Power and Temperature

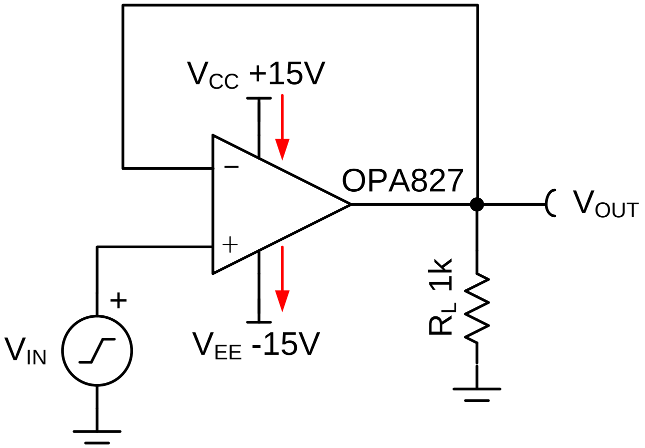
TIPL 1160
TI Precision Labs – Op Amps

Presented by Ian Williams

Prepared by Art Kay, Ian Williams and Miro Oljaca

Power Dissipation – Quiescent Current

PARAMETER		CONDITIONS	OPA827AI MIN	OPA827AI TYP	OPA827AI MAX	UNIT
POWER SUPPLY						
Specified Voltage	V_S		±4		±18	V
Quiescent Current (per amplifier)	I_Q	I_{OUT} = 0A		4.8	5.2	mA
Over Temperature					**6**	**mA**



P_Q = quiescent power = $I_Q * V_S$

I_Q = quiescent current

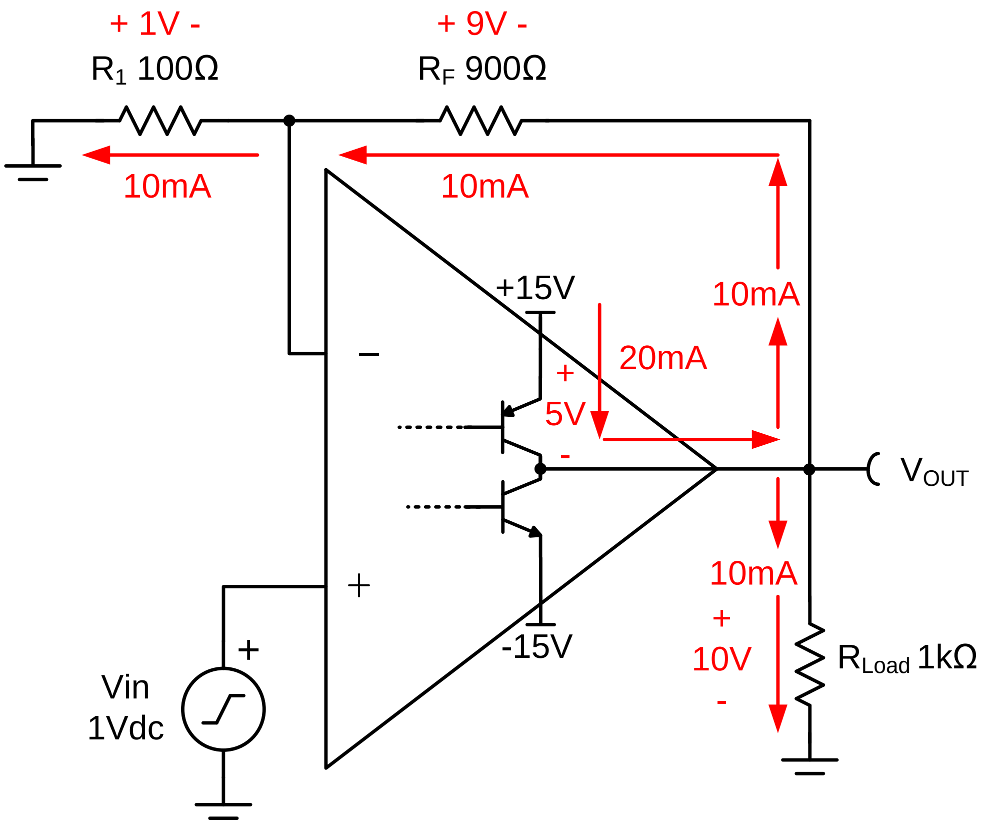
V_S = total supply voltage

$V_S = V_{CC} - V_{EE} = (15) - (-15V) =$ **30V**

Example: worst case over temperature

$P_Q = I_Q \cdot V_S = (6mA)(30V) = 180mW$

Power Dissipation – DC Load



Effective load:

$R_L = R_{Load} \,||\, (R_F + R_1)$

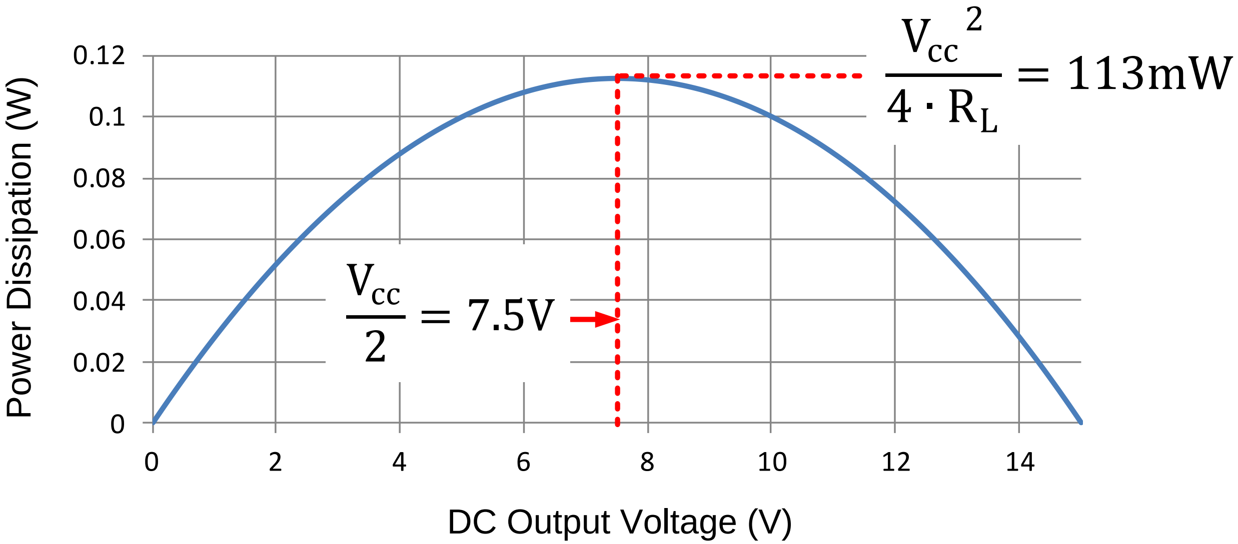
$R_L = (1k\Omega) \,||\, (900\Omega + 100\Omega)$

$R_L = 500\ \Omega$

Maximum DC Power Dissipation

$$P_{dc} = \frac{V_{out}}{R_L}(V_{cc} - V_{out})$$

$$P_{dc\_max} = P_{dc}\left[\frac{V_{cc}}{2}\right] = \frac{{V_{cc}}^2}{4 \cdot R_L}$$



Derivation of DC Maximum Power Transfer

$$P_{opa} = (V_{cc} - V_{out}) \cdot \frac{V_{out}}{R_L}$$ (1) Power dissipated in op amp

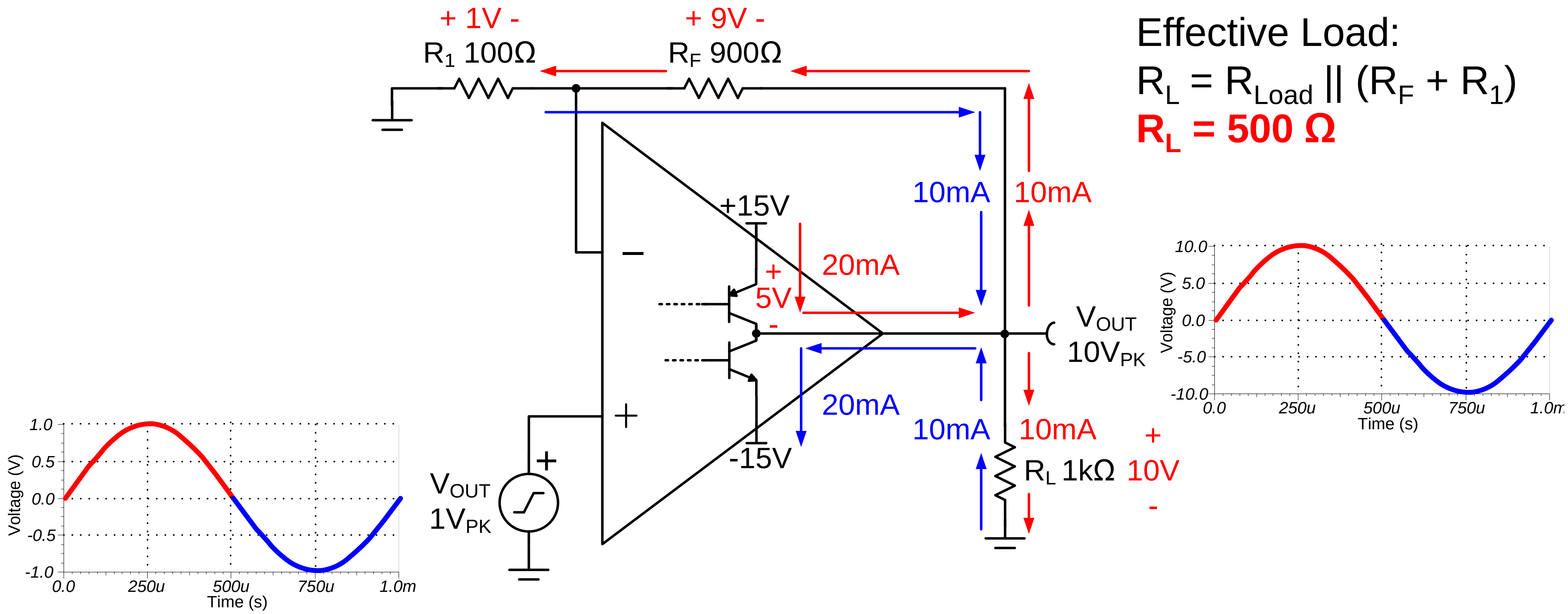
$$P_{opa}(V_{out}) = \frac{V_{out} \cdot V_{cc}}{R_L} - \frac{{V_{out}}^2}{R_L}$$ (2) Dc output voltage

$$\frac{\partial P_{opa}}{\partial V_{out}} = \frac{V_{cc} - 2 \cdot V_{out}}{R_L} = 0$$ (3) Take the partial derivative. Set to zero and solve for maxima.

$$V_{out} = \frac{V_{cc}}{2} \quad \text{when} \quad \frac{\partial P_{opa}}{\partial V_{out}} = 0$$ (4) Solve (3) for value of Vout that yields maximum power

$$P_{dc\_max} = P_{opa}\left(\frac{V_{cc}}{2}\right) = \frac{{V_{cc}}^2}{4 \cdot R_L}$$ (5) Substitute (4) into (2) to determine maximum dc power in Op Amp

Power Dissipation at AC



Effective Load:

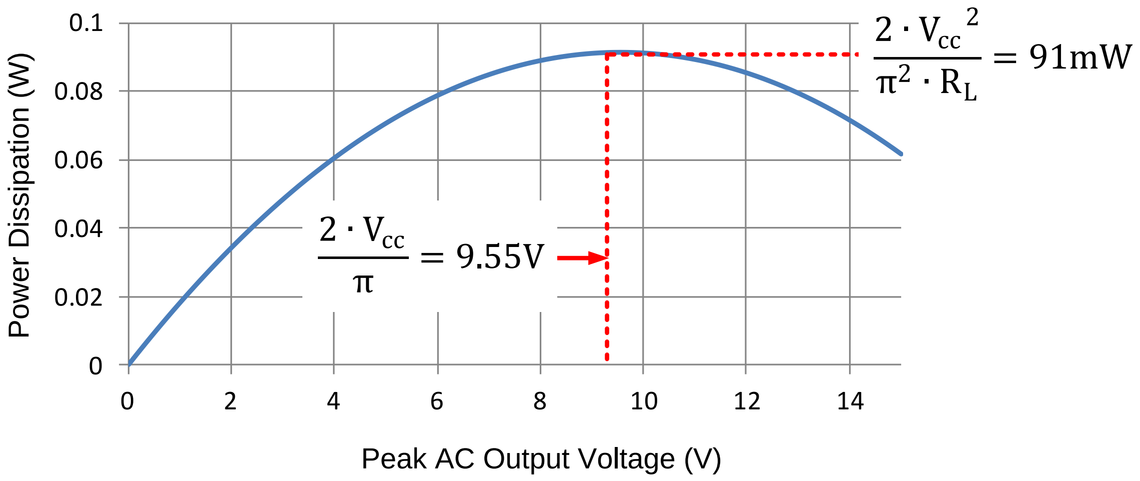
$R_L = R_{Load} \,||\, (R_F + R_1)$

R_L = 500 Ω

Maximum Average AC Power Dissipation

$$P_{ac\_avg}(V_{outpk}) = \frac{2 \cdot V_{cc} \cdot V_{outpk}}{\pi \cdot R_L} - \frac{V_{outpk}^{\;2}}{2 \cdot R_L}$$

$$P_{ac\_max\_avg} = P_{opa\_avg}\left[\frac{2 \cdot V_{cc}}{\pi}\right] = \frac{2 \cdot V_{cc}^{\;2}}{\pi^2 \cdot R_L}$$



Derivation of AC Maximum Power Transfer

$$P_{opa} = (V_{cc} - V_{out}) \cdot \frac{V_{out}}{R_L}$$ (1) Power dissipated in op amp

$$V_{out}(t) = V_{outpk} \cdot \sin(\omega \cdot t)$$ (2) ac sinusoidal wave out

$$P_{ac}(t) = \left(V_{cc} - V_{outpk} \cdot \sin(\omega \cdot t)\right) \cdot \frac{V_{outpk} \cdot \sin(\omega \cdot t)}{R_L}$$ (3) Substitute (2) into (1)

$$P_{ac}(t) = \frac{V_{cc} V_{outpk} \cdot \sin(\omega \cdot t)}{R_L} - \frac{V_{outpk}^{\ 2} \cdot \sin^2(\omega \cdot t)}{R_L}$$ (4) Power dissipated in op amp as a function of time

$$\omega = \frac{2\pi}{T}$$ (5) Angular frequency as a function of period

$$P_{ac}(t) = \frac{V_{cc} V_{outpk} \cdot \sin(\frac{2\pi}{T} \cdot t)}{R_L} - \frac{V_{outpk}^{\ 2} \cdot \sin^2(\frac{2\pi}{T} \cdot t)}{R_L}$$ (6) Substitute (5) into (4)

$$P_{ac\_avg} = \frac{1}{T/2} \int_0^{T/2} \left[\frac{V_{cc} V_{outpk} \cdot \sin(\frac{2\pi}{T} \cdot t)}{R_L} - \frac{V_{outpk}^{\ 2} \cdot \sin^2(\frac{2\pi}{T} \cdot t)}{R_L}\right] dt$$ (7) Find the average power

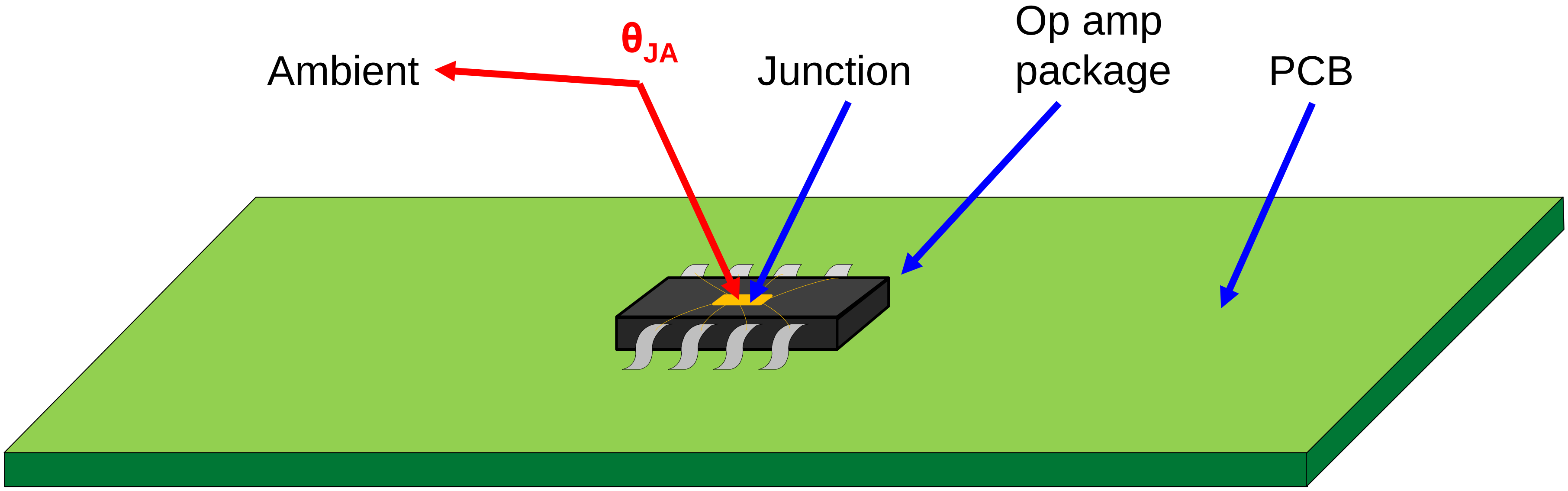
$$P_{ac\_avg}(V_{outpk}) = \frac{2 \cdot V_{cc} \cdot V_{outpk}}{\pi \cdot R_L} - \frac{V_{outpk}^{\ 2}}{2 \cdot R_L}$$ (8) Average power as a function of peak output voltage

$$\frac{\partial P_{opa\_avg}}{\partial V_{outpk}} = \frac{2 \cdot V_{cc}}{\pi \cdot R_L} - \frac{V_{outpk}}{R_L}$$ (9) Take the partial derivative to find maxima. Set to zero and solve for maxima.

$$P_{ac\_max\_avg} = P_{opa\_avg}\left[\frac{2 \cdot V_{cc}}{\pi}\right] = \frac{2 \cdot V_{cc}^{\ 2}}{\pi^2 \cdot R_L}$$ (10) Maximum power and the peak output voltage where max power occurs

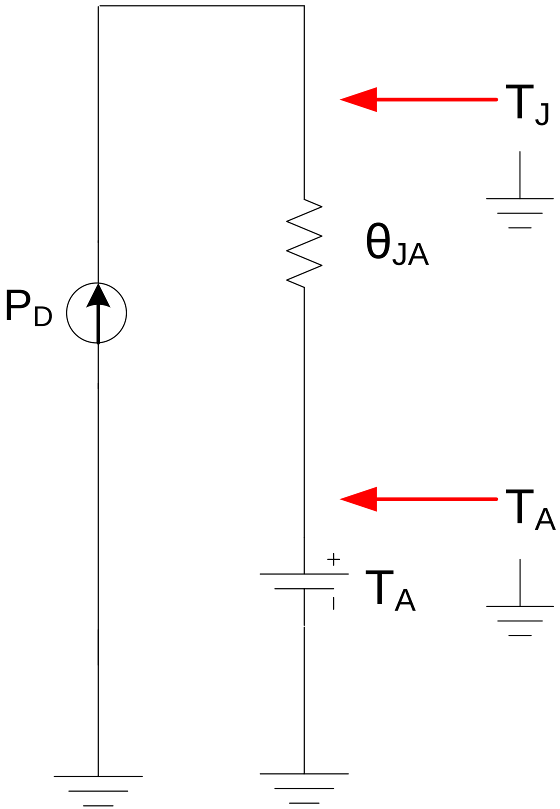
Derivation courtesy of Miro Oljaca

Thermal Device Model – No Heat Sink



θ_{JA} includes the effects of the package and PCB!

Analogous Electrical Model – No Heat Sink



$T_J = (P_D * \Theta_{JA}) + T_A$

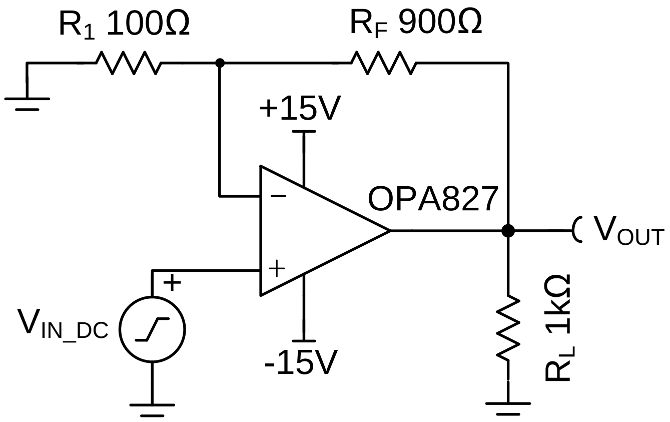
T → voltage

θ → resistance

P → current

Temperature Rise – Maximum DC Load

PARAMETER		CONDITIONS	OPA827AI			UNIT
			MIN	TYP	MAX	
TEMPERATURE RANGE						
Specified Range	T_A		–40		+125	°C
Operating Range	T_A		–55		+150	°C
Thermal Resistance	θ_{JA}					
SO-8, MSOP-8				150		°C/W



$$P_Q = I_Q \cdot V_S = (6mA) \cdot (30V) = 180mW$$

$$P_{dc\_max} = \frac{V_{cc}{}^2}{4 \cdot R_L} = \frac{(15V)^2}{4 \cdot (500\Omega)} = 113mW$$

$$P_{total} = P_Q + P_{dc\_max} = 180mW + 113mW = 293mW$$

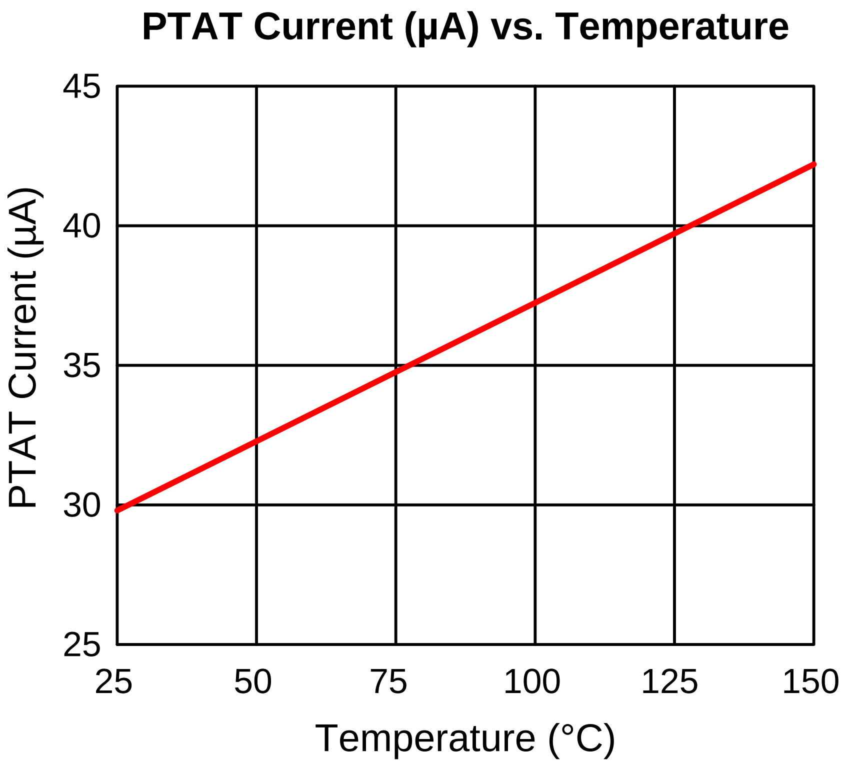
$$T_J = P_{total} \cdot \theta_{JA} + T_A = 293mW \cdot (150\,°C/W) + 25°C = 67.5°C$$

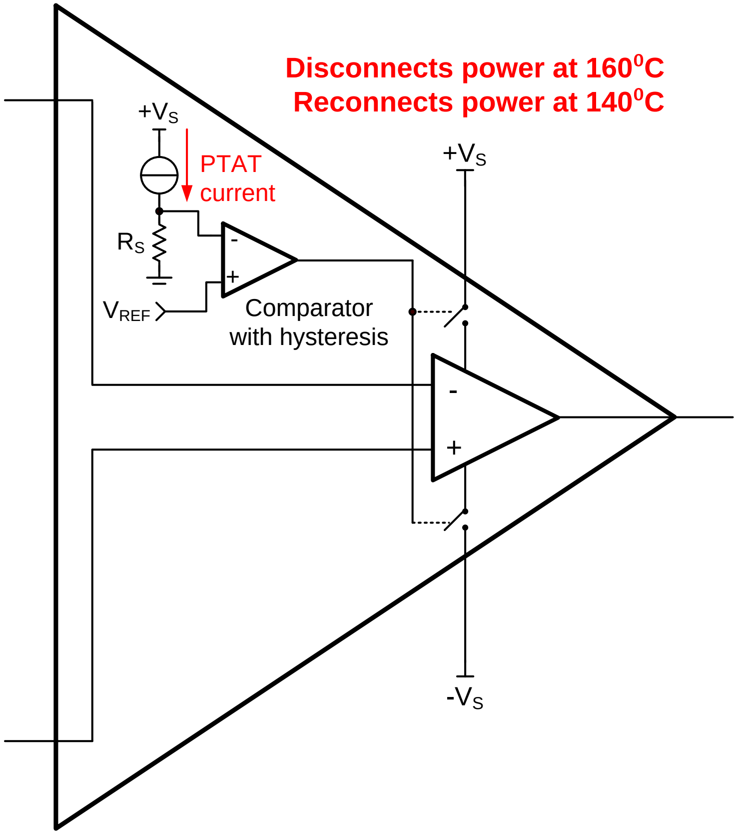
Absolute Maximum Ratings

Over operating free-air temperature range (unless otherwise noted).

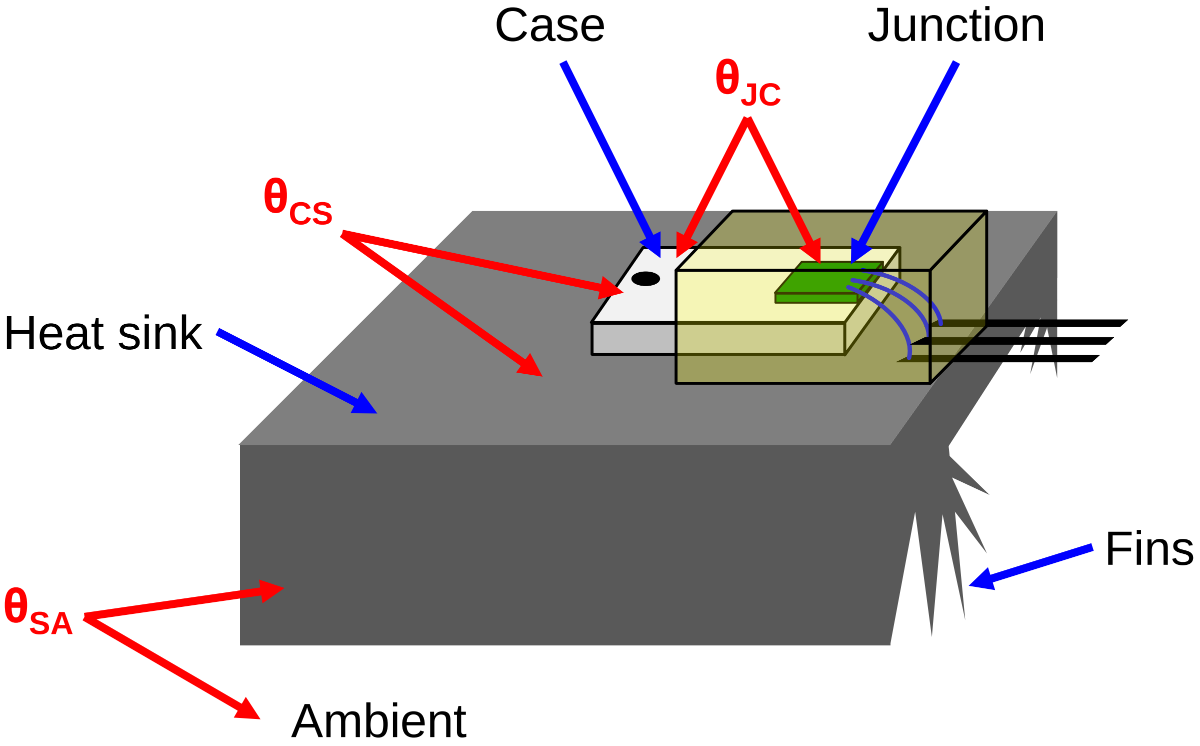
PARAMETER			VALUE	UNIT
Supply Voltage		$V_S = (V+) - (V-)$	40	V
Input Voltage[2]			(V–) – 0.5 to (V+) + 0.5	V
Input Current[2]			±10	mA
Differential Input Voltage			$\pm V_S$	V
Output Short-Circuit[3]			Continuous	
Operating Temperature		T_A	–55 to +150	°C
Storage Temperature		T_A	–65 to +150	°C
Junction Temperature		T_J	+150	°C
ESD Ratings	Human Body Model (HBM)		4000	V
	Charged Device Model (CDM)		1000	V

Thermal Protection

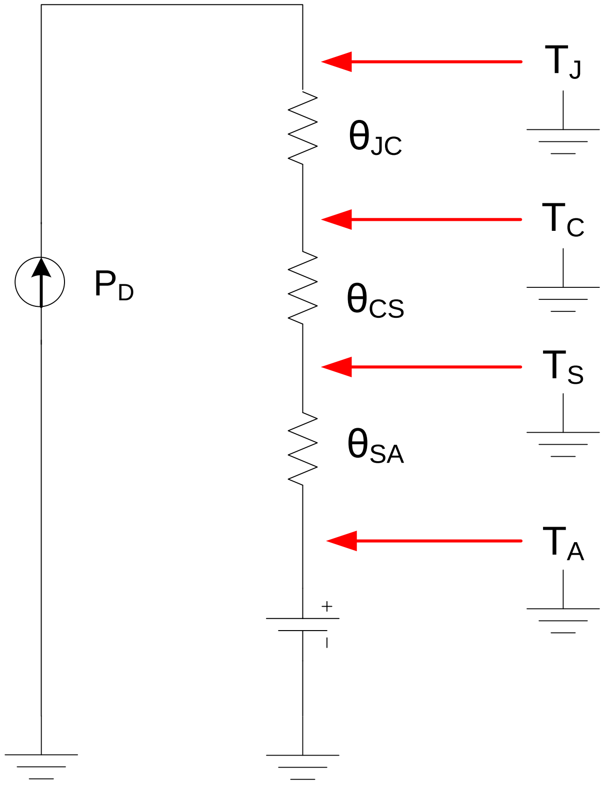




Thermal Model – Device with Heat Sink



Analogous Electrical Model – Device with Heat Sink



$$T_J = P_D*(\theta_{JC} + \theta_{CS} + \theta_{SA}) + T_A$$

P_D = total power dissipation

T_J = junction temperature

T_C = case temperature

T_S = heat sink temperature

T_A = ambient temperature

Thermal Resistance – Θ_{JC} (Junction to Case)

THERMAL RESISTANCE								
θ_{JC} (Junction-to-Case)(2)	AC Output f > 60Hz		2.5					°C/W
θ_{JC}(2)	DC Output		3					°C/W
θ_{JA} (Junction-to-Ambient)	No Heat Sink		40					°C/W
OPA541AP (Plastic)			40					°C/W

$$T_J = P_D*(\theta_{JC} + \theta_{CS} + \theta_{SA}) + T_A$$

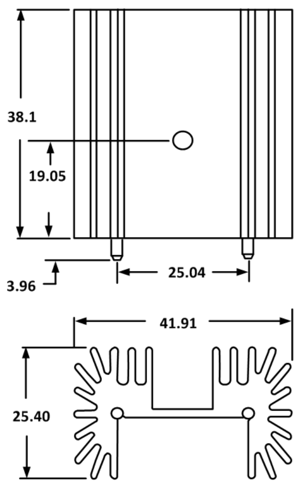
Thermal Resistance – Θ_{CS} (Case to Sink)

Typical Interface Resistances for Various Mounting Methods with a TO-220 (interface area = 1 in^2):

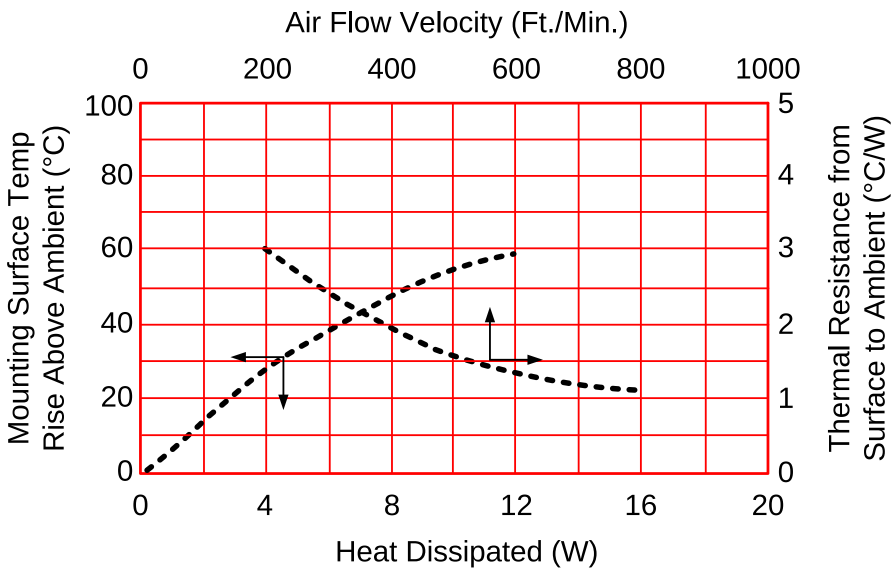
Thermal Joint Compound only (0.001 thick)	θ = 0.056℃/W
Mica (0.005) and Joint Compound (0.002)	**θ = 0.44 ℃/W**
Series 177 Beryllium Oxide Wafers (0.062) And joint Compound (0.002)	θ = 0.13 ℃/W
DeltaPad™ 173-9 (0.009)	θ = 0.50 ℃/W
Dry Mounting (0.001 assumed)	θ = 1.2 ℃/W

$$T_J = P_D*(\theta_{JC} + \theta_{CS} + \theta_{SA}) + T_A$$

Thermal Resistance – Θ_{SA} (Sink to Ambient)



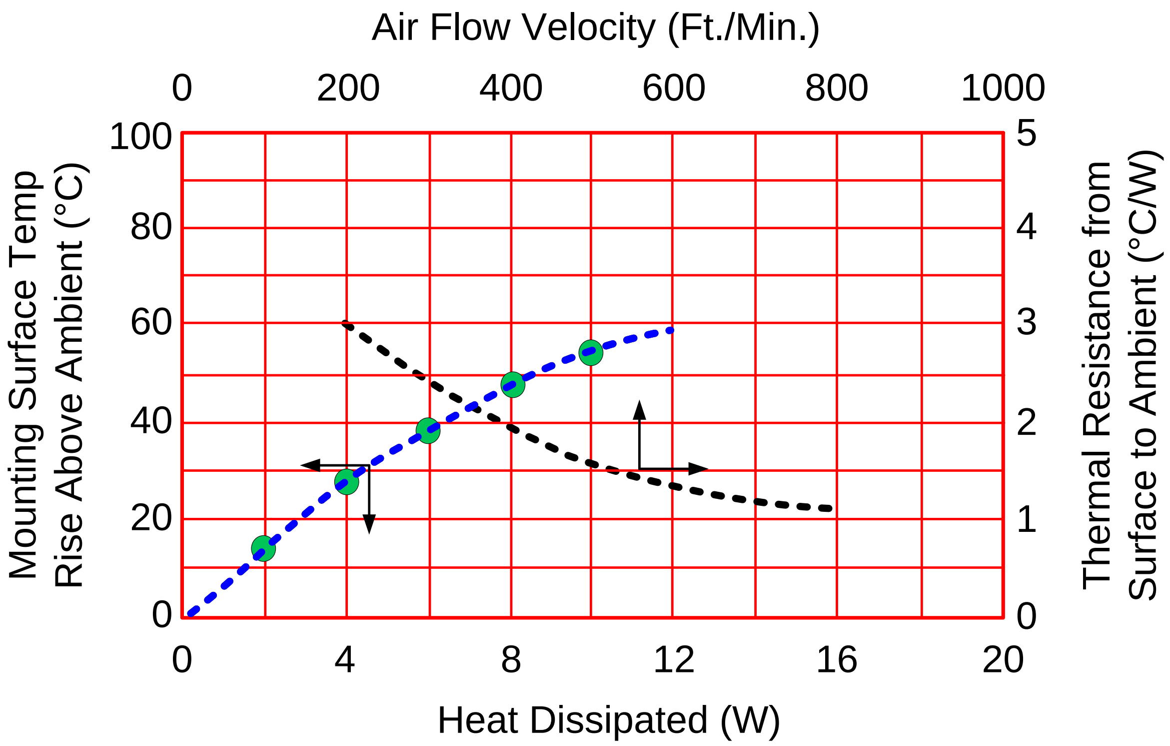
Example: Aavid Thermalloy 6398BG



$$T_J = P_D*(\theta_{JC} + \theta_{CS} + \theta_{SA}) + T_A$$

Thermal Resistance in Natural Convection*

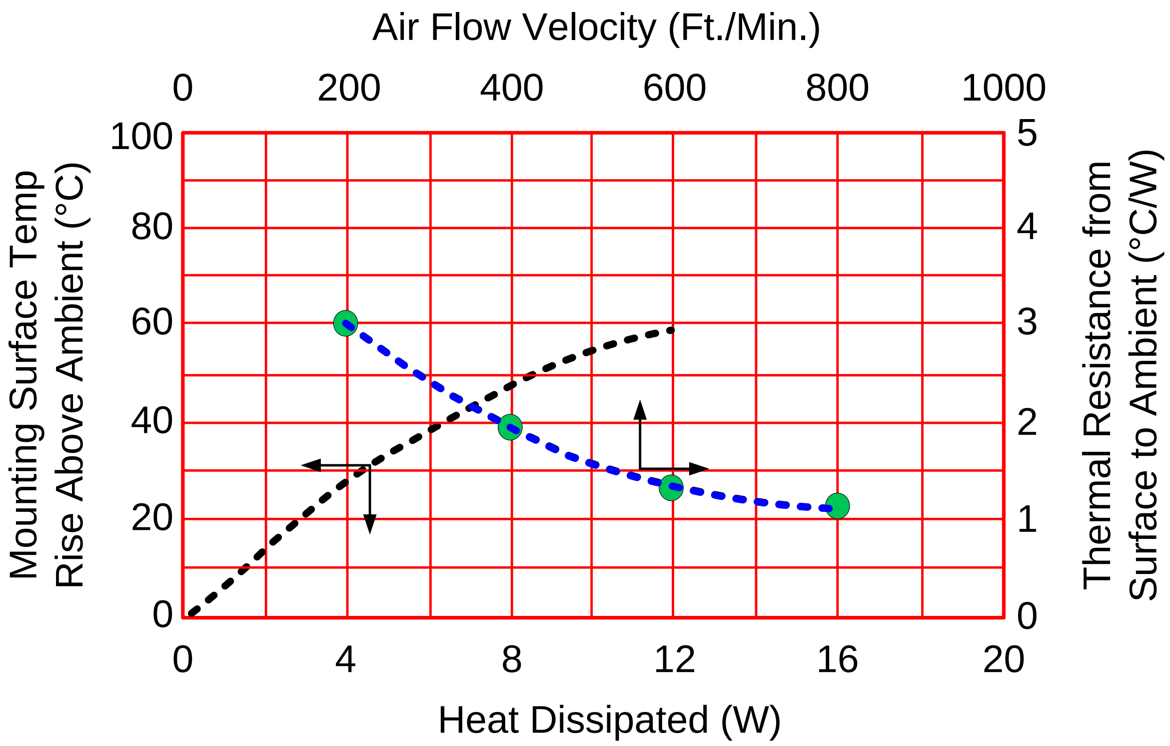
*air flow ≤ 100 ft./min



Device Power (W)	θ_{cs} Thermal Resistance (°C/W)
2	7.5
4	7.0
6	6.33
8	6.0
10	5.5

$$\theta_{SA} = \frac{\Delta T_{mount}}{P_{total}} = \frac{15℃}{2W} = 7.5\,℃/W$$

Thermal Resistance in Forced Airflow



Air Velocity (ft./min)	θ_{cs} Thermal Resistance (°C/W)
200	3
400	2
600	1.8
800	1.1

Example – Calculate Total Power

PARAMETER	CONDITIONS	OPA541AM/AP			UNITS
		MIN	TYP	MAX	
POWER SUPPLY					
Power Supply Voltage, $\pm V_S$	Specified Temperature Range	±10	±30	±35	V
Current, Quiescent			20	25	mA

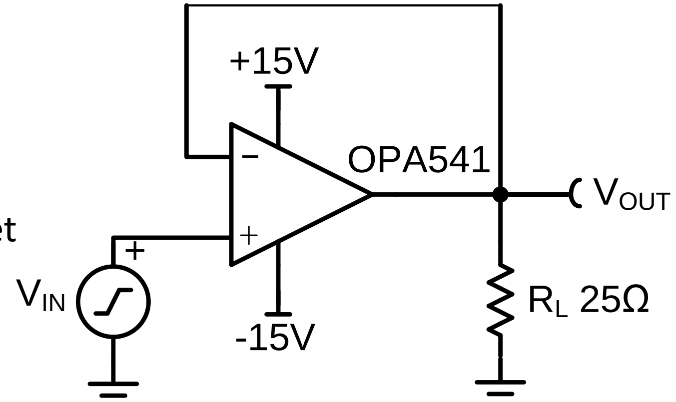
$$P_{dc} = \frac{{V_{cc}}^2}{4 \cdot R_L} = \frac{(15V)^2}{4 \cdot (25\Omega)} = 2.25W$$ Maximum dc Power

$$V_s = V_{cc} - V_{ee} = 15V - (-15V) = 30V$$ Total Supply Voltage

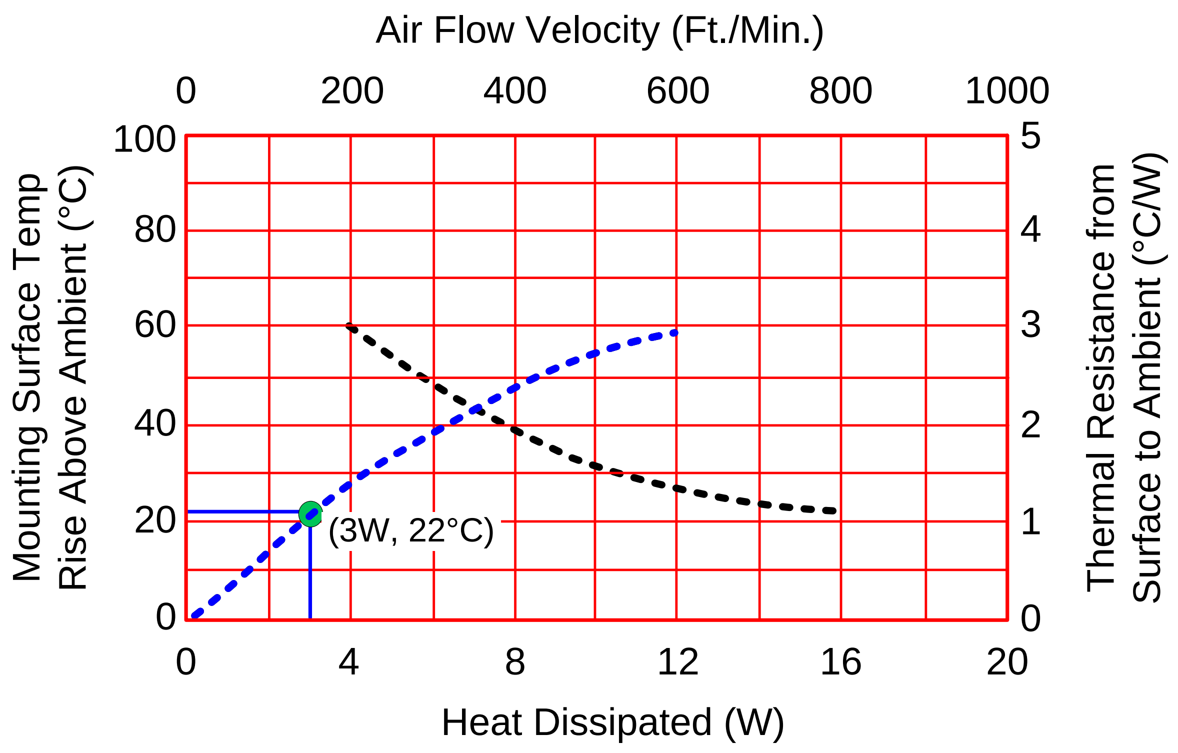
$$I_Q = 25mA$$ From OPA541 Data Sheet

$$P_Q = I_Q \cdot V_s = (25mA) \cdot (30V) = 0.75W$$ Quiescent Power

$$P_{total} = P_{dc} + P_Q = 2.25W + 0.75W = 3W$$ Total Power



Example – Calculate θ_{SA} for Given Power



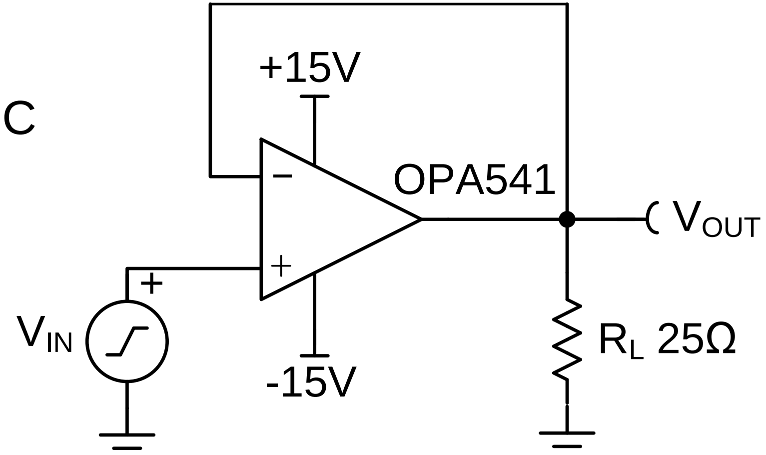
$$P_{total} = 3W$$

$$\theta_{SA} = \frac{\Delta T_{mount}}{P_{total}} = \frac{22℃}{3W} = 7.33\,℃/W$$

Example – Calculate Junction Temperature

θ_{JC} = 3°C/W from OPA541 data sheet (TO-220)
θ_{CS} = 0.44°C/W (Mica and joint compound)
θ_{SA} = 7.33°C/W (Heat sink specification at 3W)
T_A = 25°C
P_D = 3W

$T_J = P_D*(\theta_{JC} + \theta_{CS} + \theta_{SA}) + T_A$
T_J = (3W)*(3°C/W + 0.44°C/W + 7.33°C/W) + 25°C
T_J = 57.3°C



Thanks for your time! Please try the quiz.

Power and Temperature

Multiple Choice Quiz
TI Precision Labs – Op Amps

Quiz: Power and Temperature

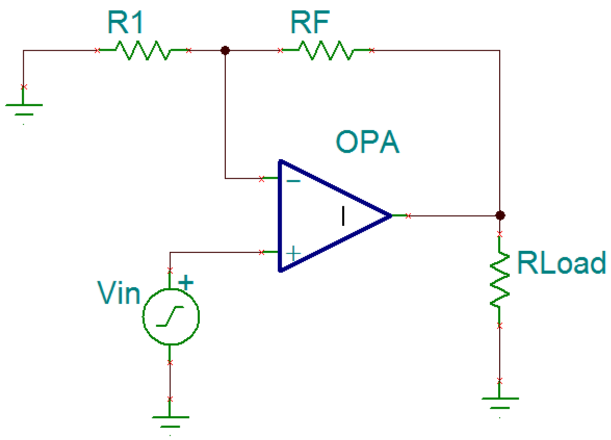
1. What is junction temperature?

a. The highest operating temperature of the die of an electronic device.
b. The recommended operating temperature of an electronic device.
c. The typical operating temperature of the case of an electronic device.
d. The temperature where the die starts separating from the package.

2. What is thermal resistance?

a. Resistance of a device over temperature.
b. A property that describes how resistant a device is to thermal damage.
c. A property that describes how a material accepts changes in heat.
d. A property that describes how a material resists heat flow.

Quiz: Power and Temperature



3. How do you calculate effective resistive load of the amplifier above?

a. $R_L = R_{Load}$
b. $R_L = R_{Load}||R_1$
c. $R_L = R_{Load}/(R_F + R_1)$
d. $R_L = R_{Load}||(R_F + R_1)$

Quiz: Power and Temperature

4. What is quiescent current (Iq)?

a. Maximum current draw of the device.
b. Minimum current draw when a device is powered with a load current.
c. Typical current draw when a device is powered with no load current.
d. Maximum current draw when a device is powered with no load current.
e. Current where the device is the quietest.

5. When is DC power dissipation at its maximum?

a. When the output voltage is equal to V+.
b. When output voltage is equal to mid-supply
c. When the load is drawing the most current.
d. When the inputs of the op amp are shorted to ground.

Quiz: Power and Temperature

6. A high thermal resistance is preferable in a package.

a. True
b. False

7. In the analogous electrical model of a thermodynamic system how do temperature, thermal resistance and power act?

a. T →Current, θ →resistance, P → Voltage source
b. T →Voltage, θ →resistance, P → Current source
c. T →Inductance, θ →Capacitance, P → Power
d. T →resistance, θ →Current, P → Capacitance

Quiz: Power and Temperature

8. What is the difference between the specified temperature range and the operating temperature range?

a. Within the specified temperature the device will work as specified in the data sheet. In the operating range the device will operate, but possibly out of spec.
b. Within the operating temperature the device will work as specified in the data sheet. In the specified range the device will operate will enhanced performance.
c. The specified temperature is the range of temperatures the device was tested on the datasheet. The operating temperature is what the customer operates the device at.
d. Within the operating temperature the device will work as specified in the data sheet. In the specified range the device will operate, but possibly out of spec.

Quiz: Power and Temperature

9. Thermal protection can protect against

a. Heating from the ambient environment
b. Heating from other components
c. Self heating of the device
d. Self heating of the device while the ambient temperature is above the absolute maximum

10. What thermal resistances are included in the thermal model of a device with a heat sink?

a. θ_{JC}, θ_{CS}, θ_{SA}
b. θ_{JA}, θ_{CS}, θ_{SA}
c. θ_{JA}, θ_{SA}
d. θ_{JA}, θ_{JC}, θ_{CS}, θ_{SA}

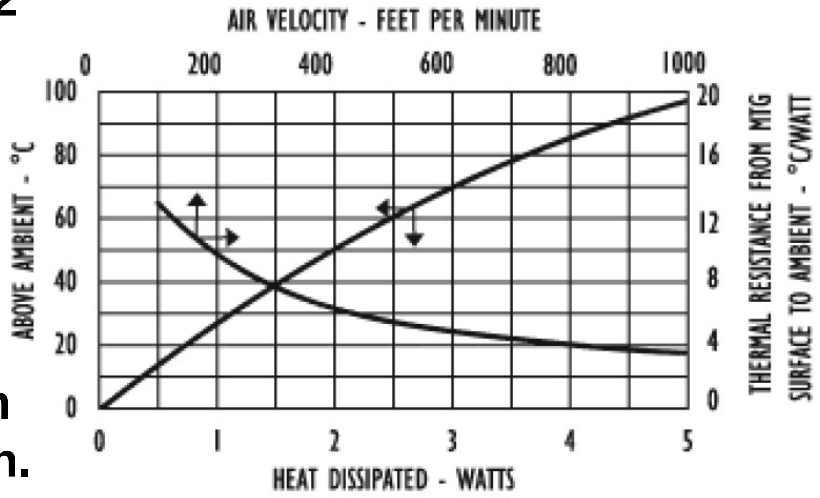
Quiz: Power and Temperature

11. What is the thermal resistance (θ_{SA}) from heatsink to ambient with a device power of 2 Watts.

a. 12.5°C/Watt
b. 25°C/Watt
c. 10°C/Watt
d. 5°C/Watt

12. What is the thermal resistance (θ_{CS}) from heatsink to case with an airflow of 800 ft/min.

a. 20°C/Watt
b. 4°C/Watt
c. 5°C/Watt
d. 15°C/Watt



Quiz: Power and Temperature

13. When a device is operating outside of this range, it becomes damaged.

a. Specified temperature
b. Absolute maximum operating temperature range
c. Absolute maximum specified temperature range
d. Characterization temperature

Quiz: Power and Temperature

***14. What is a PTAT current?**

a. Current induced when the device is below the specified temperature range.
b. Proportional to absolute temperature current which is a current used in the protection circuit of a device to cut power to the device to prevent damage.
c. Power thermal amperage threshold current which is the power which creates an amperage at a certain thermal threshold.

***15. Which of the following mounting methods has the lowest interface resistance?**

a. Series 177 Beryllium Oxide Wafers (and thermal joint compound (0.002)
b. Thermal Joint Compound only (0.001 thick)
c. DeltaPad^{TM} 173-9 (0.009)
d. Dry Mounting (0.001 assumed)

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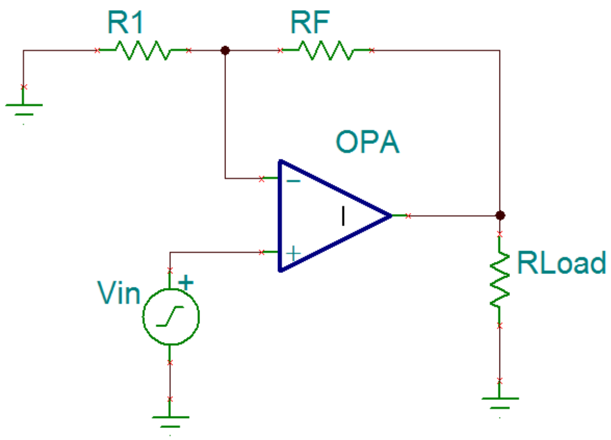

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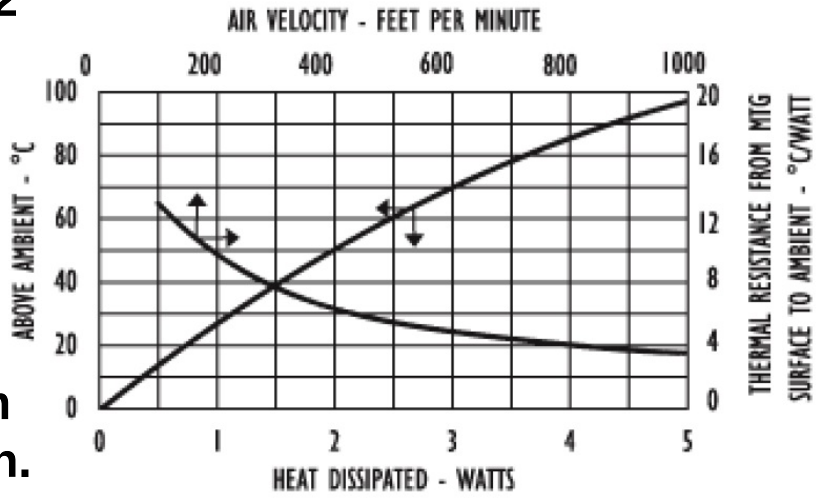

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c. Power thermal amperage threshold current which is the power which creates an amperage at a certain thermal threshold.

***15. Which of the following mounting methods has the lowest interface resistance?**

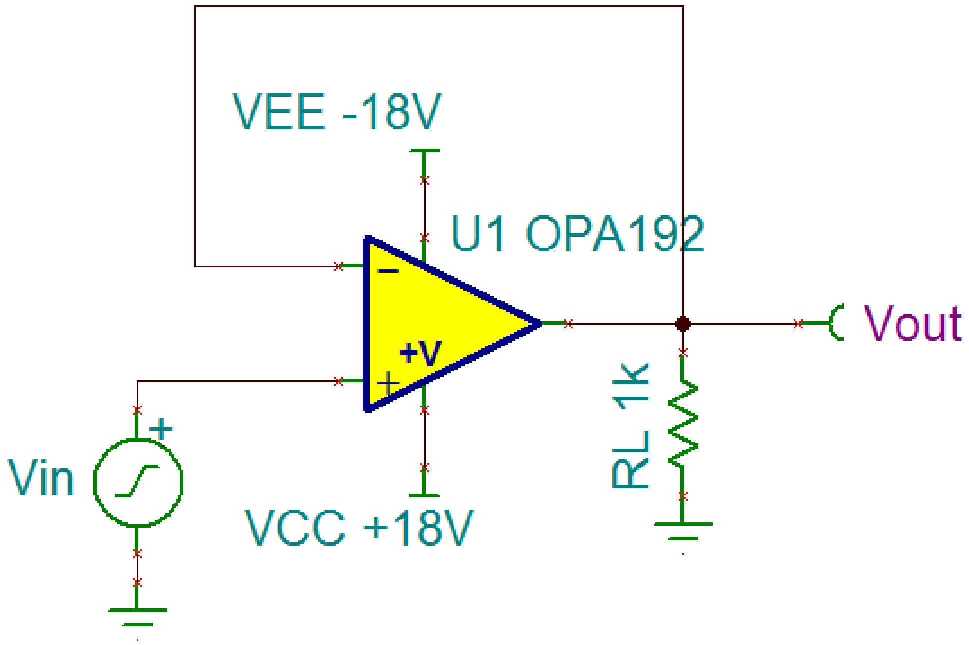
a. Series 177 Beryllium Oxide Wafers (and thermal joint compound (0.002)
b. Thermal Joint Compound only (0.001 thick)
c. DeltaPad^{TM} 173-9 (0.009)
d. Dry Mounting (0.001 assumed)

Power and Temperature

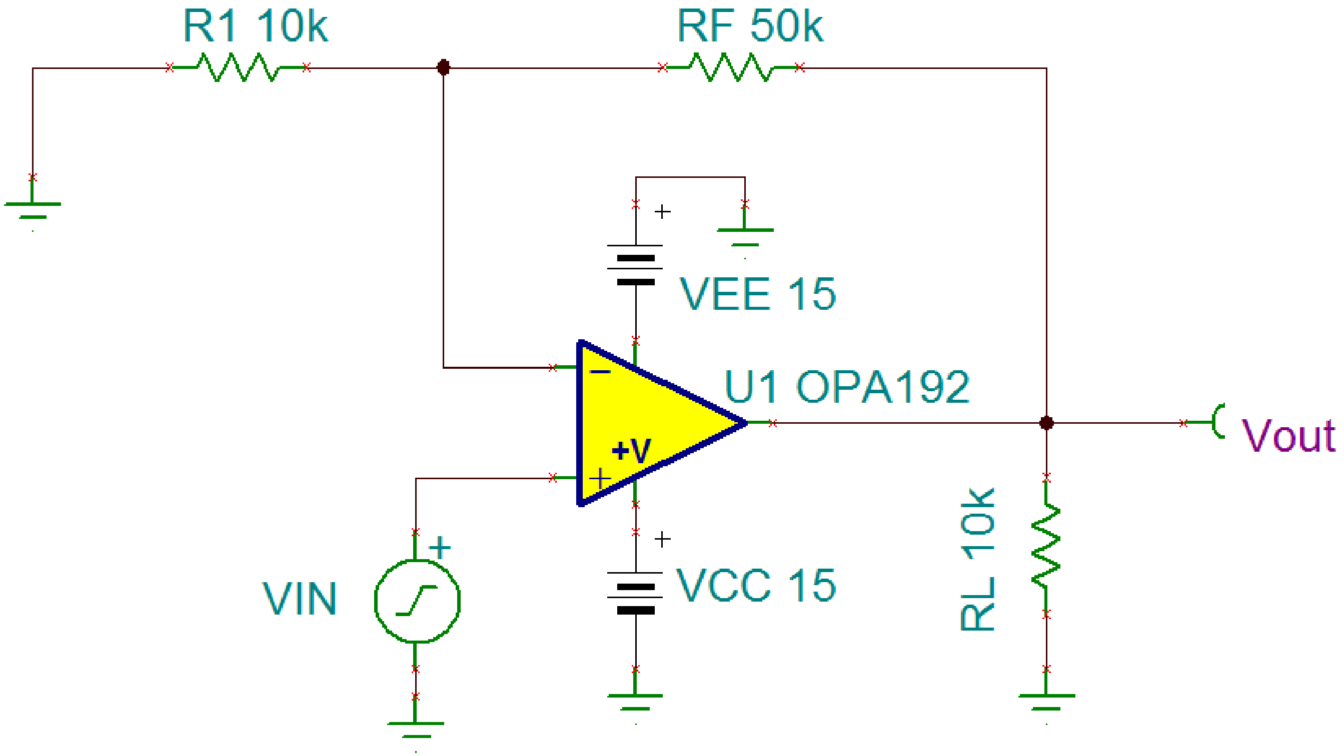
Exercises
TI Precision Labs – Op Amps

1. Calculate the maximum DC power dissipation for this circuit.

POWER SUPPLY					
I_Q	Quiescent current per amplifier	I_O = 0 A	1	1.2	mA
		T_A = –40°C to +125°C, I_O = 0 A		1.5	

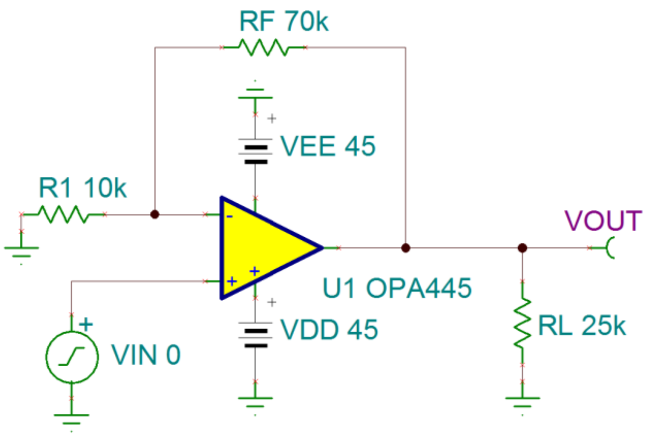


2. Calculate the maximum average AC power dissipation for this circuit assuming a sinusoidal input and a resistive load.



3a. Calculate the maximum DC power dissipation for this circuit.

PARAMETER		TEST CONDITIONS	OPA445BM			OPA445AP, AU, ADDA			UNITS
			MIN	TYP	MAX	MIN	TYP	MAX	
POWER SUPPLY									
Specified Operating Range	V_S			±40			*		V
Operating Voltage Range			±10		±45	*		*	V
Quiescent Current	I_Q	$I_O = 0$		±4.2	±4.7		*	*	mA



3b. Calculate the junction temperature at maximum DC power dissipation for the SO-8 package if the ambient temperature is 25°C and no heat sink is used. Is this within specified temperature limits?

PARAMETER		TEST CONDITIONS	OPA445BM			OPA445AP, AU, ADDA			UNITS
			MIN	TYP	MAX	MIN	TYP	MAX	
TEMPERATURE RANGE									
Specification Range			−25		+85	*		*	°C
Operating Range			−55		+125	*		*	°C
Storage Range			−65		+125	−55		+125	°C
Thermal Resistance, Junction-to-Ambient	θ_{JA}								
TO-99				200					°C/W
DIP-8							100		°C/W
SO-8 Surface-Mount							150		°C/W

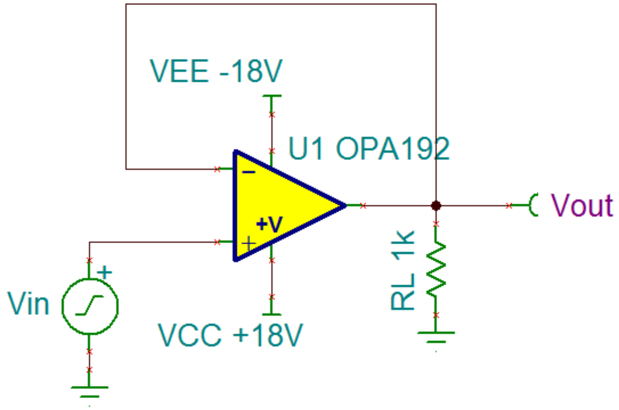
Power and Temperature

Solutions

TI Precision Labs – Op Amps

1. Calculate the maximum DC power dissipation for this circuit.

POWER SUPPLY					
I_Q	Quiescent current per amplifier	I_O = 0 A	1	1.2	mA
		T_A = –40°C to +125°C, I_O = 0 A		1.5	



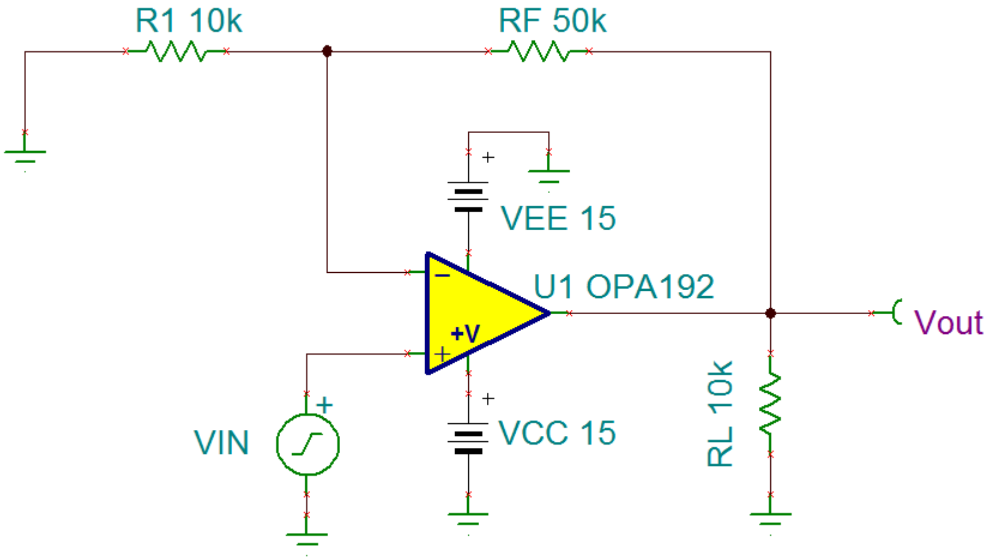
$$V_S = V_{CC} - V_{EE} = (18V) - (-18V) = 36V$$

$$P_Q = I_Q \cdot V_S = (1.5mA)(36V) = 54mW$$

$$P_{dc\_max} = \frac{(V_{cc})^2}{4 * R_L} = \frac{(18V)^2}{4 * 1k\Omega} = 81mW$$

$$P_{total} = P_{dc\_max} + P_Q = 81mw + 54mW = \mathbf{135mW}$$

2. Calculate the maximum average AC power dissipation for this circuit assuming a sinusoidal input and a resistive load.



Effective Load:

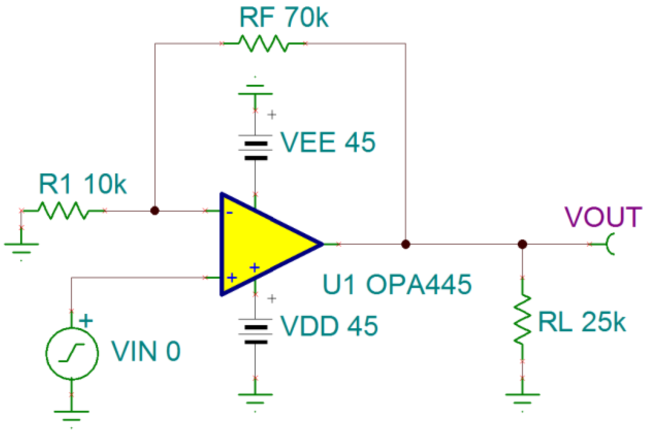
$$R_L = R_{Load}||(R_F + R_1)$$
$$R_L = 10k\Omega||(50k\Omega + 10k\Omega)$$
$$\mathbf{R_L = 8.57k\Omega}$$

Maximum Average AC Power:

$$P_{ac\_max\_avg} = \frac{2 * (V_{cc})^2}{\pi^2 * R_L}$$
$$P_{ac\_max\_avg} = \frac{2 * 15^2}{\pi^2 * 8.57k\Omega}$$
$$\mathbf{P_{ac\_max\_avg} = 5.32mW}$$

3a. Calculate the maximum DC power dissipation for this circuit.

PARAMETER		TEST CONDITIONS	OPA445BM			OPA445AP, AU, ADDA			UNITS
			MIN	TYP	MAX	MIN	TYP	MAX	
POWER SUPPLY									
Specified Operating Range	V_S			±40			*		V
Operating Voltage Range			±10		±45	*		*	V
Quiescent Current	I_Q	$I_O = 0$		±4.2	±4.7		*	*	mA



$$V_S = V_{CC} - V_{EE} = (45V) - (-45V) = 90V$$

$$R_L = R_{Load} || (R_F + R_1) = 25k\Omega || (70k\Omega + 10k\Omega) = 19k\Omega$$

$$P_Q = I_Q \cdot V_S = (4.7mA)(90V) = 423mW$$

$$P_{dc\_max} = \frac{(V_{cc})^2}{4 * R_L} = \frac{(45V)^2}{4 * 19k\Omega} = 26.6mW$$

$$P_{total} = P_{dc\_max} + P_Q = 26.6mW + 423mW = \mathbf{449.6mW}$$

3b. Calculate the junction temperature at maximum DC power dissipation for the SO-8 package if the ambient temperature is 25°C and no heat sink is used. Is this within specified temperature limits?

PARAMETER		TEST CONDITIONS	OPA445BM			OPA445AP, AU, ADDA			UNITS
			MIN	TYP	MAX	MIN	TYP	MAX	
TEMPERATURE RANGE									
Specification Range			−25		+85	*		*	°C
Operating Range			−55		+125	*		*	°C
Storage Range			−65		+125	−55		+125	°C
Thermal Resistance, Junction-to-Ambient	θ_{JA}								
TO-99				200					°C/W
DIP-8							100		°C/W
SO-8 Surface-Mount							150		°C/W

$$\Theta_{JA} = 150°C/W$$
$$T_A = 25°C$$
$$P_{total} = 449.6mW$$

$$T_J = P_{total} * \Theta_{JA} + T_A = 449.6mW * 150°C/W + 25°C$$
$$\mathbf{T_J = 92.4°C}$$

Not within the specified range (-25°C - 85°C), but within the operating range!