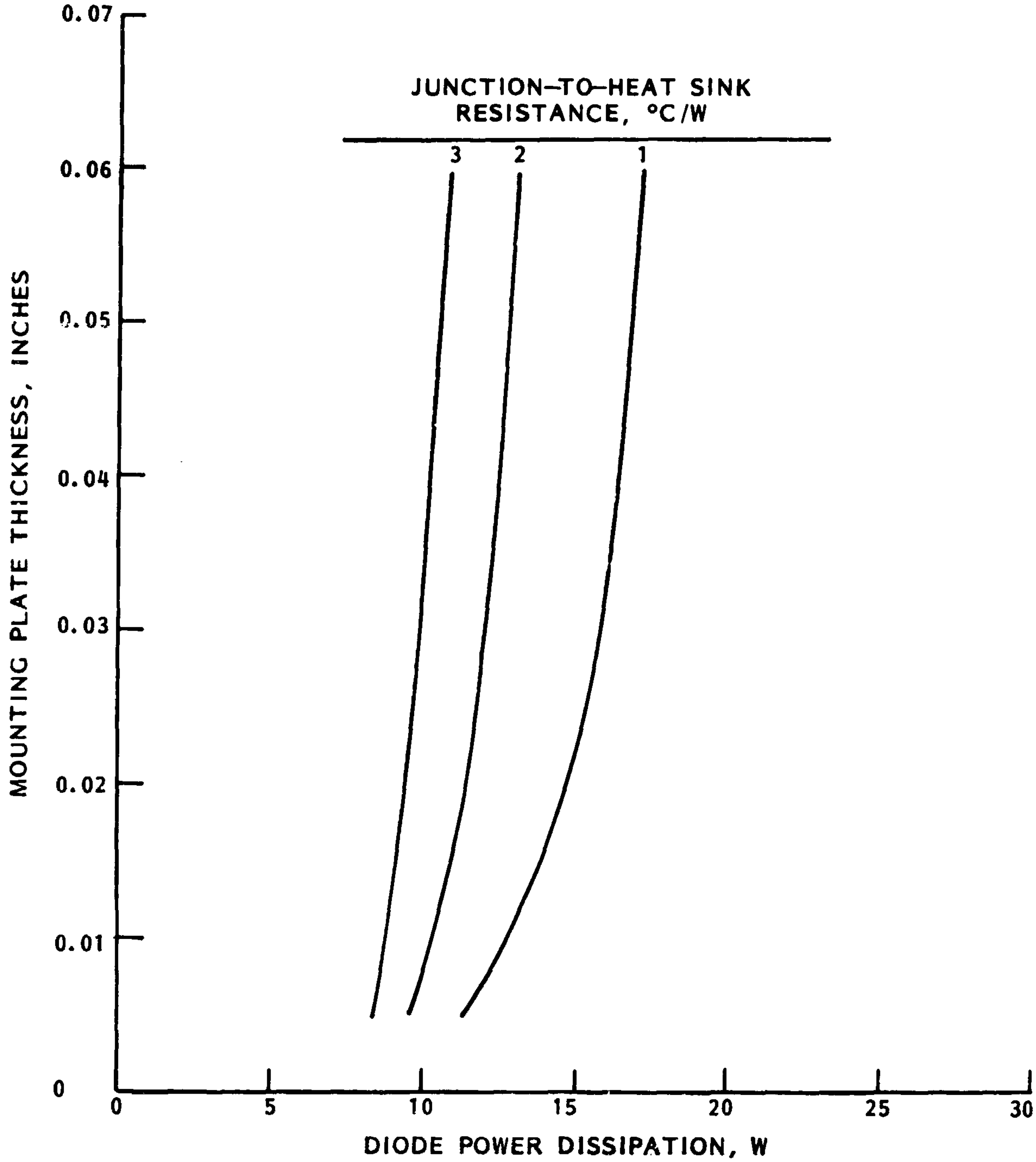


Figure 3-25. Thickness Requirements for the Encapsulated Copper Mounting Plate to Maintain Diode Junction at or Below 120°C for 6" x 6" Plate

semiconductor surface to be exposed to the external environment. Surface defects are usually detected by reverse current instability over periods of life stressing.

Mechanical defects which can occur in diodes include: (1) poor bonding of the die-to-header; (2) poor lead-to-die contact; and (3) lack of hermetic seal. Poor contact of the die to the header may increase the thermal resistance of the rectifier, resulting in high junction temperatures during high power operation. Poor contacts may also cause hot spots, but this is of secondary importance for relatively low level applications.

Bulk defects in diodes are generally a less frequent cause of poor reliability than surface or mechanical defects. Included in this classification of defects are crystal imperfections which can cause non-uniform diffusion (resulting in high current concentrations and hot spots), and undesired impurities which can result in uneven voltage gradients. These uneven voltage gradients can cause, in a worst case, failure due to punch-through. A second class of bulk defects results from diffusion of impurities and metal contacts into the bulk material at normal operating temperatures. This problem is generally minimized in a well-designed and fabricated diode.

An idealized component failure rate versus time curve is shown in Figure 3-26. Several features of this familiar "bathtub" curve are important in any consideration of diode reliability. The first portion of this curve indicates a sharply increasing and then a steadily decreasing failure rate during the "burn-in portion" of diode life. The increasing failure rate for the very early life portion of Figure 3-26 may not always be seen. The portion of this curve which shows a decreasing failure rate for diodes has been demonstrated. These early life failures are generally classified as a result of poor workmanship.

After this initial burn-in period, where the failures can be attributed to workmanship faults not detected during the manufacturing process, a period of relatively constant failure rate can be expected.

The final portion of Figure 3-26 shows an increasing failure rate identified as "wear-out." This portion is extremely difficult to define and will vary depending on the method of fabrication and applied stress. This increasing failure rate can be introduced by such mechanisms as thermal fatigue of the solders between the silicon die and the mount (due to repeated cycling of junction temperature while the case is at a more or less fixed temperature), by glass hermetic seal failures (due to environmental cycling), by fatigue of internal construction (due to mechanical stress), or by bulk defects. Little data are available from either life tests or system field tests to permit an accurate picture of this portion of the curve. Contrary to the early life failures which may be characterized as workmanship faults, the failures which occur in the wear-out period are believed to be a result of basic design limitations.

Since many early life limiting failures are the result of manufacturing flaws, it is possible to develop a screening and burn-in procedure which can effectively remove these devices before assembly in the end use product. The additional cost of such a screening procedure must be carefully evaluated against its effectiveness to determine if it can be economically justified for a specific diode type.

Derating is a valuable tool which can be used to increase device reliability. This is illustrated by the data presented in Figure 3-27, which graphs the failure rate per 1,000 hours of operation for diode rectifiers as a function of both the junction temperature and the percent of rated reverse voltage. These data clearly illustrate the value of derating as a means of enhancing the reliability of a rectifier. A study of the derating curves shows that a reduction in the junction temperature gives a larger reduction in the failure rate than a similar reduction in the applied voltage. Referring to Figure 3-27, it can be seen that the failure rate at 175°C and 100 percent of rated reverse voltage is 3 percent per 1,000 hours. If the voltage is lowered to 75 percent of the rated value and the junction temperature is decreased to 125°C, the failure rate is approximately 0.3 percent per 1,000 hours, which is a factor of 10 lower. A similar relationship applies to forward current and diode junction temperature. Either lowering the forward current below rated value or utilizing a higher current rated diode for a particular application will enhance reliability by lowering junction temperature.

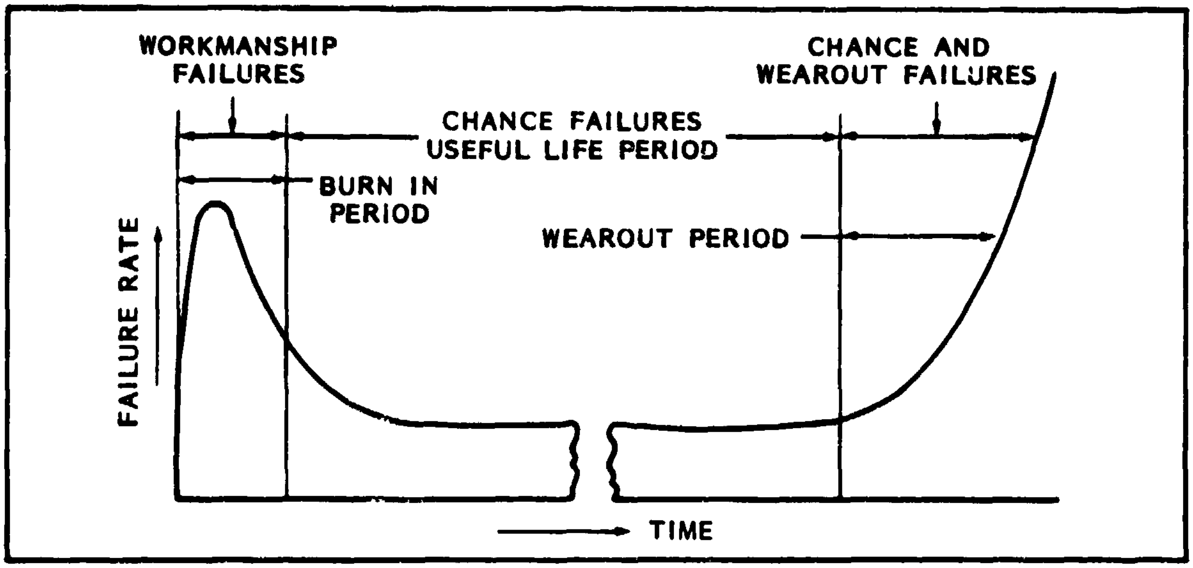


Figure 3-26. Semiconductor Failure Rate As a Function of Time

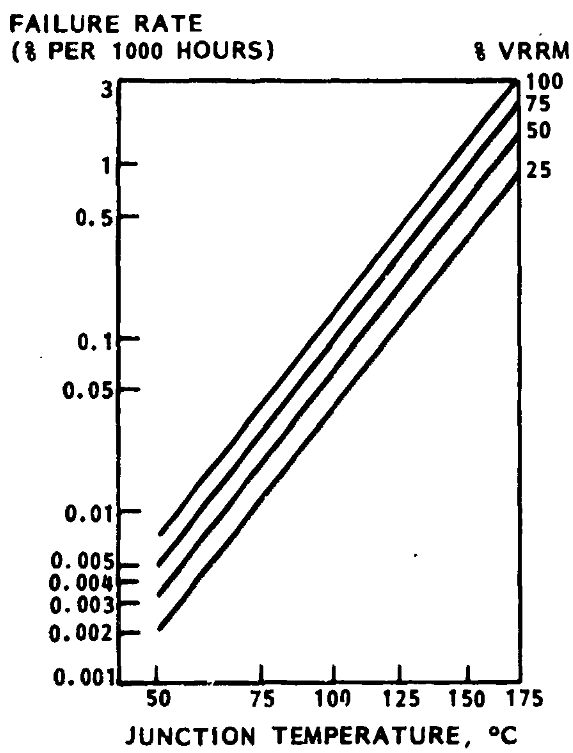


Figure 3-27. Estimated Failure Rate for Diode Rectifiers

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

The following observations and conclusions have resulted from this study activity:

1. When coupled with the requirement to have less than 30 volts open-circuit voltage at 100 mW/cm^2 insolation and -20°C cell temperature, an increase in the module size will result in higher module short-circuit currents. The mechanical and thermal integration of the bypass diodes required to accommodate these higher currents represents a significant problem which must be adequately addressed in the design. The material contained in the report should aid in this design solution.

2. Schottky diodes, which make use of the rectification effect of a metal-to-silicon barrier, have a lower forward voltage drop than conventional PN diodes of equivalent ratings. A lower reverse blocking voltage and higher reverse leakage current are also characteristic of these devices. Thus the Schottky diode is ideally matched to a photovoltaic module bypass diode application where low forward voltage drop means lower heat dissipation with correspondingly small heat spreader sizes. The lower reverse voltage and higher leakage current characteristics of these devices are well within the operating limits of photovoltaic bypass applications where the reverse voltage is generally limited to 12 volts.

   However, the cost of a Schottky diode may be typically 50 percent higher than an equivalent PN junction device. A design trade-off between these two choices, which includes the cost of the heat sink, is required for each specific application.

3. The mechanical and thermal integration of packaged diodes within photovoltaic modules requires that design provisions be incorporated to accommodate (a) the attachment of the cathode lead to the diode case, (b) the electrical grounding of the heat sink, (c) the electrical isolation of the diode case from the heat sink mounting surface, (d) the protection of the electrically "hot" diode case from the environment and from physical contact by personnel, and (e) the strain-relief and environmental protection of the diode lead wires. The design accommodation of these provisions can lead to a complex and costly diode installation.

4. The direct mounting of diode chips onto copper heat spreader plates, which are laminated within the module encapsulant, is an attractive installation option offering the following advantages: (a) the thermal resistance from the diode junction-to-heat sink can be somewhat lower with the chip, since the case, which is associated with the packaged diode, has been eliminated and replaced with a relatively large heat sink plate, (b) the chip is much smaller than the packaged diode and therefore its placement in the module is not limited to locations that are large enough to accommodate the rather bulky diode case, and (c) the environmental protection and electrical insulation are provided by the module encapsulant.

Based on these study results and conclusions, it is recommended that further research activity be initiated to investigate the specific design details associated with the mounting of bypass diode chips within the module encapsulant. This activity should consider a range of module short-circuit currents from 3 to 18 amperes and should include the fabrication of laboratory test specimens for several point designs within this range.

APPENDIX A

DETAIL OPERATING CHARACTERISTICS OF A SELECTED NUMBER OF PN JUNCTION AND SCHOTTKY DIODES IN VARIOUS STANDARD PACKAGE TYPES

6 AMP AXIAL LEAD PN JUNCTION DIODE OPERATING CHARACTERISTICS

(INTERNATIONAL RECTIFIER - MODEL NO. 60S05)

SPECIFIC RATINGS AND CHARACTERISTICS

TYPE	60S05	60S1	60S2	60S3	60S4	60S5	60S6	60S8	60S10
$V_{RM(rep)}$ – Maximum repetitive peak reverse voltage (V)	50	100	200	300	400	500	600	800	1000
$V_{R(RMS)}$ – Maximum RMS reverse voltage (V)	35	70	140	210	280	350	420	560	700
V_R – Maximum DC blocking voltage (V)	50	100	200	300	400	500	600	800	1000
$I_{R(AV)}$ – Maximum average reverse current @ maximum rated I_O and $V_{RM(rep)}$ @ T_C = 95°C (length of leads 3/8") (mA)	2.0	2.0	1.0	1.0	0.8	0.8	0.5	0.5	0.5

ELECTRICAL RATINGS

I_O	Maximum average rectified output current @ T_C = 95°C (Length of leads① 3/8")	6A
I_{FM} (surge)	Maximum peak one cycle, non-repetitive surge current (60 Hz sine wave, one-phase operation), @ maximum rated load conditions	400A
I^2t	Maximum I^2t rating (non-repetitive, for 5 to 8.3 msec)	650A²t
V_{FM}	Maximum peak forward voltage drop @ I_F = 6A peak and T_J = 25°C	0.91V

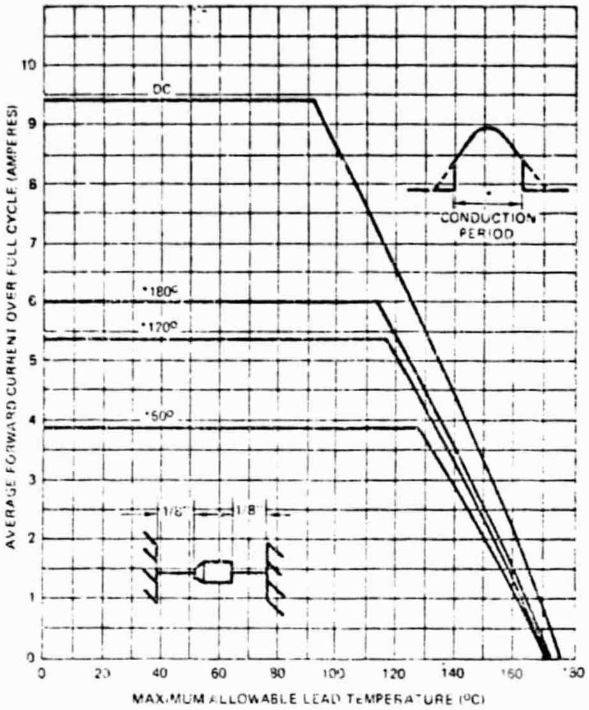
THERMAL-MECHANICAL SPECIFICATIONS

T_J	Maximum operating junction temperature range	–40 to 175°C
T_{stg}	Maximum storage temperature range	–40 to 175°C
$R_{\theta JC}$	Maximum thermal resistance, junction-to-leads, double-side cooling (composite values)	
	Length of leads① 1/8"	11.0° C/W
	Length of leads① 3/8"	14.7° C/W
	Length of leads① 3/4"	20.0° C/W
	Approximate Weight (grams)	1.5

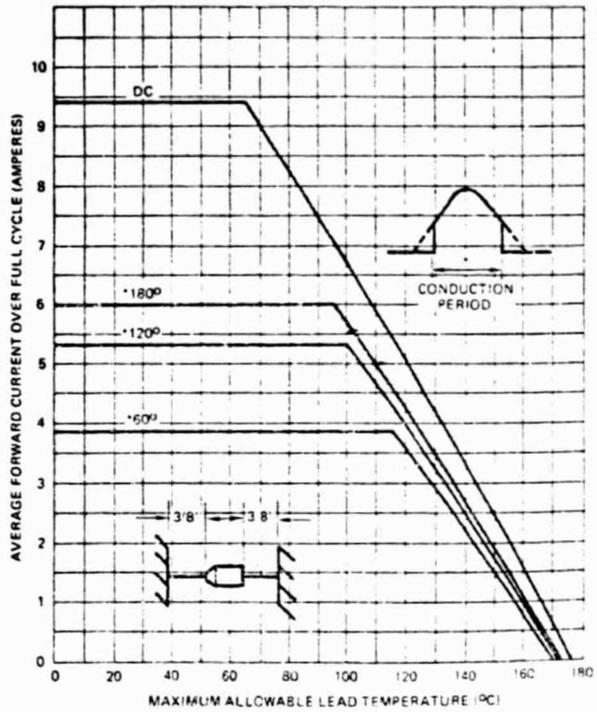
① *Length of leads to the temperature measurement points (heat sinks).*

6 AMP AXIAL LEAD PN JUNCTION DIODE OPERATING CHARACTERISTICS

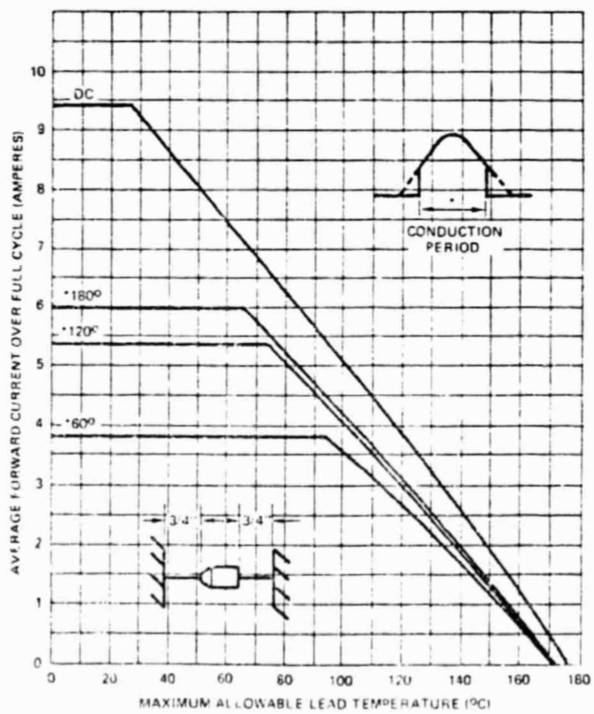
(INTERNATIONAL RECTIFIER - MODEL NO. 60S05)



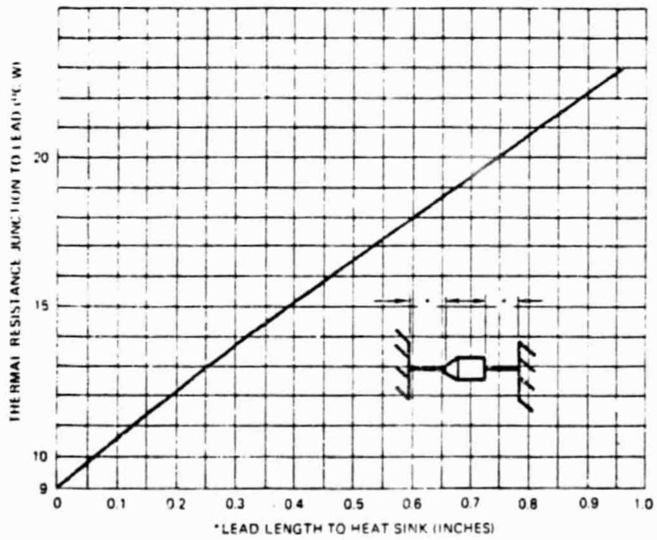
Average Forward Current Vs. Lead Temperature at Heat Sinks – L = 1/8 inch.



Average Forward Current Vs. Lead Temperature at Heat Sinks – L = 3/8 inch.



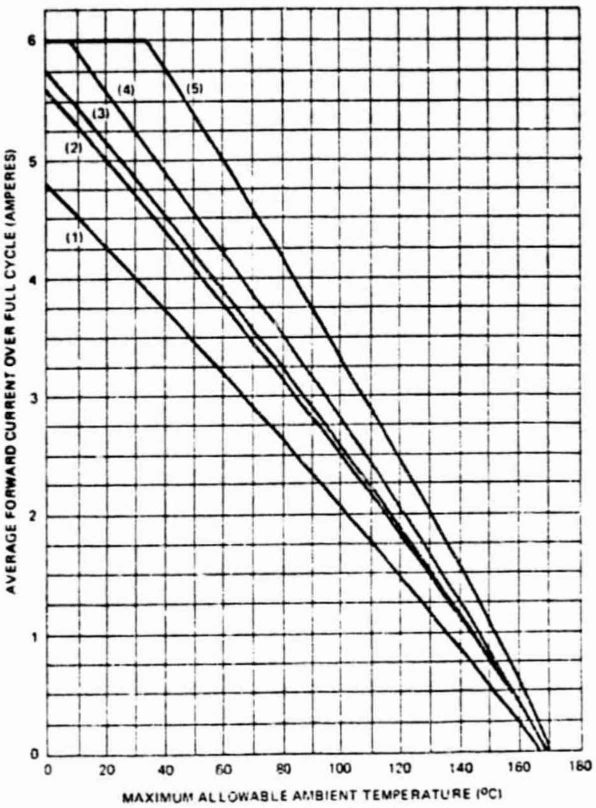
Average Forward Current Vs. Lead Temperature at Heat Sinks – L = 3/4 inch.



Maximum Thermal Resistance Vs. Lead Length

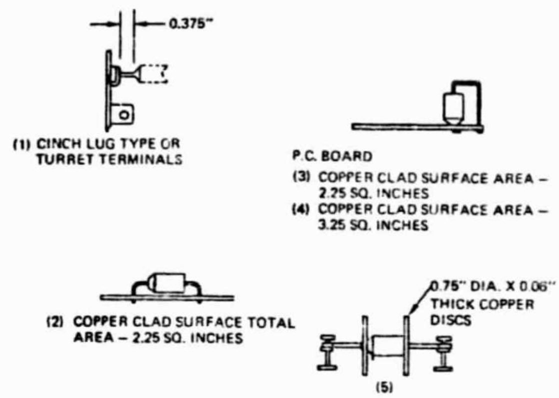
6 AMP AXIAL LEAD PN JUNCTION DIODE OPERATING CHARACTERISTICS

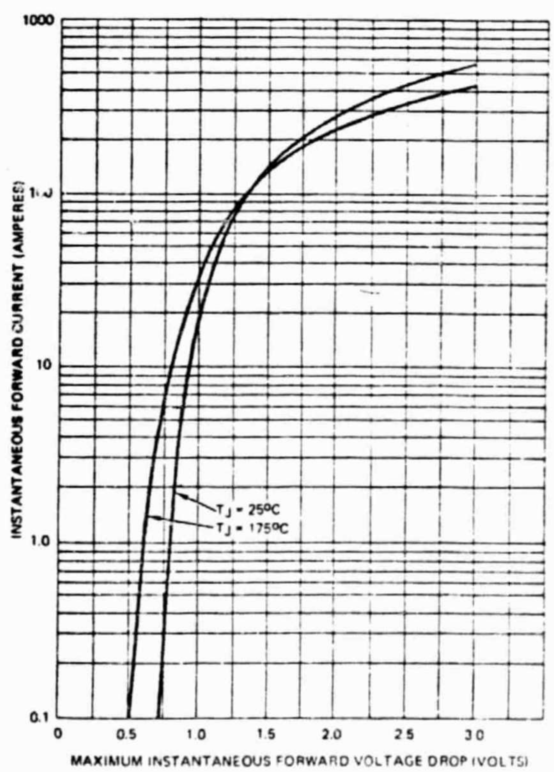
(INTERNATIONAL RECTIFIER - MODEL NO. 60S05)



Average Forward Current Vs. Ambient Temperature for Various Mounting Methods.

Mounting Details:





Maximum Instantaneous Forward Voltage Drop Vs. Instantaneous Forward Current

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8 AMP AXIAL LEAD SHOTTKY DIODE OPERATING CHARACTERISTICS

(INTERNATIONAL RECTIFIER - MODEL NO. 80SQ030)

VOLTAGE RATINGS

Part Numbers	V_{RWM} – Max. Working Peak Reverse Voltage (V) ①	V_{RRM} – Max. Repetitive Peak Reverse Voltage (V) ① (200 ns Max. Pulse Width)	V_R – Max. DC Reverse Voltage (V) ①
80SQ030	30	36	30
80SQ040	40	48	40
80SQ045	45	54	45

ELECTRICAL SPECIFICATIONS

Series		80SQ	Units	Conditions	
$I_{F(AV)}$	Max. average forward current	8	A	180° conduction @ T_L = -65 to 92° rectangular waveform ④③	
		7.2		180° conduction @ T_L = -65 to 97°C sinusoidal waveform ④⑤	
I_{FSM}	Max. peak one cycle, non-repetitive surge current	380	A	Half cycle 50 Hz sine wave or 6 ms rectangular pulse	Following any rated load condition and with rated V_{RWM} reapplied.
		400		Half cycle 60 Hz sine wave or 5 ms rectangular pulse	
I^2t	Maximum I^2t for fusing	730	A^2s	t = 10 ms	With rated V_{RRM} following surge
		665		t = 8.3 ms	
	Maximum I^2t for individual device fusing	730	A^2s	t = 5 ms	With V_{RRM} = 0 following surge
		400		t = 1.5 ms	
$I^2\sqrt{t}$	Maximum $I^2\sqrt{t}$ for individual device fusing ⑤	10330	$A^2\sqrt{s}$	t = 0.1 to 10ms, with V_{RRM} = 0 following surge.	
V_{FM}	Max. peak forward voltage	0.70	V	T_J = 25°C	Rated $I_{F(AV)}$ (16A peak) square wave, 180° conduction
		0.58		T_J = 150°C	
		0.55		T_J = 175°C	
I_{RM}	Max. peak reverse current	5.0	mA	T_J = 25°C	V_{RWM} = rated value
		12		T_J = 125°C	
		30		T_J = 150°C	
C_t	Max. junction capacitance	1500	pF	T_C = 25°C, V_R = 5 Vdc (Test signal in the range of 100 kHz to 1 MHz)	
dv/dt	Max. rate of reverse voltage application	600	V/μs	T_C = 25°C, V_{RM} = rated V_{RRM}	

THERMAL-MECHANICAL SPECIFICATIONS

T_J	Max. operating junction temperature range		-65 to 175	°C	
T_{stg}	Max. storage temperature range		-65 to 175	°C	
$R_{\theta JL}$	Maximum thermal resistance, junction-to-leads, double side cooling (composite values)			°C/W	
	Lead Length ①	ℓ = 3.2mm (1/8 in.)	11.0		
		ℓ = 9.5mm (3/8 in.)	14.7		
		ℓ = 19.0mm (3/4 in.)	20.0		
	Approximate weight		1.5 (0.053)	g (oz)	
	Case Style		C-15		

① T_C = -65°C to 158°C

② T_C = 0°C to 158°C

③ T_C = -65°C to 115°C

④ ℓ = 9.5mm (3/8 in.)

⑤ I^2t for time $t_x = I^2\sqrt{t} \cdot \sqrt{t_x}$

⑥ Length of leads to temperature measurement points (heat sinks)

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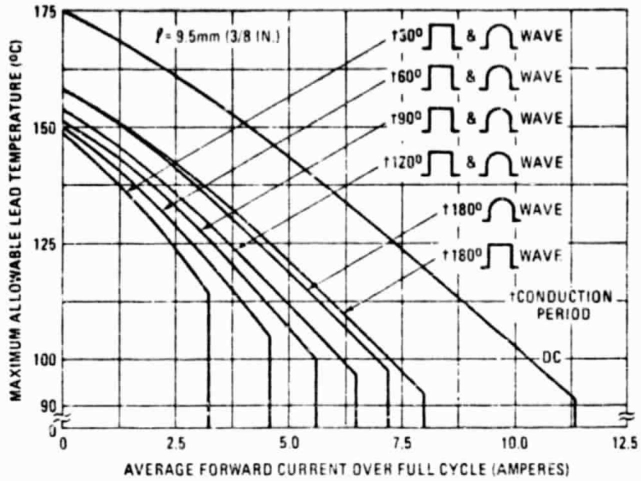
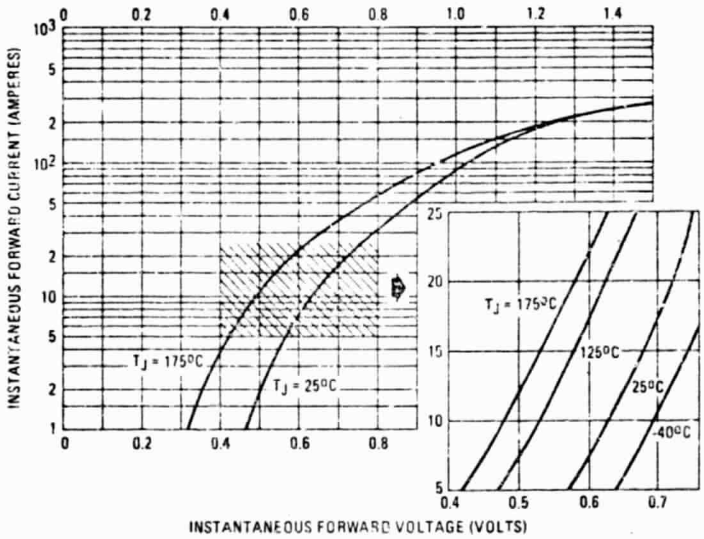
8 AMP AXIAL LEAD SHOTTKY DIODE OPERATING CHARACTERISTICS

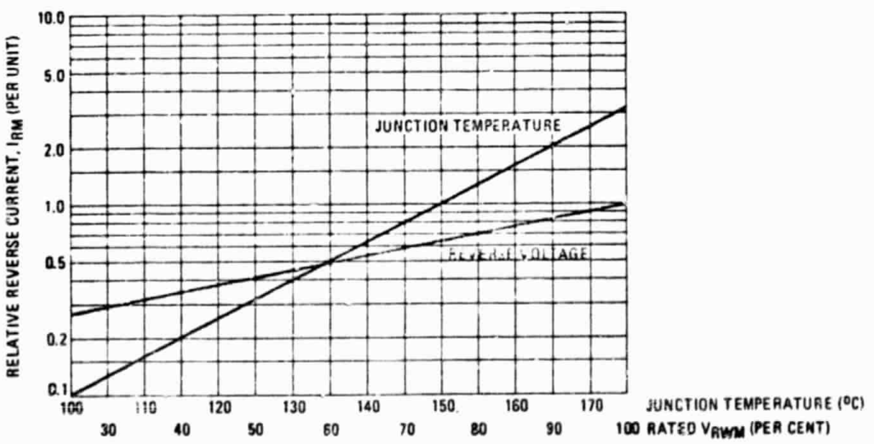
(INTERNATIONAL RECTIFIER - MODEL NO. 80SQ030)



Maximum Allowable Lead Temperature Vs. Average Forward Current (50 Hz to 100 kHz)



Maximum Forward Voltage Vs. Forward Current



Typical Variation of Reverse Current Vs. Junction Temperature and Reverse Voltage

12 AMP T0220 SCHOTTKY DIODE OPERATING CHARACTERISTICS

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(UNITRODE - MODEL NO. USD820)

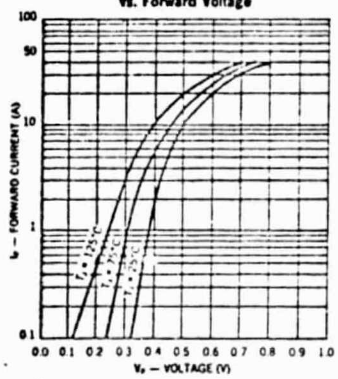
ABSOLUTE MAXIMUM RATINGS

	USD820	USD835	USD840	USD845
Working Peak Reverse Voltage, V_{RWM}	20V	35V	40V	45V
DC Blocking Voltage, V_R	20V	35V	40V	45V
Peak Repetitive Surge Voltage, V_S	20V	35V	40V	45V
Average Rectified Forward Current @ T_C = 115°C, I_O	12A			
Peak Repetitive Forward Current (Rated V_R, Square Wave, 20KHz, 50% Duty Cycle, @ T_C = 115°C), I_{FRM}	24A			
Non-repetitive Peak Surge Current (8.3mS), I_{FSM}	200A			
Reverse Transient Capability				
Reverse Transient Current, Pk	1A			
Reverse Transient Power, Pk	50W			
Peak Operating Junction Temperature, T_{jmax}	150°C			
Storage Temperature Range, T_{Stg}	−55°C to +150°C			
Thermal Resistance, Junction to Case, $R_{\theta JC}$	2.4°C/W			

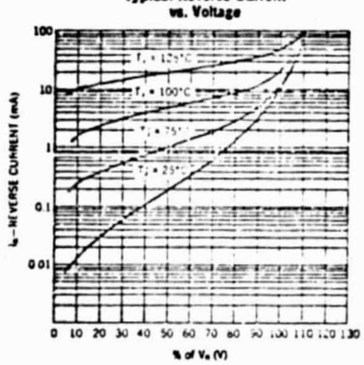
ELECTRICAL CHARACTERISTICS (T_{CASE} = 25°C)

CHARACTERISTIC	SYMBOL	LIMIT	UNITS	CONDITIONS
Maximum Instantaneous Reverse Current	i_R	20	mA	$V_R = V_{RWM}$ Pulse Width = 400μS Duty Cycle = 1 percent
Typical Instantaneous Reverse Current	i_R	50	mA	$V_R = V_{RWM}$ Pulse Width = 400μS Duty Cycle = 1 percent T_C = 125°C
Maximum Instantaneous Forward Voltage	V_F	0.55	V	i_F = 12A
		0.45	V	i_F = 12A T_C = 125°C
Capacitance	C_t	2000	pF	V_R = 5V
Voltage Rate of Change	dv/dt	1000	V/μS	$V_R = V_{RWM}$

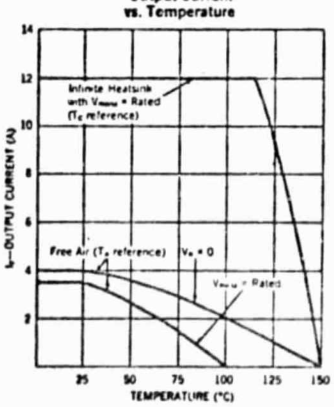
Typical Forward Current vs. Forward Voltage



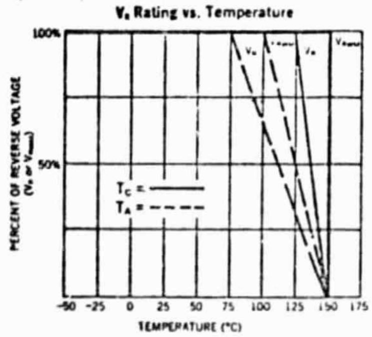
Typical Reverse Current vs. Voltage



Output Current vs. Temperature



V_R Rating vs. Temperature



20 AMP TO3* SCHOTTKY DIODE
OPERATING CHARACTERISTICS

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(GENERAL INSTRUMENTS - MODEL NO. 3020*)

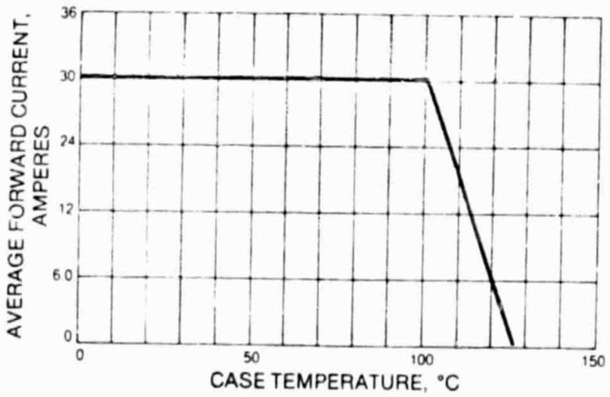
MAXIMUM RATINGS AND ELECTRICAL CHARACTERISTICS

Ratings at 25° ambient temperature unless otherwise specified.
Single phase, half wave, 60Hz, resistive or inductive load.
For capacitive load, derate current by 20%.

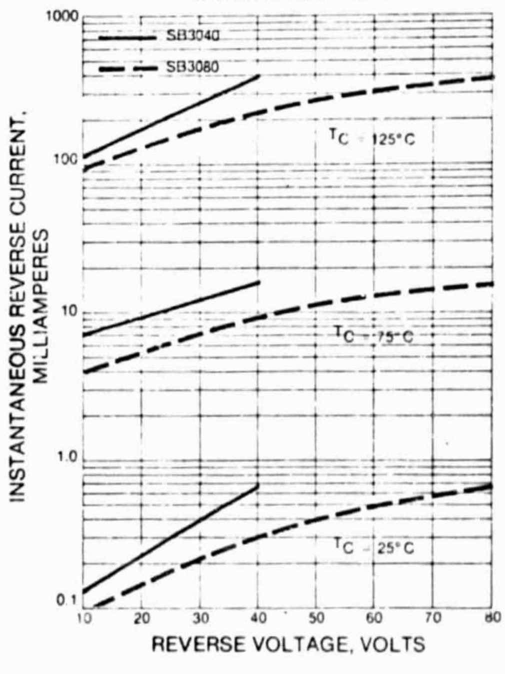
	SB3020	SB3030	SB3040	SB3050	SB3060	SB3080	UNITS
Maximum Recurrent Peak Reverse Voltage	20	30	40	50	60	80	V
Maximum RMS Voltage	14	21	28	35	42	56	V
Maximum DC Blocking Voltage	20	30	40	50	60	80	V
Maximum Average Forward Rectified Current at TC = 100°C				30			A
Peak Foward Surge Current. 8.3 ms single half sine-wave superimposed on rated load (JEDEC method)				300			A
Maximum Forward Voltage at 15A per element		.55			.65		V
Maximum Average Reverse Current at Rated DC Blocking Voltage per element. TC = 25°C				10			mA
TC = 100°C				100			mA
Typical Thermal Resistance RθJA (Note 1)				1.4			°C/W
Typical Junction Capacitance (Note 2)				2000			pF
Storage and Operating Temperature Range TC				− 65 to + 125			°C

NOTES 1 — Thermal Resistance Junction to CASE
2 — Measured at 1 MHz and applied reverse voltage of 4.0 volts

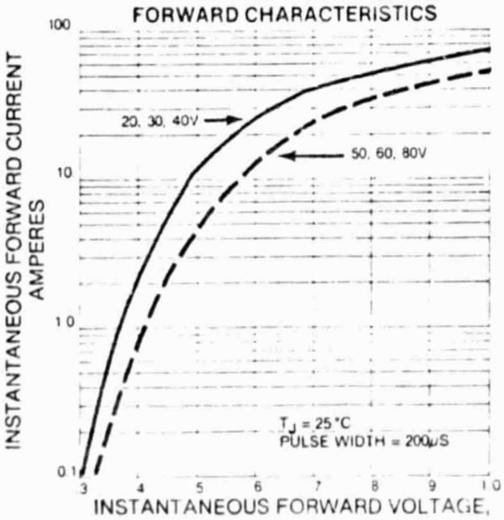
FORWARD CURRENT DERATING CURVE



TYPICAL REVERSE CHARACTERISTICS



TYPICAL INSTANTANEOUS FORWARD CHARACTERISTICS



*THIS PACKAGE USUALLY CONTAINS TWO DIODES (FOR TRANSFORMER CENTER TOP FULL WAVE AC RECTIFICATION). AVAILABLE WITH ONE DIODE ON REQUEST.

25 AMP DO21 PN JUNCTION DIODE OPERATING CHARACTERISTICS

(MOTOROLA - MODEL NO. IN3491)

*MAXIMUM RATINGS

Rating	Symbol	1N3491	1N3492	1N3493	1N3494	1N3495	MR327	MR328	MR330	MR331	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	200	300	400	500	600	800	1000	Volts
RMS Reverse Voltage	$V_{R(RMS)}$	35	70	140	210	280	350	420	560	700	Volts
Average Rectified Forward Current (single phase, resistive load, 60 Hz, see Figure 3) $T_C = 100°C$	I_O	25									Amp
Nonrepetitive Peak Surge Current (surge applied at rated load conditions, see Figure 5)	I_{FSM}	300 (for 1/2 cycle)									Amp
Operating and Storage Junction Temperature Range	T_J, T_{stg}	-65 to +175									°C

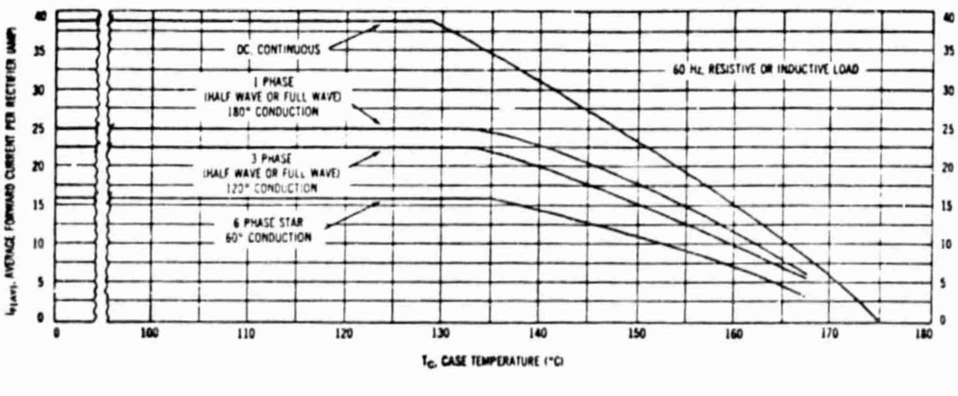
THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	1.2	°C/Watt

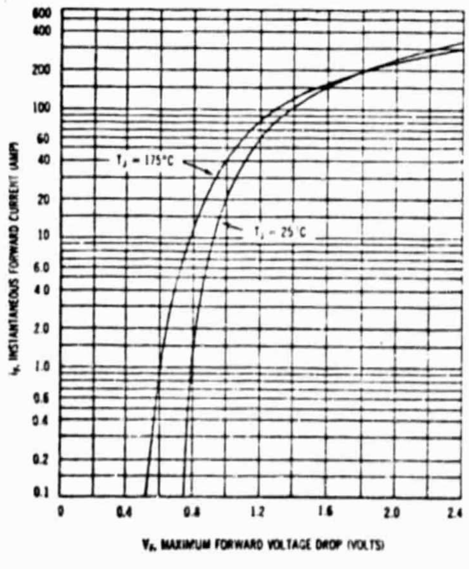
*ELECTRICAL CHARACTERISTICS

Characteristic and Conditions	Symbol	Max	Unit
Instantaneous Forward Voltage Drop (i_F = 57 Amps, T_J = 25°C)	v_F	1.7	Volts
Full Cycle Average Reverse Current (18 Amp AV and V_r, single phase, 60 Hz, T_C = 150°C)	$I_{R(AV)}$		mA
1N3491		10	
1N3492		10	
1N3493		8.0	
1N3494		6.0	
1N3495		4.0	
MR327		3.0	
MR328		2.5	
MR330		2.0	
MR331		1.5	
DC Reverse Current (Rated V_R, T_C = 25°C)	I_R	1.0	mA

MAXIMUM CURRENT RATINGS



MAXIMUM FORWARD VOLTAGE DROP



40 AMP DO21 SCHOTTKY DIODE OPERATING CHARACTERISTICS (MOTOROLA - MODEL NO. 4020PF)

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MAXIMUM RATINGS

Rating	Symbol	MBR4020PF	MBR4030PF	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	20	30	Vo-ts
Non-Repetitive Peak Reverse Voltage	V_{RSM}	24	36	Volts
Average Rectified Forward Current $V_{R(equiv)} \leq 0.2\ V_{R(dc)}$, $T_C = 50°C$	I_O	← 40 →		Amp
Ambient Temperature Rated $V_{R(dc)}$, $P_{F(AV)} = 0$, $R_{\theta JA} = 2.0°C/W$	T_A	100	95	°C
Non-Repetitive Peak Surge Current (surge applied at rated load conditions halfwave, single phase, 60 Hz)	I_{FSM}	→ 800 (for 1 cycle) →		Amp
Operating and Storage Junction Temperature Ranps (Reverse voltage applied)	T_J, T_{stg}	← -65 to +125 →		°C
Peak Operating Junction Temperature (Forward Current Applied)	$T_{J(pk)}$	← 150 →		°C

THERMAL CHARACTERISTICS

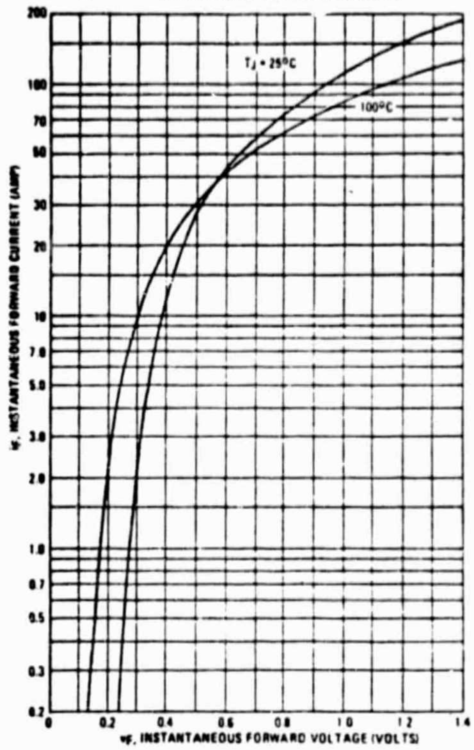
Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction to Case	$R_{\theta JC}$	1.3	°C/W

ELECTRICAL CHARACTERISTICS ($T_C = 25°C$ unless otherwise noted.)

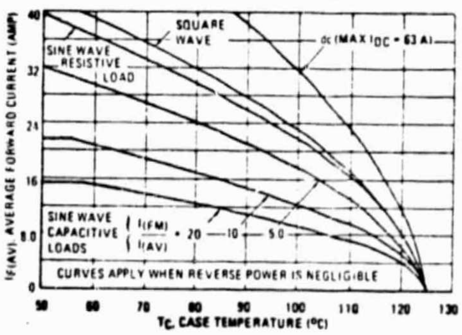
Characteristic	Symbol	Min	Typ	Max	Unit
Maximum Instantaneous Forward Voltage (1) ($i_F = 40$ Amp)	v_F	–	0.57	0.630	Volts
Maximum Instantaneous Reverse Current @ rated dc Voltage (1) $T_C = 100°C$	i_R	– –	– –	20 150	mA

(1) Pulse Test: Pulse Width = 300 μs, Duty Cycle = 2.0%.

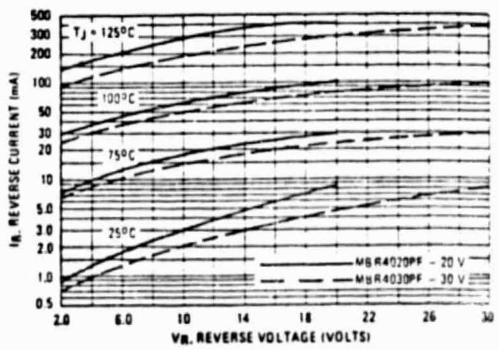
TYPICAL FORWARD VOLTAGE



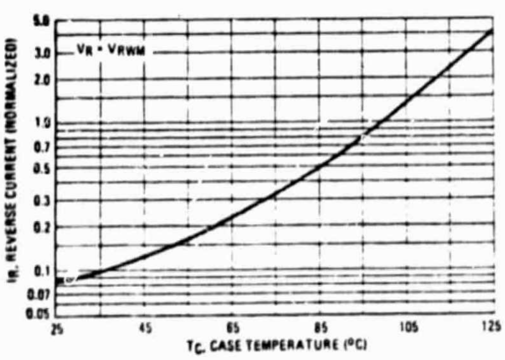
CURRENT DERATING



TYPICAL REVERSE CURRENT



NORMALIZED REVERSE CURRENT



16 AMP D04 PN JUNCTION DIODE OPERATING CHARACTERISTICS

ELECTRICAL SPECIFICATIONS

Series		1N3615 to 1N3624	16F	Units	Conditions
$I_{F(AV)}$	Max. average forward current	16*	16	A	1 phase operation, T_C = 150°C
I_{FSM}	Max. peak one cycle, non-repetitive surge current	300*	300	A	60 Hz half sine wave, following any rated load condition.
V_{FM}	Max. peak forward voltage	1.2*	1.2	V	Rated $I_{F(AV)}$ (50A peak) T_C = 150°C

THERMAL–MECHANICAL SPECIFICATIONS

T_J	Max. operating junction temperature range	−65° to 200*	°C	
T_{stg}	Max. storage temperature range	−65° to 200*	°C	
$R_{\theta JC}$	Max. thermal resistance, junction-to-case	1*	°C/W	Dc operation
$R_{\theta CS}$	Thermal resistance, case to sink	0.50	°C/W	Mounting surface flat, smooth, and greased
	Mounting torque Min. / Max.	12 (1.36) / 15 (1.69)	lbf-in. (N-m)	Non-lubricated threads
	Approximate weight (mass)	1/4 (7.09)	oz (g)	

*JEDEC registered values

VOLTAGE RATINGS

PART NUMBER ①		V_{RRM} MAX. REPETITIVE PEAK REVERSE VOLTAGE (V)	V_{RSM} MAX. NON-REPETITIVE PEAK REVERSE VOLTAGE (V)	$V_{R(RMS)}$ MAX. RMS INPUT VOLTAGE (V)	V_R MAX. DC BLOCKING VOLTAGE (V)	$I_{R(AV)}$ MAX. AVERAGE REVERSE CURRENT @ MAX. RATED $I_{F(AV)}$ AND V_{RRM} T_C = 150°C (1 PHASE OPERATION) (mA)
1N3615	16F5	50*	100*	35*	50*	3.0 *
1N3616	16F10	100*	200*	70*	100*	2.5 *
1N3617	16F15	150*	300*	105*	150*	2.25*
1N3618	16F20	200*	350*	140*	200*	2.0 *
1N3619	16F30	300*	500*	210*	300*	1.75*
1N3620	16F40	400*	600*	280*	400*	1.5 *
1N3621	16F50	500*	700*	350*	500*	1.25*
1N3622	16F60	600*	800*	420*	600*	1.0 *
1N3623	16F80	800*	1000*	560*	800*	0.75*
1N3624	16F100	1000*	1200*	700*	1000*	0.6 *

① Cathode-to-case. For anode-to-case add "R" to base number, i.e. 1N3615R, 16FR50.

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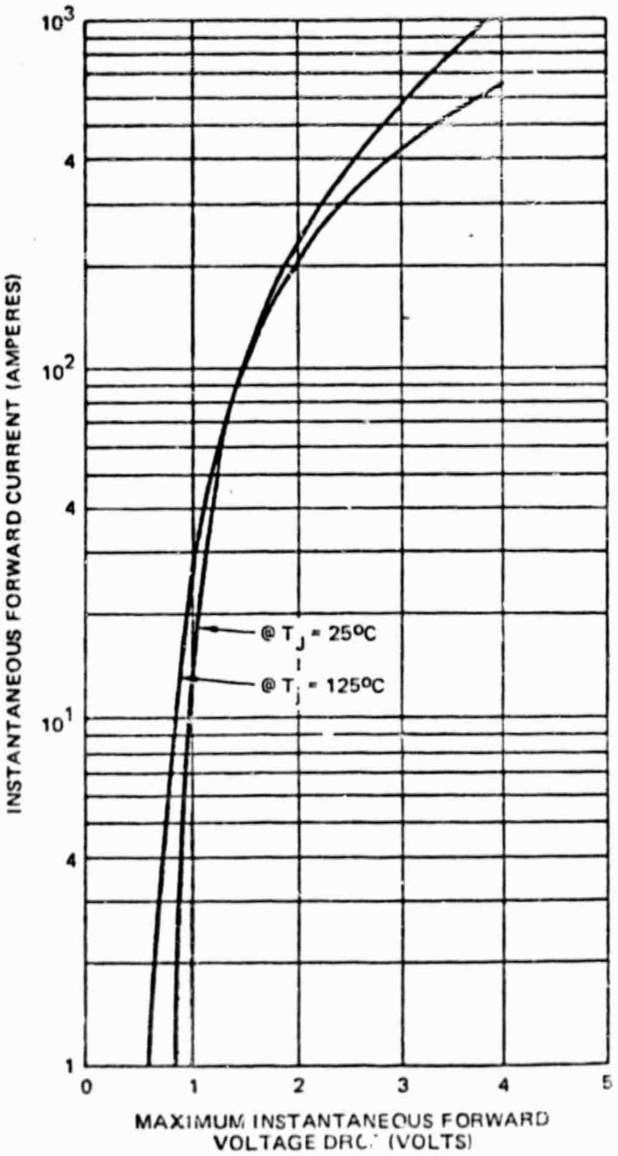
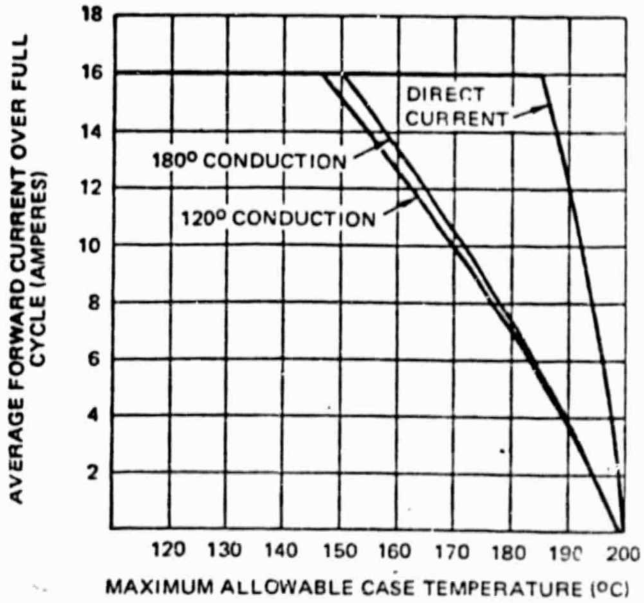
16 AMP D04 PN JUNCTION DIODE OPERATING CHARACTERISTICS

(INTERNATIONAL RECEIFIER - MODEL NO. IN3615)



Maximum Forward Voltage Drop Vs Forward Current



Average Forward Current Vs Case Temperature (Resistive Load)

35 AMP DO5 PN JUNCTION DIODE OPERATING CHARACTERISTICS

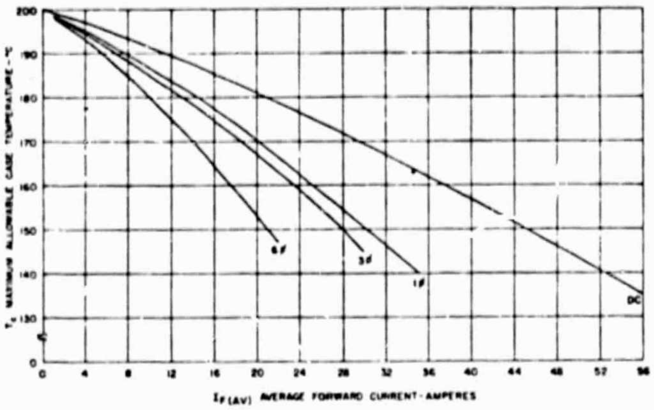
(GENERAL ELECTRIC - MODEL NO. 1183)

ratings & specifications (60 cps, Resistive or Inductive Load)

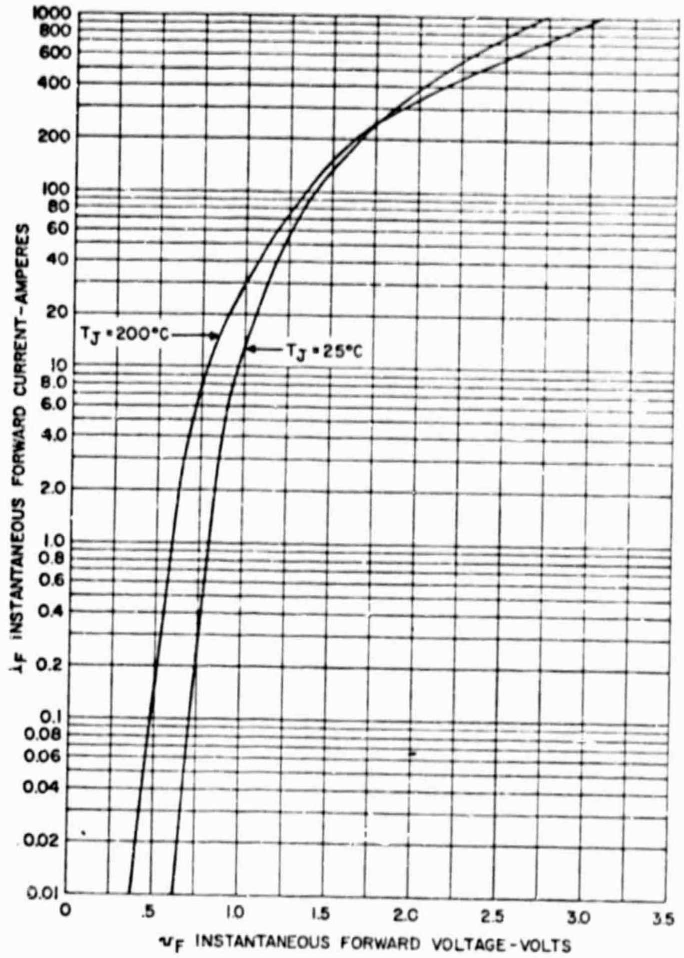
	1N1183	1N1184	1N1185	1N1186	1N1187	1N1188	1N1189	1N1190	1N3765	1N3766	1N3767	1N3768	1N5332	
*Maximum Allowable Repetitive and Working Peak Reverse Voltage, V_{RM} (rep) & V_{RM} (wkg.)[1]	50	100	150	200	300	400	500	600	700	800	900	1000	1200	volts
Maximum Allowable RMS Voltage, V_r	* 35.5	* 71	* 106	* 142	* 212	* 284	* 355	* 424	495	565	635	710	852	volts
*Maximum Allowable DC Blocking Voltage, V_R[2]	40	80	120	160	240	320	400	480	700	800	900	1000	1200	volts
*Maximum Allowable Average Forward Current (180° conduction angle, 60 cps, half sine wave current at T_C = 140°C), I_0	← 35 Adc →													
*Maximum Allowable Peak One Cycle Surge Current (non-recurrent), I_{FM} (surge)	← 500 →								← 400 →				← 500 →	amperes
I²t Rating (for t greater than .001 sec. and less than .0083 sec., non-recurrent)	← 500 (Amp RMS)²Sec min. value, See Chart 6 →													
*Maximum Peak Forward Voltage Drop (I_0 = 35 Adc at T_C = 140°C), $V_{F(AV)}$	← 1.7 →								← 1.8 →				← 1.7 →	Vdc
*Maximum Average Reverse Current (I_0 = 35 Adc at T_C = 140°C), $I_{R(AV)}$	10	10	10	10	10	10	10	10	5	4	3	2	2	mA
Maximum Effective Thermal Resistance Junction to Case, $R_{\theta JC}$	* 1.0	* 1.0	* 1.0	* 1.0	* 1.0	* 1.0	* 1.0	* 1.0	1.0	1.0	1.0	1.0	1.0	°c/w
Junction Operating & Storage Temperature Range, T_J & T_{stg}	← −65° C to +200°C →													
Stud Torque	← 30 inch pounds (35K_g-cm) →													

[1] Maximum voltages apply with a heat sink thermal resistance of 10°C/w or less at maximum rated junction temperature.
[2] Maximum voltages apply with a heat sink thermal resistance of 5°C/w or less at maximum rated junction temperature.
NOTE: Case temperature is measured at the center of any one of the hex flats.
*The asterisk denotes JEDEC (EIA) registered information.

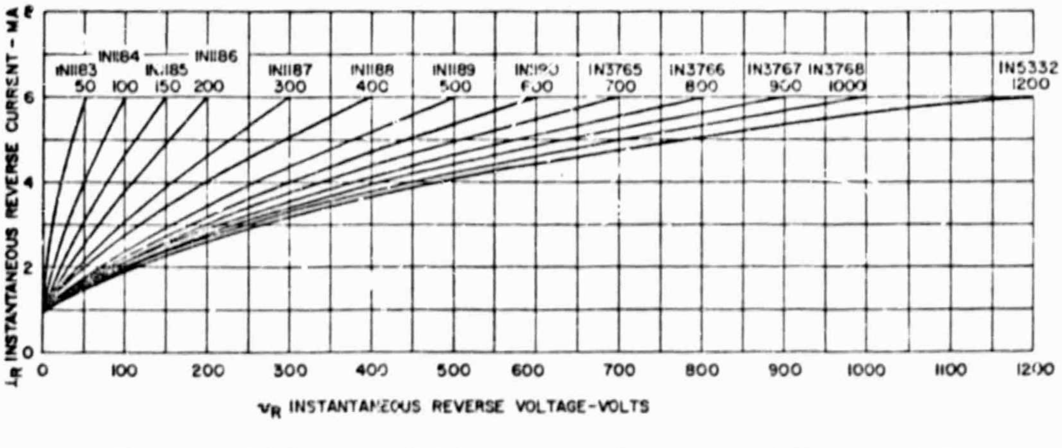
35 AMP DO5 PN JUNCTION DIODE
OPERATING CHARACTERISTICS
(GENERAL ELECTRIC - MODEL NO. 1183)



AVERAGE CURRENT RATING AS A FUNCTION OF CASE TEMPERATURE



MAXIMUM FORWARD CHARACTERISTICS



TYPICAL REVERSE CHARACTERISTICS $T_J = 200°C$ FOR VARIOUS VOLTAGE GRADES

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25 AMP (DO4) AND 50 AMP (DO5) SCHOTTKY DIODES OPERATING CHARACTERISTICS

(TRW - MODEL NOS. 1N6095 (25 AMP) AND 1N6097 (50 AMP))

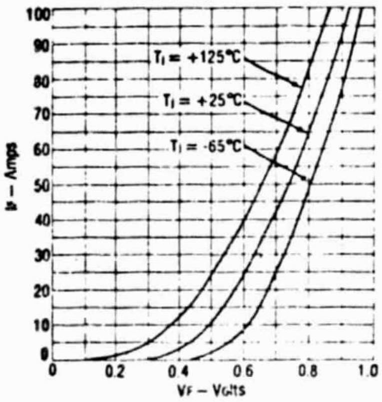
Maximum Ratings — JEDEC Registered

Symbol	Characteristics	1N6095	1N6096	1N6097	1N6098
V_R	D.C. Blocking Voltage	30V	40V	30V	40V
V_{RWM}	Peak Reverse Working Voltage	30V	40V	30V	40V
V_{RSM}	Non-Rep. Peak Reverse Voltage	36V	48V	36V	48V
I_o	Average Constant Forward Current	25A	25A	50A	50A
I_S	Peak Forward Surge Current	400A	400A	800A	800A
T_{OP}	Operating Temperature — No Derating (T_{CASE})	-65°C to +70°C			
T_{STG}	Storage Temperature	-65°C to +125°C			
T_J	Peak Junction Temperature	+150°C			
θ_{JC}	Thermal Impedance	2°C/W	2°C/W	1°C/W	1°C/W

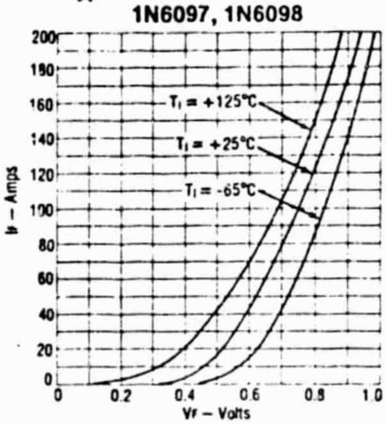
Maximum Electrical Characteristics — JEDEC Registered

Symbol	Characteristics	Test Conditions	1N6095 1N6096	1N6097 1N6098
V_{RWM}	Peak Reverse Current	V_{RWM}, $T_J = +125°C$ Pulsed Test, P.W. ≤ 300μs, D.C. ≤ 2%	250mA	250mA
I_R	D.C. Reverse Current	V_R, $T_J = +125°C$	250mA	250mA
V_{FM}	Peak Forward Voltage	I_o, $T_{CASE} = +70°C$	0.86V	0.86V
C_T	Junction Capacitance	$V_R = 1.0V$, $T_{CASE} = +25°C$ 100KHz ≤ f ≤ 1MHz	6000pF	7000pF

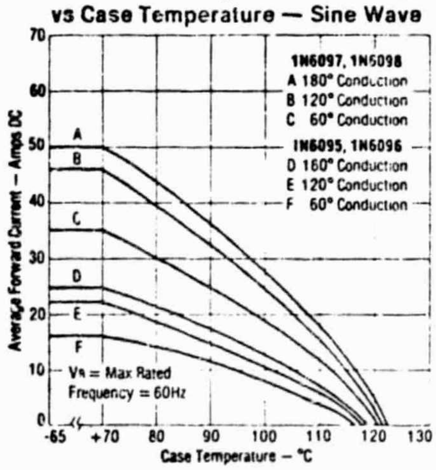
Typical Instantaneous I_F vs V_F 1N6095, 1N6096



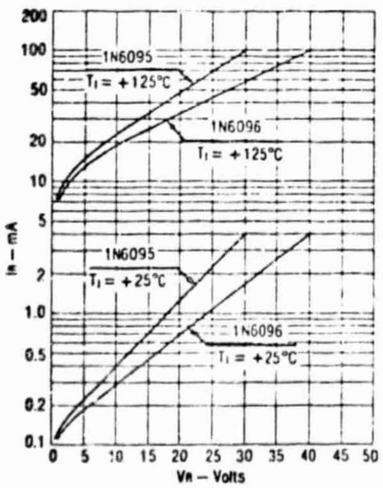
Typical Instantaneous I_F vs V_F 1N6097, 1N6098



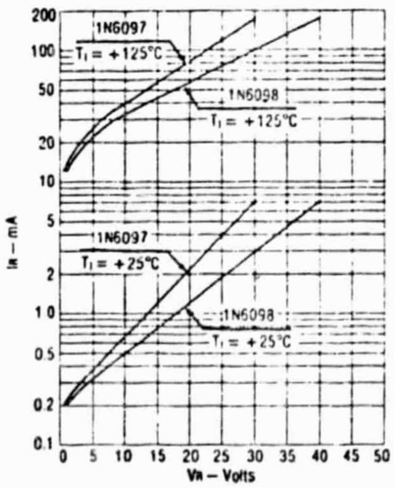
Maximum Average Forward Current vs Case Temperature — Sine Wave



Typical Instantaneous I_R vs V_R 1N6095, 1N6096



Typical Instantaneous I_R vs V_R 1N6097, 1N6098



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