Operational Manual

Team 13

Designing & Testing a Thermal Management System for a SiC PV Converter

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Sponsor/s

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Aero-Propulsion, Mechatronics and Energy (AME)

PowerAmerica – U.S. Department of Energy

Instructor/s

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ABSTRACT

Team 13 optimized a thermal management system for a Silicon Carbide (SiC) Photovoltaic (PV) converter that was developed by the Center for Advanced Power Systems (CAPS) after discovering that their current cooling system was overdesigned. The team also developed heat source emulators, designed to mimic the heat generated by the SiC power modules in the PV converter. These emulators were used for testing heatsinks to ensure that the thermal management systems being studied were adequate. Prior to using the heatsink and fan cooling system, as well as the emulator, the user must know how to assemble and properly operate them. This manual provides a functional analysis, product specifications and assembly, operator instructions, troubleshooting, and maintenance guidelines as well as recommendations on spare parts. The user should be thoroughly familiar with the components of both assemblies before attempting to operate them.

ACKNOWLEDGMENTS

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Lastly, Team 13 gives thanks to Dr. Shih and Dr. Hooker for coordinating the team configuration and providing the guidelines needed for a successful project.

1. Introduction

The goal of this project, sponsored by Power America, was to design a cost-effective, lightweight, thermal cooling system for a SiC PV converter being developed by researchers at CAPS. Their goal for this converter is to have the highest power density available on the market. However, the original heatsink that was dissipating heat from the power modules in the converter was overdesigned, and accounting for a significant portion of the weight of the system. By reducing the weight of the thermal cooling system, Team 13 helps CAPS increase the power density from 2.5 kW/kg. The objective was completed by using three different approaches: theoretical analysis, experimental testing, and thermal simulations using COMSOL Multiphysics. A heat source emulator was developed for testing, and an optimized heatsink was designed after simulations, calculations, and testing were verified with one another. The final solution was to have 4 pin-fin heatsinks that housed 2 power modules each. Each heatsink has a thermal resistance of about 0.3 K/W, and weighs 211 grams. The optimized cooling system had a 71% reduction in weight from the original cooling system, and is designed to keep the power modules well under their max operating temperatures. Overall, this thermal management system helps to bring the power density of the PV converter up to 6.54 kW/kg.

2. Functional Analysis

The primary objective of this project was to design a lightweight heatsink for the power modules contained in a SiC PV converter. The original heatsink that was used for the converter was overdesigned. It was a plate fin heatsink with a total of 8 fans fixed on the sides and it housed 8 power modules on its baseplate. The thermal cooling system weighs a total of 6.45 kg, and was “cold to the touch” during operation. Team 13’s solution had to meet the following criteria.

- Prevent 8 power modules from exceeding 120˚C (30 degrees below failure point) at steady state (while PV Converter produces 100 kW)
- Reduce the size and weight of the current design (6.45kg)
- Have a maximum thermal resistance of 0.792 K/W

Team 13 considered two different heatsink designs: a plate fin heatsink and a cylindrical pin fin heatsink. After conducting theoretical analyses, simulations using COMSOL, and experimental testing the group decided to pursue a thermal management system that consisted of 4 pin fin heatsinks with fans fixed to the bottom instead of on the sides. This configuration is known as impingement cooling, and provides more uniform cooling throughout. Each heatsink would house 2 power modules.

In addition to designing a thermal management system, Team 13 was tasked with the design, fabrication, and usage of a testing mechanism to verify and compare the capabilities of both plate and pin fin heatsink types. Power modules could not be used in order to protect against damage from an inadequate heatsink design. Heat source emulators were developed to mimic the SiC power modules, and were made from high power resistors connected in series. The resistors were chosen based on dimensional limitations, as well as based on the available power supply. The DC power supply had to provide the required amount of power needed to generate the amount of heat desired. Based on the available resources, Team 13 was able to come up with a solution, utilizing high power resistors with low resistances to simulate the emulators. A functional diagram of the thermal management system being tested with the heat source emulators is included in Figure 1. Figure 2 has the functional diagram for the heatsink being used inside the PV converter.

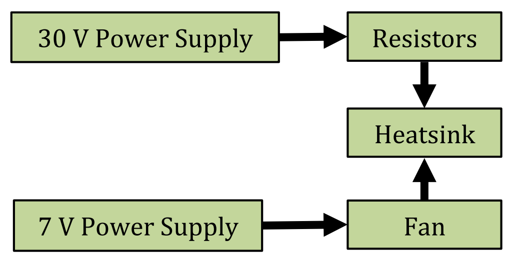


Figure 1: Functional Diagram of Heat Source Emulators with Active Heatsink

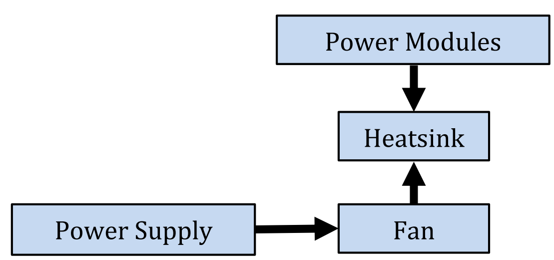


Figure 2: Functional Diagram of Power Modules with Active Heatsink

3. Product Specifications

Team 13 designed the heatsink shown in Figure 3. It's a simple pin fin heatsink made from Aluminum 6063 with a 15 x 15 array of 3mm diameter pins that are 10mm long. The base is 115mm x 115mm x 4.7 mm. This size allows for a 1.5 gap of separation between the two power modules (which is their minimum separation distance) and is just thick enough for 4-40 screws to be used for connecting the fan, utilizing L shaped brackets that the team developed. The heatsink weighs 211 g.

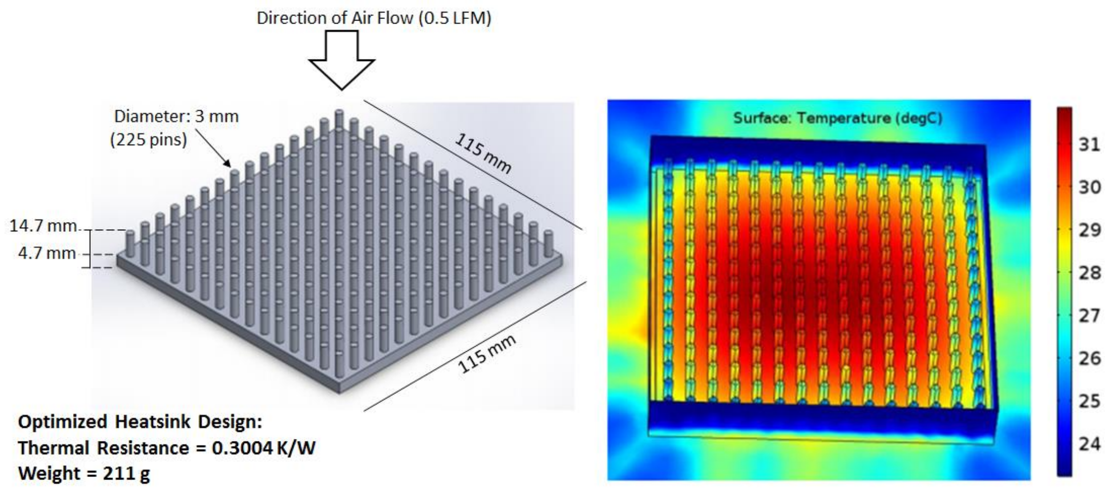


Figure 3: Optimized heatsink design (left) with COMSOL simulation (right)

A 120mm x 120mm x 25mm fan weighing 157 g is connected to the bottom of the heatsink, providing uniform cooling throughout the array. The fan has a volumetric flow rate of 0.5 LFM and is rated at 12V. A total of 16 screws, 4 L brackets, and 4 nuts are used in the assembly, weighing a total of 62 g.

At their maximum capacity, each power module has losses of 52.6W. This means that the max heat dissipation for each heatsink is 105.2 W. The max temperature that the baseplate will reach is 31.6˚C. The weight of the entire optimized system is 1.72 kg (0.43 kg / heatsink & assembly). With this solution, the thermal management system weight was reduced by 77%, which results in a power density increase to 6.54 kW/kg.

Each SiC power module had dimensions known to be 108mm x 46mm x 2mm, with its max loss assumed to be 100 W. Due to this size constraint, only two resistors could be used to emulate a power module. For each emulator, two high power resistors were connected in series. Each was capable of handling 50W. The team had access to a 30V power supply, and using Ohm's law, they determined a total resistance of 10 Ω was needed per emulator. Thus, each resistor needed to be 5 Ω. Figure 4 shows the emulator configuration using Multisim.

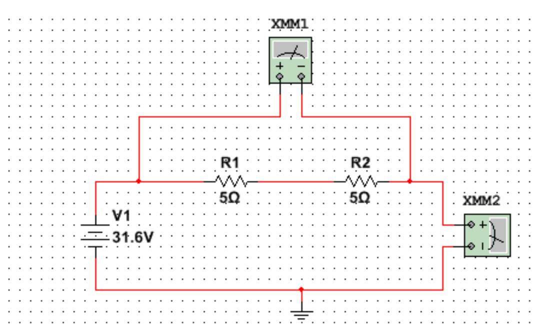


Figure 4: Heat Source Emulator Configuration

4. Product Assembly

The overall assembly of the heatsink and fan system is fairly simple. The fan is connected to 4 L-brackets with screws and nuts. The top of the L-brackets are connected to the sides of the heatsink. When this assembly is used with the heat source emulators, the 2 sets of resistors are simply screwed into the top of the baseplate. As previously mentioned, the resistors are connected in series. The setup is seen in Figure 5. It should be noted that during experimental testing, the team had screws that were sized for the fan attachments but not for the resistors which meant they were too long. These screws didn't supply the downward force needed to press the resistors firmly against the top of baseplate, which was important for heat transfer between the materials. In order to compensate for their extra length, the team used readily available nuts to fill in the gaps between the tops of the screws and resistors. This was an immediate solution that didn't require extra funds or time. It is not a permanent solution for the power modules, but was sufficient for testing purposes. Furthermore, the attachment of the power modules is similar to that attachment of the heat source emulators. The 2 power modules are screwed in to the top of the baseplate with a layer of thermal grease in between. A schematic of the setup of this assembly can be seen in Figure 6.

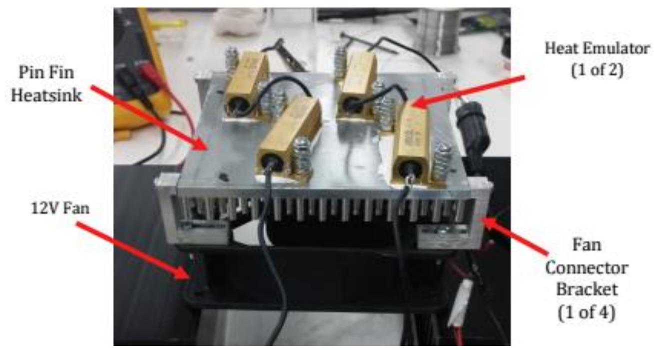


Figure 5: Test Setup with Heat Source Emulator

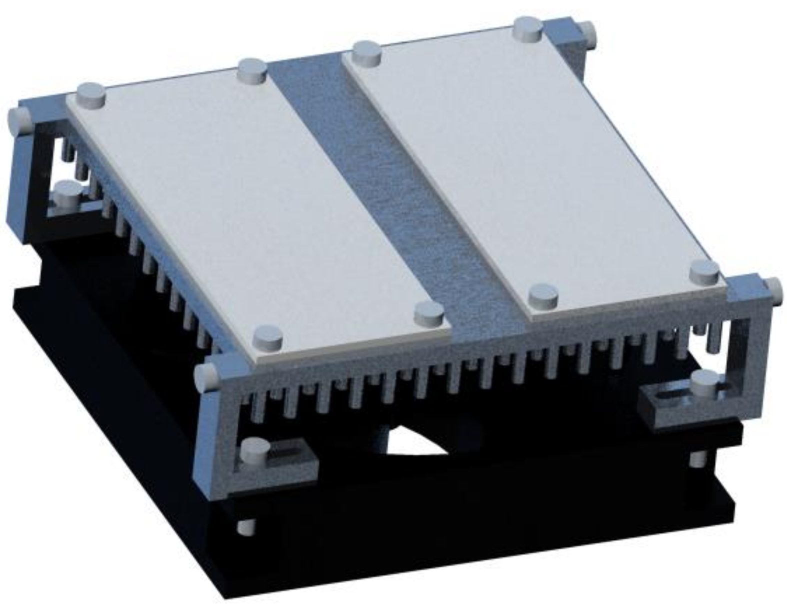


Figure 6: CAD Model of Power Module Heatsink Assembly

Heatsink & Fan Assembly:

1. Orient the fan on a flat surface facing upwards (fan specs label facing up).
2. Tightly screw all 4 L-Brackets into the holes in the sides of the heatsink, orienting them as shown Figure 5.
3. Place a screw facing downwards inside the slot at the bottom of each connector bracket.
4. Carefully place the heatsink and bracket assembly on the fan, aligning the loose screws with the holes on the outer edges of the fan.
5. Use the nuts provided to secure the screws, fastening the bottom of the connector bracket to the fan.

Emulator Construction:

The equipment, tools, and materials needed to construct the emulator is as follows:

- Four 50W, 5Ω resistors → this makes two emulators
- Any wire gauge capable of handling up to 5A of current (about 5 ft)
- Wire cutters/strippers
- Soldering iron & solder
- Thermal compound
- 8 screws

Step-by-step instructions:

1. Cut 4 wire sections of about 3 – 4 inches in length.
2. Cut 2 wire sections of about 2 inches in length.
3. Solder the shorter wire to the end of one resistor and the end of another resistor. Do this again for the second emulator. (1x shorter wire per emulator)
4. Solder the longer wire to the other end of each resistor. Do this again for the second emulator. (2x longer wire per emulator)
5. Liberally apply thermal compound to the bottom of each resistor.
6. Use 4 screws to secure the emulator to the baseplate of the heatsink. Do this again for the second emulator. The finished emulator should look similar as shown in Figure 7.

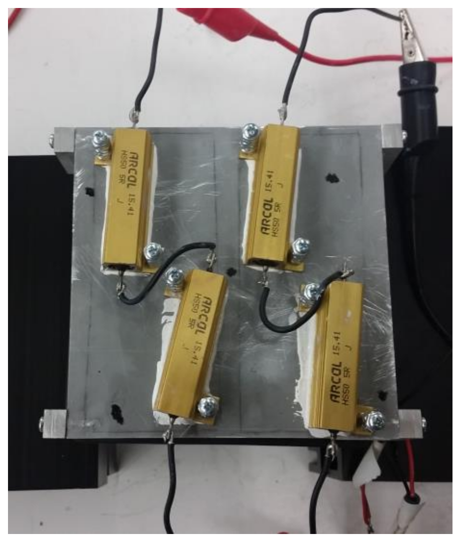


Figure 7: 2 Heat Source Emulators Side by Side

Once the emulators have been built, they must be tested to make sure they are in working order. Two methods should be used to verify this. The first method is to measure the resistance found across each resistor and the entire emulator to verify that they are in fact connected in series. The second test is to measure the connection of the emulator through a 'diode' or 'connection' test using a multimeter. Once both these methods have been verified, it can be safely assumed that the emulator is in full working condition.

5. Operation Instructions

With the heatsink assembled and the emulators constructed and mounted to the baseplate, they can be tested with a heatsink. As mentioned before, an emulator refers to two resistors in series capable of handling up to 50W each. This gives a total power dissipation of no more than 100W. For using the emulators, at no time should the power exceed 100W.

For testing a heatsink, it is important to determine its thermal conductivity properties, namely the thermal resistance. Although this can be calculated, it can also be observed through testing. Since the emulators are simply resistive components that will not exceed 100W, these resistors are capable of handling more heat than what will be generated during the testing. This makes them safer components to use and test on a heatsink without the risk of damaging equipment, if proper precautions are taken.

<u>Emulator Operation:</u>

Note: Due to the large amount of power required for each emulator (up to 100W) it may be necessary to use two power supplies or a single power supply with two independent channels.

Warning: Do not touch the power supply or heatsink with bare hands while powered up and in operation. Improper procedure can result in electric shock and/or burns.

1. Turn on the fan by connecting the positive and negative ends to the positive and negative ends of the 7V power supply, respectively.
2. Proceed to test the emulators.
3. Make sure the 30V power supply is off and turned down to 0 V.
4. Connect the power supply to the emulators by attaching the positive to one end of the emulator and the negative end to the other end. Do this for both emulators.
5. Turn on the power supply.
6. Starting with 0V, use an infrared temperature reader to measure the temperature of the baseplate in the 5 locations shown in Figure 8. Record the temperatures.
7. Increase the power output of the power supply by 15W. Be sure to keep the power supply the same for both emulators. Wait for steady state temperatures to be reached (about 5 minutes).
8. Using the infrared gun, measure the temperature of the baseplate in the 5 locations shown in Figure 8. Record temperatures. These will be averaged later.
9. Repeat steps 5-6, ranging the power from 0W-90W with increments of 15W. (The power supply team 13 used could not exceed 90W.)
10. After the final temperatures have been recorded, turn both power supplies down to 0V, and then turn it off.
11. Allow the heatsink to cool (2 hours).
12. Disconnect the power supply from the emulators and fans.

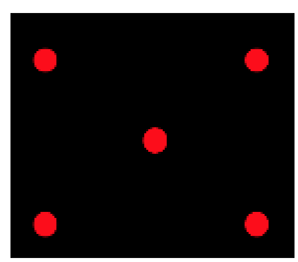


Figure 8: Locations to Measure Temperatures

6. Troubleshooting

Due to the nature of this project, only a few complications can arise during testing. The first complication would be from overheating if a fan is not used in conjunction with the heatsink while testing with the emulators. The emulators cannot endure temperatures exceeding 200C and if a fan is not used, the heatsink will not be able to dissipate the needed heat quickly enough to avoid overheating. If overheating does occur, the integrity of the emulators may be compromised. Using the test methods for operational use of the emulator as outlined in the product assembly section, one can verify the condition of the emulator. If the connection is broken, either the cabling or the resistors or both must be replaced, depending on the results shown from the multimeter connection test. One must also consider the situation where the fan fails during operation. This will likely be a product of a using the fan at max speed for prolonged periods of time which causes faster wear-and-tear. In an internal fault with the manufactured fan occurs, a new fan would need to be ordered. When the heatsinks are used in conjunction with the power modules, care must be taken to ensure that the fans have a reliable power source and do not exceed the rated voltage.

Another complication to consider for testing is if the emulators are in working condition but are not producing heat. This is most likely due to the power supply not supplying the required amount of power. It is important to know that if the power supply is at or near its maximum capacity, the power supply may have an overvoltage or overcurrent protection. If a test has triggered one of these protection schemes, the power supply voltage must be returned to zero, turned off, and unplugged from the power outlet for 5 minutes. This will essentially ‘reset’ the power supply and allow for use again. Of course, each power supply maker has different protection schemes and thus, consulting the operation manual of the power supply will yield the best troubleshooting methods.

Prior to testing and use of the thermal management system and the heat source emulators, connection in wires should be checked. In the event that a connection between the power supply and fans is severed via the connector falling off, the power should be turned off immediately to the entire system, including the emulators.

7. Regular Maintenance

There is not much regular maintenance that must take place for the thermal management system. The heatsink and brackets are not prone to rust because they are made from aluminum. The same goes for the screws, as they are made of zinc. Aluminum can be corrosive, so occasional visual check-ups can occur to ensure they’re in good condition. Upon being used in conjunction with the power modules, care should be taken to ensure that the fans are working well and not being run at their peak capacity all the time. The fans should only be used up to their expected life cycle as well.

With regards to the heat source emulators, it is important to make sure there is plenty of thermal grease used between them and the heatsink. When they are being stored, they should be wiped clean and kept in a closed off environment away from dust.

8. Spare Parts

Heatsink:

To avoid operation interruption, it is recommended to have 1 extra fan in inventory. The following table is list of parts provided in the package.

Table 1: Parts List for Thermal Cooling System

Part Name	QTY
Pin Fin Heatsink Body	4
12 V DC Fan	4
L-Bracket Connector	16
4-40 screws	64
4-40 Nuts	16

Emulators:

1 testing unit is provided. To avoid operation disruption it is recommended to have 1 extra resistor.

Table 2: Parts List for Heat Source Emulator

Part Name	QTY
5 Ω, 50W Resistor	4
5A Wire Gauge	1
Thermal Grease	1

9. Conclusion

Team 13 customized an active heatsink to be used for dissipating the heat from power modules within the SiC converter developed by CAPS. The team also created a testing system for it that included heat source emulators made from high power, low resistance resistors. This manual includes a functional analysis of both systems, as well as product specifications and assemblies, operation instructions, troubleshooting, maintenance, and recommended spare parts. With the knowledge provided in this manual, the user is now equipped to use both systems. A reminder that caution should be taken during assembly and testing, as shocks and burns can result in improper use. For more information about the thermal management system for a SiC PV Converter, visit http://www.eng.famu.fsu.edu/me/senior_design/2017/team13/

References

[1] "Sparse Configuration: Aluminum." *Cool Innovations*. Cool Innovations, n.d. Web. 04 Apr. 2017.

[2] "EEC0251B1-000U-A99." *Sunon Fans | Fans, Thermal Management | DigiKey*. Digikey Electronics, n.d. Web. 07 Apr. 2017.

[3] "100 Watts Aluminium Housed Resistor | Heat Sink Resistor | Arcol Resistors Arcol Resistors." *Arcol Resistors*. Arcol, n.d. Web. 07 Apr. 2017

Appendix A: Pin Fin Heatsink Tested On

COOLINNOVATIONS ADVANCED HEAT SINKS

FOOTPRINT 4.48" X 4.48"

SPARSE CONFIGURATION | ALUMINUM

SPECIFICATIONS

Overview

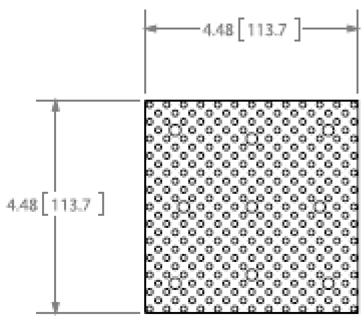
- Provides outstanding cooling power
- Omnidirectional
- Recommended airspeed range: 0 to 800 LFM (0 to 4 m/s)
- RoHS compliant

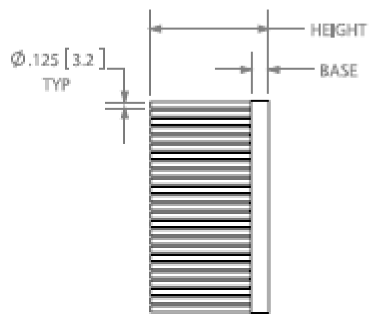
Technical

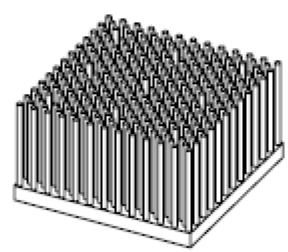
- Material: Pure Aluminum
- Mfg. process: Cold forging
- Plating options: Black/clear anodize, chemical conversion coating
- Base finish: Lapped
  Flatness: Better than 0.001 in/in
  Surface roughness: 16 RMS

Flexible Parameters

- Footprint (length and width)
- Height (pin length & base thickness)
- Single or multiple pins can be eliminated
- Comprehensive machining (holes, threads, clearances, etc.)







THE PIN FIN APPROACH: Round pin formations produce outstanding cooling power

P/N	Height in(mm)	Base in(mm)	Weight lb(g)	Thermal Resistance in ºC/W 0(0)*	200(1)	400(2)	600(3)
3-454503M	0.30(7.6)	0.13(3.2)	0.30(137)	4.8	1.37	0.76	0.55
3-454505M	0.50(12.7)	0.19(4.7)	0.48(219)	3.1	0.89	0.49	0.35
3-454507M	0.70(17.8)	0.19(4.7)	0.56(253)	2.2	0.59	0.33	0.24
3-454510M	1.00(25.4)	0.25(6.4)	0.77(349)	1.71	0.43	0.24	0.181
3-454512M	1.20(30.5)	0.25(6.4)	0.84(383)	1.52	0.35	0.21	0.159
3-454515M	1.50(38.1)	0.38(9.5)	1.15(523)	1.40	0.30	0.185	0.144
3-454518M	1.80(45.7)	0.38(9.5)	1.27(574)	1.20	0.24	0.157	0.124
3-454520M	2.00(50.8)	0.38(9.5)	1.34(608)	1.08	0.21	0.142	0.113
3-454522M	2.20(55.9)	0.38(9.5)	1.41(642)	0.97	0.192	0.130	0.104
3-454525M	2.50(63.5)	0.38(9.5)	1.53(693)	0.81	0.167	0.116	0.093

Disclaimer: www.coolinnovations.com

*Air Speed in LFM (m/s)

www.coolinnovations.com • sales@coolinnovations.com • Tel: (905) 760-1992 • Fax: (905) 760-1994

Appendix B: Fan

Product Overview	
Digi-Key Part Number	259-1479-ND
Quantity Available	632 Can ship immediately
Manufacturer	Sunon Fans
Manufacturer Part Number	EEC0251B1-000U-A99
Description	FAN AXIAL 120X25MM 12VDC WIRE
Lead Free Status / RoHS Status	Lead free / RoHS Compliant
Moisture Sensitivity Level (MSL)	1 (Unlimited)
Manufacturer Standard Lead Time	14 Weeks

Documents & Media	
Datasheets	EEC0251B1-0000-A99 Spec Sheet
Product Training Modules	DR MagLev Fan Series
Video File	Sunon DR Maglev
RoHS Information	RoHS Certificate
Featured Product	E Series Fans
Online Catalog	DR (E), DRMagLev® Series

Product Attributes		Select All ☐
Categories	Fans, Thermal Management	○
	DC Fans	◉
Manufacturer	Sunon Fans	☐
Series	DR MagLev®	☐
Part Status	Active	☐
Voltage - Rated	12VDC	☐
Size / Dimension	Square - 120mm L x 120mm H	☐
Width	25.00mm	☐
Air Flow	108.2 CFM (3.06m³/min)	☐
Static Pressure	0.280 in H2O (69.7 Pa)	☐
Bearing Type	Ball	☐
Fan Type	Tubeaxial	☐
Features	AutoRestart	☐
Noise	44.5 dB(A)	☐
Power (Watts)	5.30W	☐
RPM	3100 RPM	☐
Termination	2 Wire Leads	☐
Ingress Protection	-	☐
Operating Temperature	14 ~ 158°F (-10 ~ 70°C)	☐
Approvals	CE, CUR, TUV, UL	☐
Weight	0.346 lb (156.94g)	☐
Current Rating	0.445A	☐
Voltage Range	6 ~ 13.8VDC	☐
Material - Frame	Polybutylene Terephthalate (PBT)	☐
Material - Blade	Polybutylene Terephthalate (PBT)	☐
Lifetime @ Temp.	100000 Hrs @ 40°C	☐

Appendix C: Resistors

HS Aluminium Housed Resistors

ARCOL

Manufactured in line with the requirements of MIL 18546 and IEC 115, designed for direct heatsink mounting with thermal compound to achieve maximum performance.

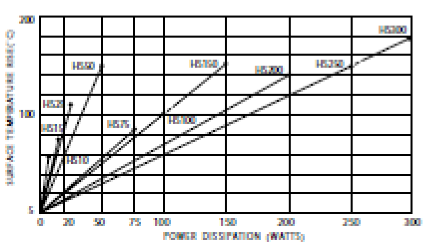
- High Power to volume
- Wound to maximise High Pulse Capability
- Values from R005 to 100K
- Custom designs welcome
- RoHS Compliant

Characteristics

Tolerance (Code):	Standard ±5% (J) and ±10% (K). Also available ±1% (F), ±2% (G) and ±3% (H)
Tolerance for low Ω values:	Typically ≥ R05 ±5% ≤ R047 ±10%
Temperature coefficients:	Typical values < 1K 100ppm Std. > 1K 25ppm Std. For lower TCR's please contact Arcol
Insulation resistance (Dry):	10,000 MΩ minimum
Power dissipation:	At high ambient temperature dissipation derates linearly to zero at 200°C
Ohmic values:	From R005 to 100K depending on wattage size
Low inductive (NHS):	Specify by adding N before HS Series code, e.g. NHS50
NHS ohmic value:	Divide standard HS maximum value by 4
NHS working volts:	Divide standard HS maximum working voltage by 1.414

Temp. Rise & Power Dissipation

Surface temperature of resistor related to power dissipation. The resistor is standard heatsink mounted using a proprietary heatsink compound.



Heat Dissipation

Heat dissipation: Whilst the use of proprietary heat sinks with lower thermal resistances is acceptable, uprating is not recommended. For maximum heat transfer it is recommended that a heat sink compound be applied between the resistor base and heat sink chassis mounting surface. It is essential that the maximum hot spot temperature of 200°C is not exceeded, therefore, the resistor must be mounted on a heat sink of correct thermal resistance for the power being dissipated.

Ordering Procedure

Standard Resistor. To specify standard: Series, Watts, Ohmic Value, Tolerance Code, e.g.: HS25 2R2 J

Non Inductive Resistor. To specify add N, e.g.: NHS100 10R J

ARCOL UK Limited,
Threemilestone Ind. Estate,
Truro, Cornwall, TR4 9LG, UK.
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F +44 (0) 1872 222002
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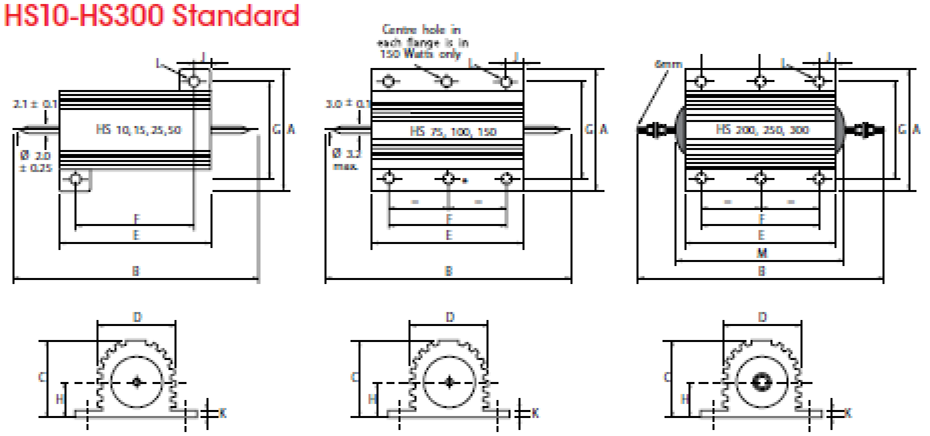
HS Aluminium Housed Resistors

Electrical Specifications

Size	Style MIL-R 18546	Power rating on std. heatsink @25°C	Watts with no heatsink @25°C	Resis-tance range	Limiting element voltage	Voltage proof AC Peak	Voltage proof AC rms.	Approx weight gms	Typical surface rise HS mounted	Standard heatsink	
										cm²	Thickness mm
HS10	RE 60	10	5	R005-10K	160	1400	1000	4	5.8	415	1
HS15	RE 65	15	7	R005-10K	265	1400	1000	7	5.1	415	1
HS25	RE 70	25	9	R005-36K	550	3500	2500	14	4.2	535	1
HS50	RE 75	50	14	R01-86K	1250	3500	2500	32	3.0	535	1
HS75		75	24	R01-50K	1400	6363	4500	85	1.1	995	3
HS100		100	30	R01-70K	1900	6363	4500	115	1.0	995	3
HS150		150	45	R01-100K	2500	6363	4500	175	1.0	995	3
HS200		200	50	R01-50K	1900	7070	5000	475	0.7	3750	3
HS250		250	55	R01-50K	2200	7070	5000	600	0.6	4765	3
HS300		300	60	R01-68K	2500	7070	5000	700	0.6	5790	3

HS10-HS300 Standard



Dimensions (mm)

Size	A Max	B Max	C Max	D Max	E Max	F±0.3	G±0.3	H Max	J Max	K Max	L ±0.25*	M Max
HS10	16.5	30.0	8.8	8.5	15.9	11.3	12.4	4.5	2.4	1.8	2.4	
HS15	21.0	36.5	11.0	11.2	19.9	14.3	15.9	5.5	2.8	1.8	2.4	
HS25	28.0	51.0	14.6	14.0	27.3	18.3	19.8	7.3	4.7	2.6	3.2	
HS50	29.7	72.5	14.8	14.2	49.1	39.7	21.4	8.5	5.2	2.6	3.2	
HS75	47.5	72.0	24.1	27.3	48.7	29.0	37.0	11.8	10.4	3.7	4.4	
HS100	47.5	88.0	24.1	27.3	65.2	35.0	37.0	11.8	15.4	3.7	4.4	
HS150	47.5	121.0	24.1	27.3	97.7	58.0	37.0	11.8	20.4	3.7	4.4	
HS200	72.5	145.7	41.8	45.5	89.7	70.0	57.2	20.5	10.4	5.5	5.1	103.4
HS250	72.5	167.0	41.8	45.5	109.7	89.0	57.2	20.5	10.4	5.5	5.1	122.4
HS300	72.5	184.4	41.8	45.5	127.7	104.0	59.0	20.5	12.4	5.5	6.6	141.4

* HS200-HS300 Watts is ± 0.45