Power Operational Amplifiers

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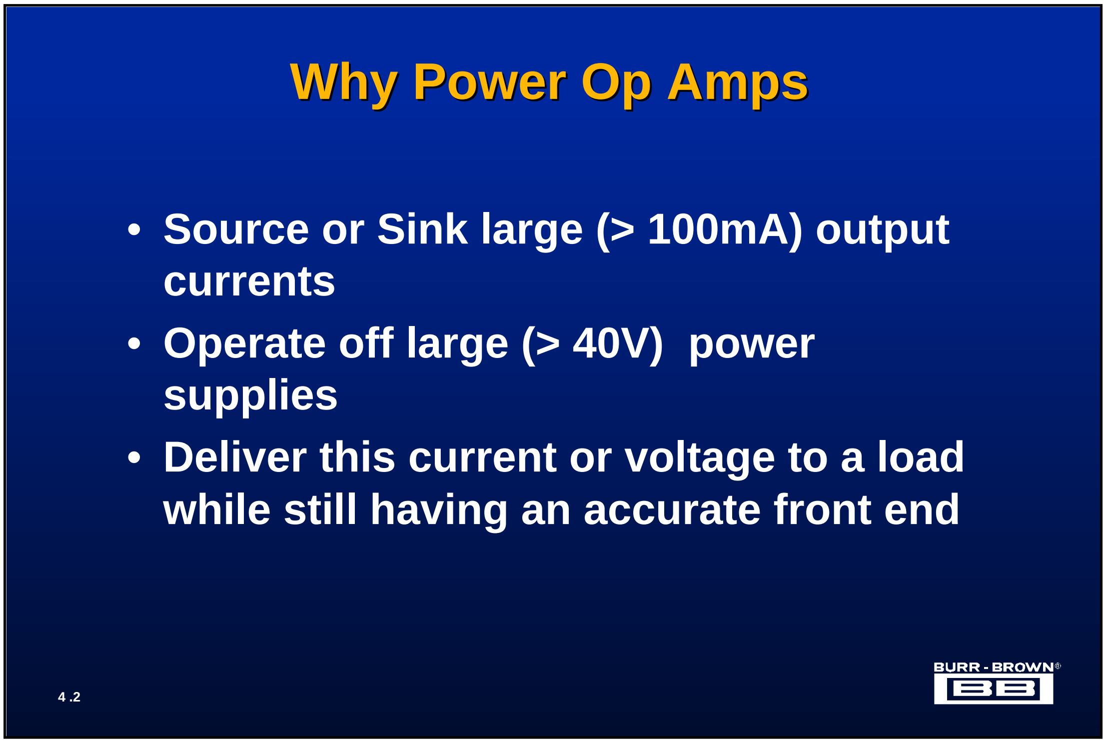
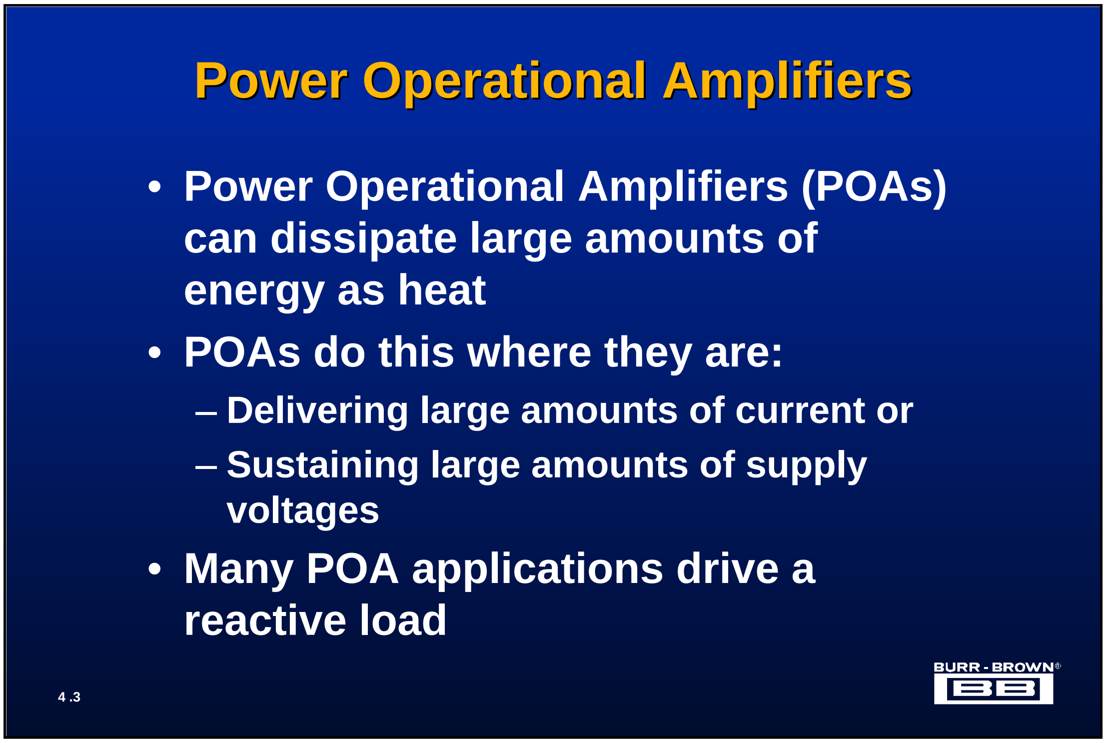


The simplest way to envision a Power-Operational amplifier is to think of it as a conventional op amp built with high voltage transistors and physically large output devices. In fact, some of the earliest power operational amplifiers were built by combining a high voltage, low current op amp with an output stage made from high current darlington transistors.

Many of the same topologies and design considerations are common to both the power and conventional types of op amps. Techniques such as bias current cancellation and FET input stages that lead to accurate, high input impedance input stages are now used in the power operational amplifier designs.



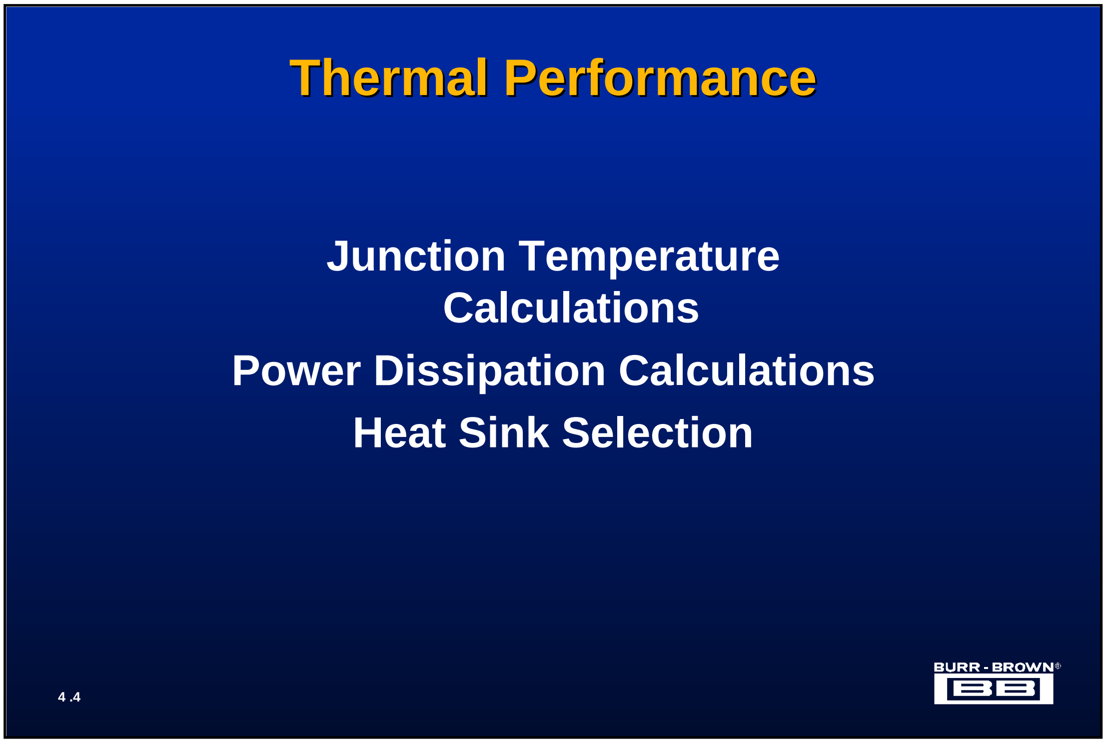
While the great majority of operational amplifier applications are for conditioning small signals and driving high impedances, there are occasions where a low impedance or reactive load is driven or controlled. These are the applications that require a Power Operational Amplifier or POA. A POA is simply an operational amplifier that can deliver large voltages or currents to a load. If the amplifier or load must sustain more than 100mW, the application requires a POA.

POAs are typified by low electrical and thermal resistances. For small signal amplifiers, output impedances are typically on the order of 100s of ohms (open-loop). Thermal resistance, junction to case (θ_{JC}) is also high, in the realm of 100s of °C/W.

POAs have impedances for these characteristics that are 10 to 100 times lower. This allows the POA to deliver larger amounts of current and dissipate more power than small signal devices at the expense of physical size and cost.

The following table gives some typical parameters for these two types of operational amplifiers.

Device Type	Output Impedance Open-Loop DC	Thermal Resistance θ_{JA}
POA	1 to 10Ω	30 to 40°C/W
Small Signal Op Amp	10 to 100Ω	100 to 200°C/W

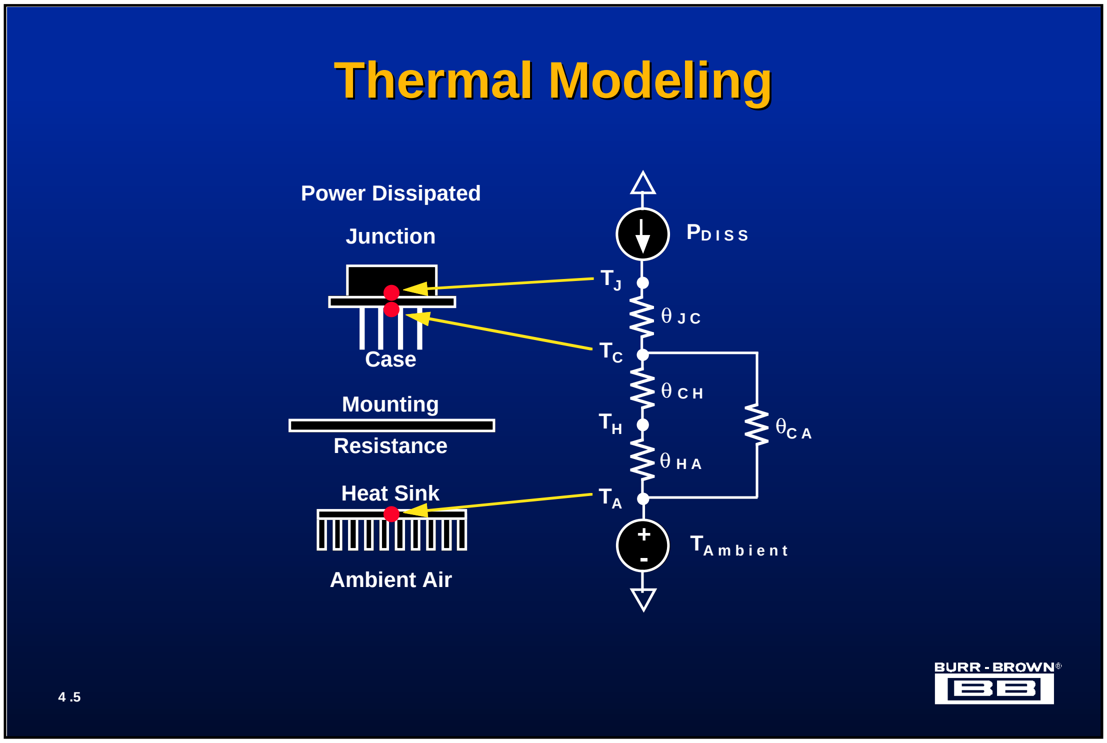


Maintaining a low junction temperature is the key to long term reliable operation in a POA application.

The steps to achieving this goal involve setting up an accurate thermal model of the POA heat removal system, calculating the maximum power to be dissipated by the amplifier, and finally selecting the appropriate heat removal method and hardware.

The thermal model used is an electrically equivalent "circuit" that involves the thermal resistances from the POAs data sheet. Calculating power dissipation requires that the load impedance and driving frequencies are known. Heat sink selection or thermal design can only be accomplished if the desired mode of heat removal has been established or selected. The table below shows the resulting thermal parameter that is determined by the electrical parameter from the POA.

Electrical Design Parameter	→	Resulting Thermal Parameter
Type or Model of POA	→	Thermal Impedances θ_{JA} and θ_{JC}
Load type and frequency of operation	→	Power Dissipation
Reliability or desired MTBF	→	Maximum Junction Temperature



Just because a POA has been selected for an op amp application, that does not ensure it will operate reliably unless a thermal analysis is performed. The data necessary for such an analysis is the thermal resistance of the op amp, the amount of power being dissipated by the amplifier, and the expected maximum ambient temperature.

In all junction temperature calculations dissipated **Power** is equated as **Current** (Watts ->Amps), **Temperatures** are modeled as **Voltages**, (Degrees -> Volts), and **Thermal Resistances** are represented as **Resistors** (°C/Watt -> Ohms). The result is an electrical system that can be analyzed using simple circuit analysis.

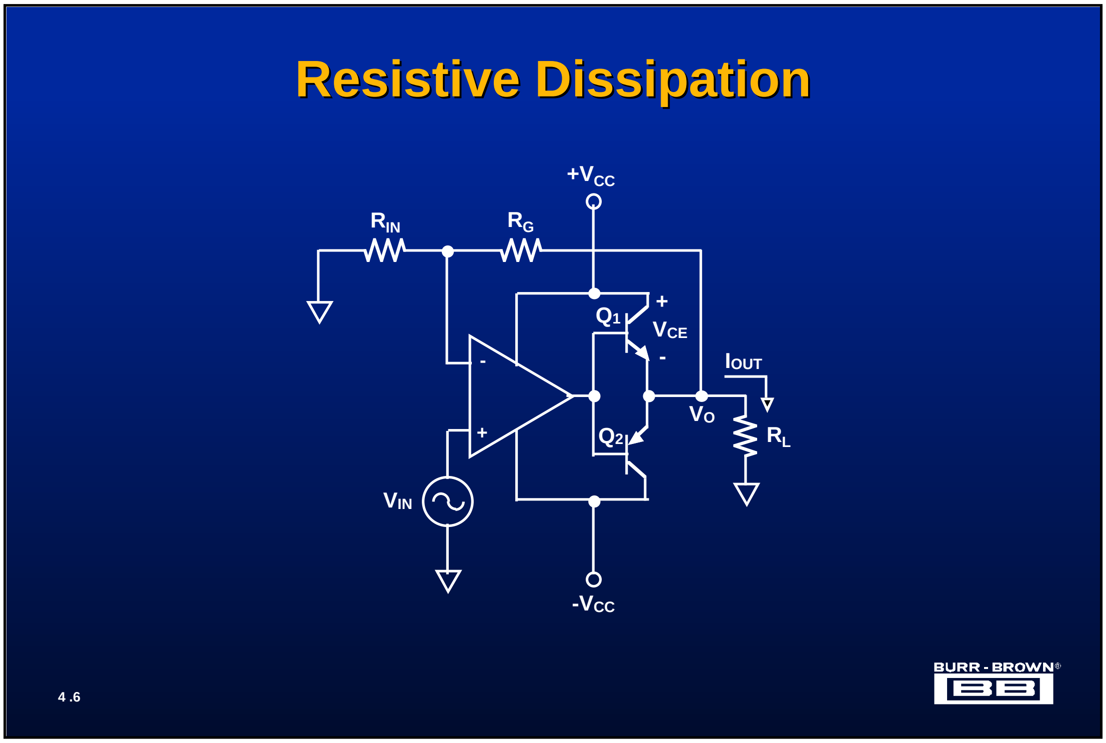
The desired information from this analysis is how much, if any, extra heat sinking will be required for the system. The following formula can be used to calculate the minimum required thermal impedance, heatsink to ambient, necessary to keep the case below a certain temperature.

$$\theta_{HA}(\max) = \frac{\theta_{CA}(T_C - T_A)}{P_{DISS}\,\theta_{CA} + T_A - T_C} - \theta_{CH}$$

Although it may be tempting to simply insert the manufacture's maximum junction temperature into this formula, usually 150 or 175°C, this should only be done if long term reliability is not an issue. If the desired MTBF is known for a given case temperature then the resulting junction temperature for this failure rate can be used. If MTBF data is either unavailable or not known then 125°C should be used as a guideline for a maximum junction temperature.

Once this calculation has been performed, the resulting case to ambient thermal resistance can be checked against the rated impedance of the case type being used. Normally this number is 30°C/W for a TO-3 case. If additional thermal resistance is necessary, then additional heat sinking will be required.

Another point, that must be remembered is that the junction to case impedance, as listed in the manufacturer's data sheet, does not make allowance for contact resistance, shown as θ_{CH}, between the case and the surface it is mounted to. Depending on the application this will add between 0.1 and 1.5°C/W to the θ_{CH} resistance.



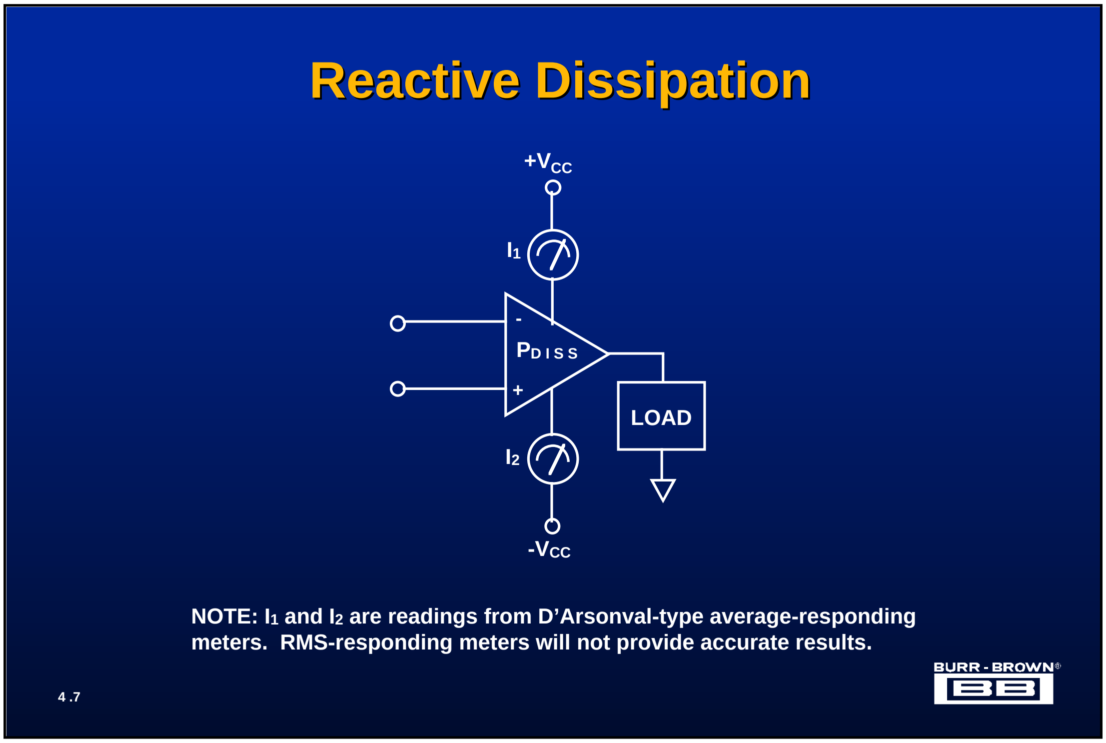
The above diagram shows a simple model of an op amp being driven by an ac signal into a resistive load. The output stage of the POA has been modeled as a pair of transistors. The power dissipated by either Q_1 or Q_2 at any instant is given by the multiplication of V_{CE} times I_{OUT}.

A resistive load is the easiest load to evaluate power dissipation. When calculating the power dissipated of any amplifier, two numbers are of interest: The RMS or steady state dissipation and the worst case or peak dissipation.

The RMS calculation is simply the supply voltage power minus the RMS value of output voltage times the RMS value of output current taken over a half period of any periodic output cycle. As the above figure shows, the amplifier is actually separated into two output stages where each stage is responsible for either positive or negative output voltages. **This RMS value must also be added to the quiescent power dissipation to find the total power dissipation.**

The following formula is used to calculate the maximum power dissipation. The results of this calculation can be used to determine if the junction temperature ever goes above a certain point.

$$P_{DISS}(max) = \frac{V_{CC}^2}{4 \cdot R_L}$$



When a reactive load is being driven by a POA power dissipation calculations are more complex to both perform and measure. The above diagram shows how to measure the power being taken from a power supply. The difference between the power supply power and the power being delivered to the load is the power that is dissipated by the amplifier. This method can be used to make steady state or RMS power readings. If the load is 100% reactive, one fact that should always be remembered, all of the power taken from the power supplies is dissipated by the amplifier.

In order to perform peak ac power dissipation calculations, the frequency of the ac signal being amplified, the phase angle between the current and voltage into the load in degrees, and the magnitude of the load impedance at that frequency must be known. For the most reliable operation in such an application the peak dissipated power should be used to select the appropriate heat sink.

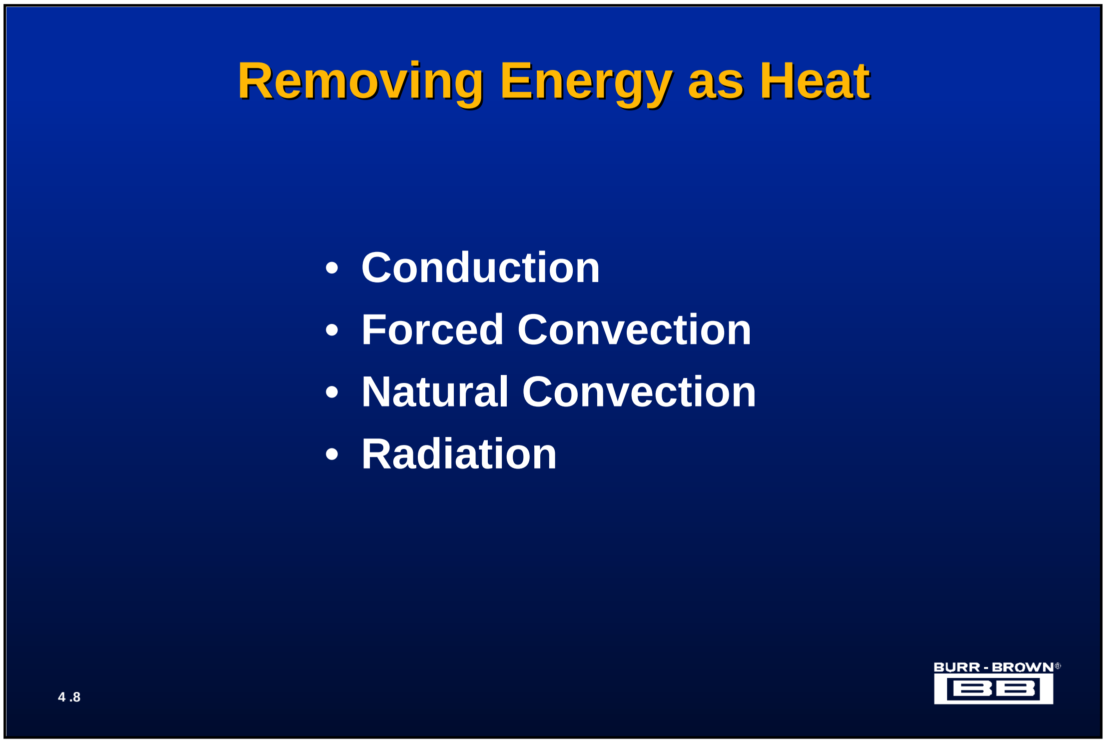
If the phase angle is less than 40°, than the maximum power dissipation is given by the following equation.

$$P_{DISS}\,(max) = \frac{2\text{-}V_{CC}^2}{\pi\ |Z_L| - \cos\theta}$$

If however the phase angle is greater than 40° then the power dissipation is calculated using this formula.

$$P_{DISS}\,(max) = \frac{V_{CC}^2}{2\ |Z_L|}\left[\frac{4}{\pi} - \cos\theta\right]$$

The peak power must be added to the quiescent power dissipation to establish the total dissipated power for a worst case design.



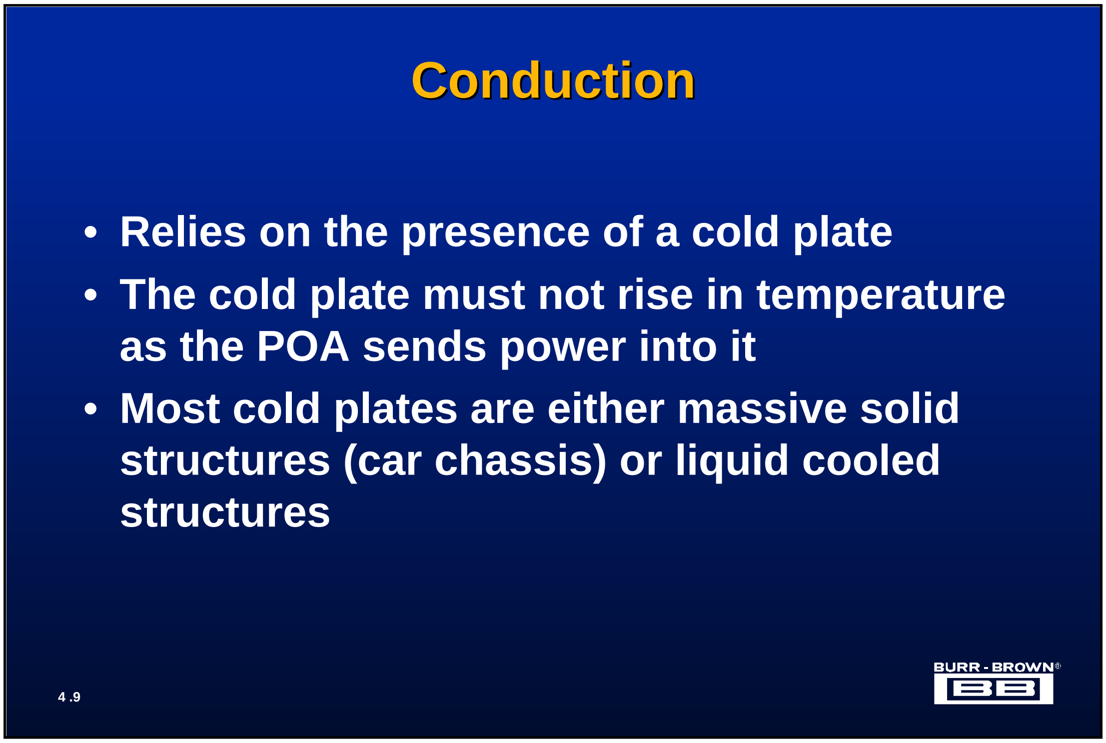
Now that a way of determining the amount of heat sinking required for a POA application has been defined, a choice must be made as to how to accomplish the task of removing this heat.

Conduction, as the name implies, is a method the moves the heat from a source of high temperature to a lower one by conducting it through a physical, solid medium. This is the method that the silicon in a POA uses to move its energy as heat from the junction of the die to the bottom of the package. Thus it can be said that θ_{JC} is a conduction resistance.

Convection, whether forced or natural, relies on a fluid or air flow, to move the heat to a cooler ambient environment. The thermal resistance θ_{JA} is a convection related thermal impedance.

Radiation is a method which relies on the Stefan-Boltzman equation to determine the amount of heat loss. This method is only mentioned here for the sake of completeness. The most common application for this method is in Space based applications where there is no physical body for the heat generated by electronic equipment to be dissipated into.

As to the overall efficiency, Conduction is about 10 times better than Convection and approximately 1000 times more efficient than Radiation. In this discussion efficiency is the amount of heat sinking hardware (heat sinks, fans etc.) that is necessary to move the same amount of energy from a package to another environment and maintain the same junction temperature.



If the system that the POA is being used in has a solid continuous temperature body, the dissipated power from the op amp can be moved to this body. This cool body is sometimes referred to as a cool plate. For example, the chassis of a car or airplane could be a cool plate if the chassis is sufficiently large. Of course, the power being added to the chassis would increase its temperature if the power was not removed by another heat removal method, usually convection.

A solid material is used as the conduit to dissipate power. If the material is a rectangular bar of area A and length L the following formula can be used to calculate its thermal resistance. The factor k is the thermal conductivity of the material itself.

$$\theta = \frac{L}{kA}$$

A has units of length ^{2} (meters ^{2})

L has units of length (meters)

k has units of power/(length*temperature) (W/(m • °C))

Forced Convection

- The most efficient way of removing heat from a POA
- Requires the additional expense of a fan
- Relies on a source of cool ambient air

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Forced convection is a heat sink with air or liquid from a fan flowing over it. Most data sheets for heat sinks show a graph of the heat sinks θ_{HA} versus air flow. Usually this graph is drawn with the units of SCFM for air flow, which stands for Standard Cubic Feet per Minute. SCFM is air flow measured in cubic feet at standard temperature and pressure, i.e. sea level and 25°C. These graphs also go down to zero air flow and this would be the number used with no air flow.

Heat sinks used in these applications are sensitive to the orientation of the heat sink to the air flow. As with free convection either turbulent or laminar flow can occur. Turning the heat sink the other direction with respect to the flow frequently changes the flow type.

As a general rule of thumb the forced convection type of heat removal is required when the power being dissipated divided by the entire heat sink area (including the package) exceeds $0.1W/in^2$.

Free Air or Natural Convection

- Amount of Heat Loss depends on many conditions
- θ_{HA} given by manufacturer's data sheet depends on this loss method
- Can be made lower only by increasing the heat removing area

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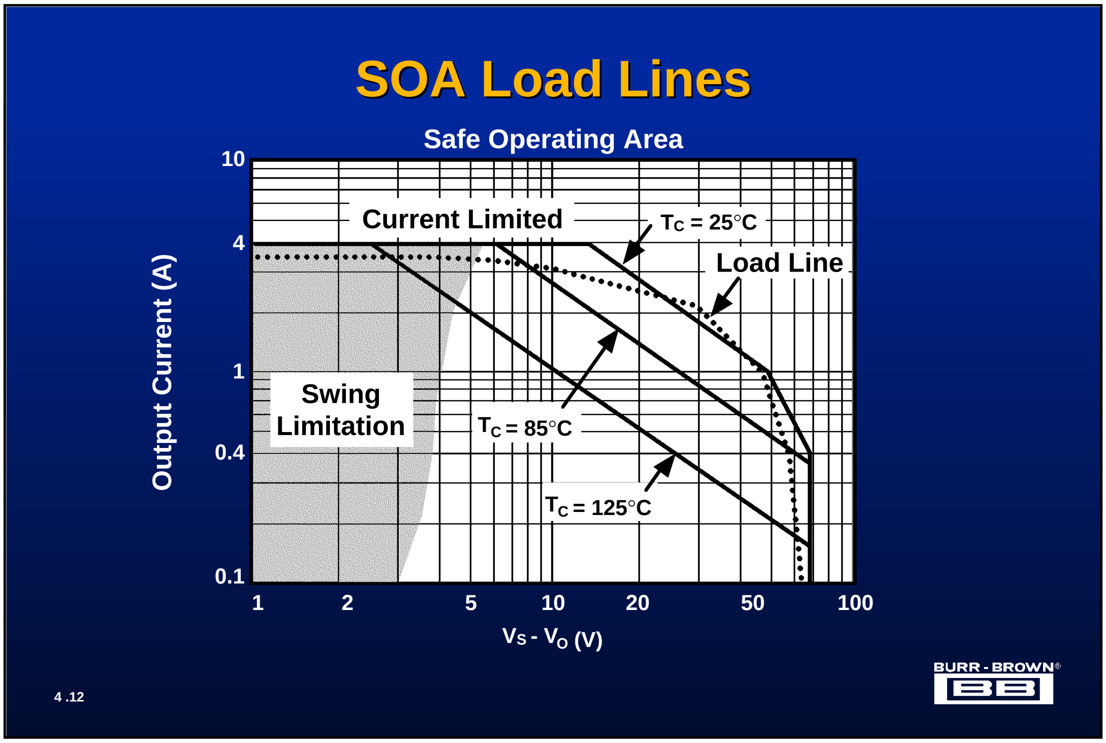
Free air or natural convection is the most common way that electronic devices shed energy as heat. This is also the method that all heat sinks work when not in the presence of forced air i.e. a fan.

Determining the exact value of θ_{HA} is a very difficult task and is beyond the scope of this discussion. An example of free convection can be seen as the waves of heat (actually hot air) that rise from a hot surface like the hood of a car or pavement on a hot summer day. Suffice to say that there are two modes in which the heat sink can operate in, either laminar or turbulent air flow. The mode will depend on the amount of power being dissipated and the size and type of heat sink in use.

The laminar mode occurs when the air flowing across the surface of the heat sink flows in sheets parallel to the heat sink surface. The turbulent mode occurs when either the power being dissipated, or the difference between the air temperature and heat sink surface is large enough to cause the air flow to become random or turbulent.

The only way to increase the efficiency of this mode of heat dissipation is to increase the area of the heat sink surface.



The above graph shows Safe Operating Area or SOA chart for the OPA544. This chart is useful for evaluating the safe electrical and thermal limits of an op amp.

The X-axis shows the allowable values of supply voltage minus the output voltage, or the voltage across the amplifier. Note that maximum ratings for both supplies are added together so that in the case of the OPA544 this is 70 volts. The Y-axis shows allowable values for output current.

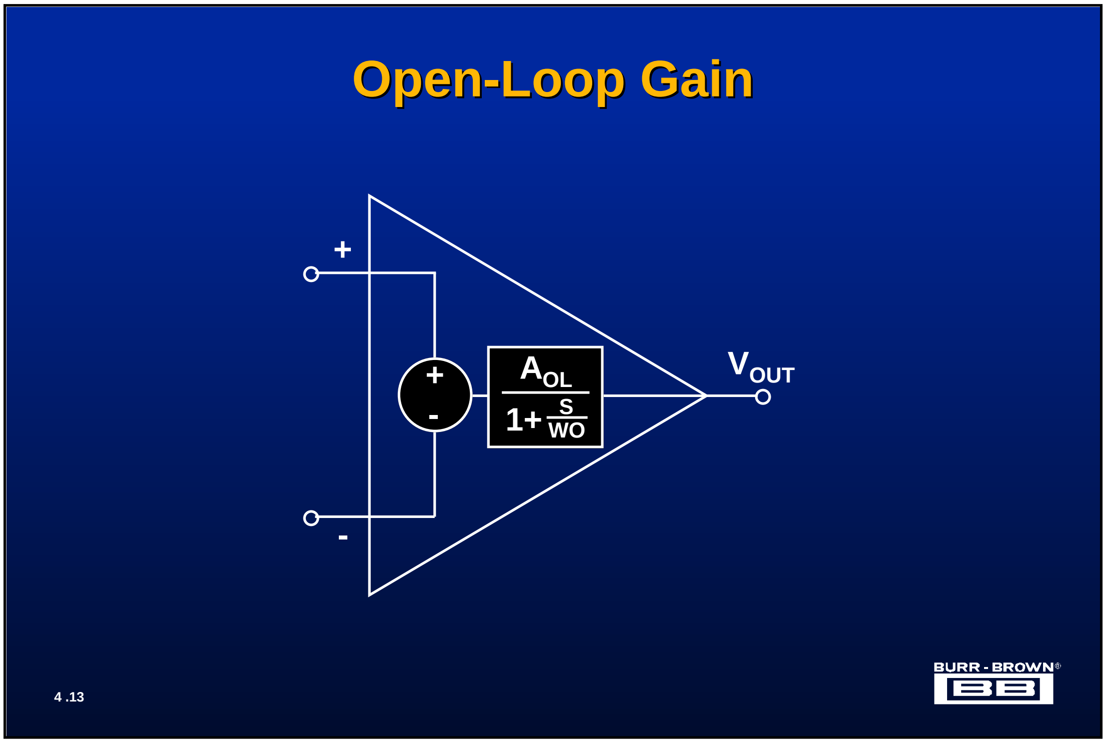
The thermal limits show the case temperatures attained assuming a maximum junction temperature of 150°C.

A simple way to check for SOA violations is to first determine the maximum case temperature desired in the application and to plot the necessary supply minus output voltage, currents for the load, and power supplies to be used. Thus a load line for the amplifier is plotted within the SOA graph and any excursions outside of the allowed areas are easily identified.

As an example the load line for a 20Ω load, with power supplies of +70V and a desired maximum case temperature of 25°C is shown sketched on to the SOA graph (load line). The output current condition in this example of 2A goes outside of the SOA line for T_C=25°C. To stay within SOA conditions, the case temperature must be limited to less than 25°C or the amplifier must be run off of a lower power supply voltage.

The output voltage swing of the amplifier versus current can also be plotted onto the SOA graph to indicate where the output of the amplifier can never go electrically because of output swing limitations. (This is the shaded area on the left side of the above figure.) For example the output of the amplifier can not swing to less than approximately 4V from the power supply when the output current is above 0.5A.

If the load line had intersected the shaded-in area this would not have been indicative of an SOA violation. Instead this condition would have represented the point at which the amplifier could have no longer attained the output voltage desired, for the load in question.



The bode-plot or frequency response of an operational amplifier is almost always shown in a data sheet with either no load or a large resistive load connected to its output. In the typical case, the frequency response is shown to go down 20dB for every decade increase in frequency. This type of response is easily modeled as an amplifier with high DC gain and a single pole filter in series with the amplifier as shown above.

Unfortunately op amp manufactures can not ship the types of devices that are represented by this simple model because they do not exist in the real world. In fact every op amp that is in use today has extra poles, and sometimes zeroes, built into the open-loop gain curve which is caused by load interaction with the output impedance of the amplifier. This output impedance interacts with reactive loads to change the single pole, 20dB/decade response into a multi-pole, 40dB/decade or greater, response.

There are two key points to remember when reading this section:

1) The open loop-gain of an amplifier used to analyze an application for stability is **not** what the manufacturer prints in the data book, unless the application calls for the output to drive a high value of resistance, i.e. not a POA application. It **is** the transfer function of the output divided by the input (in Volts/Volts) with the feedback elements open. The **load** is still attached and its effects are thus included.

2) The open-loop gain is measured or analyzed at the point in the circuit that feedback is taken.

Output Impedance

- Power Op Amps have a Finite Output Impedance
- The simplest model shows this impedance as a resistance in series with the output of the gain setting block
- Depending on the Load this impedance has different effects on the electrical stability of the application circuit

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If an op amp had no output impedance, the op amp would be stable under any load conditions. Unfortunately all op amps have some output impedance which has an effect on the stability of the circuitry with respect to load.

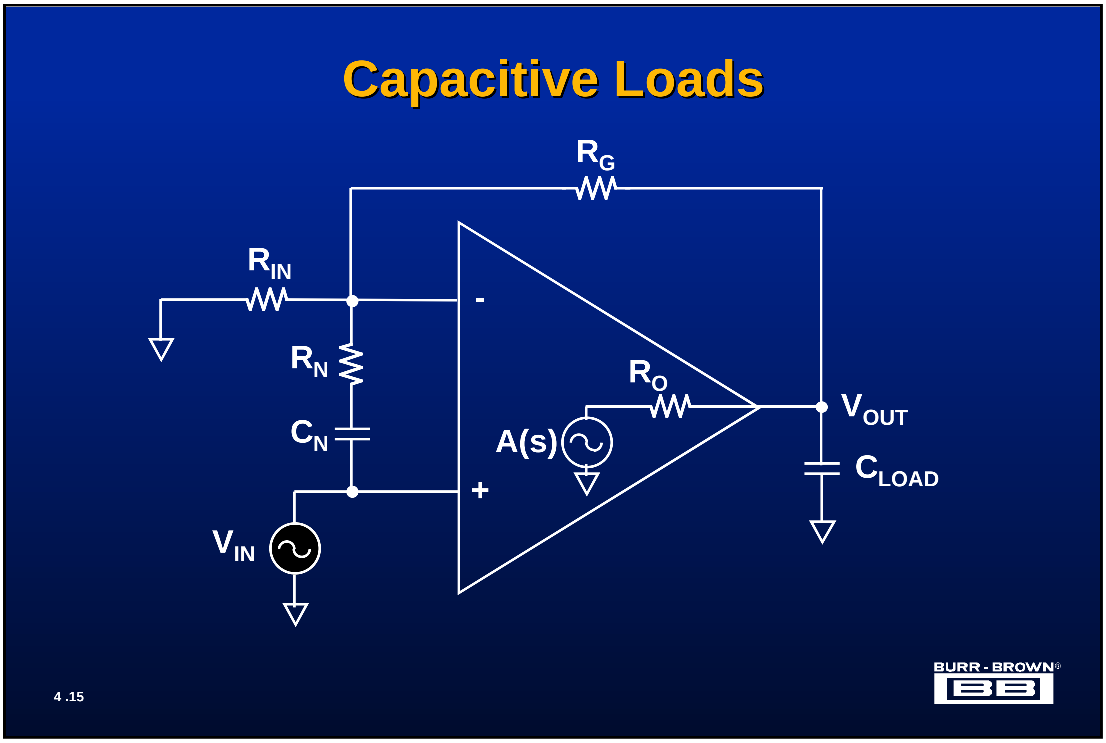
The classic feedback equation is of use in explaining this behavior. This equation is as follows:

$$A_{CL} = \frac{A}{1 + A \cdot \beta}$$

In this equation A_{CL} is the closed-loop gain (in Volts/Volts) , A is the open loop gain of the amplifier (in Volts/Volts), and β is the feedback factor (which is dimensionless). If the amplifier was configured in the non-inverting manner and the output impedance of the amplifier was zero, this feedback factor would only involve the gain setting elements.

When the output impedance is non-zero, the load element values together with the output impedance of the amplifier modify the apparent open-loop gain of the amplifier. What this means is that the amplifier can no longer be treated as a single pole device. Since the open-loop gain of the amplifier also depends on the application it is imperative that the designer perform a stability analysis of the power op amp application when a reactive load is driven.

It is not the purpose of this section to cover stability analysis in great detail. The appropriate models and equations for various reactive loads and some general guidelines for overcoming the stability problems inherent in driving reactive loads will be discussed, however.



The above diagram shows the pertinent circuit elements used to evaluate the performance of the op amp when presented with a capacitive load. The output impedance has been modeled as simply a resistance of constant value, R_O. While most output impedances also have a reactive element associated with this resistance, it is usually not necessary to include this for a successful stability analysis.

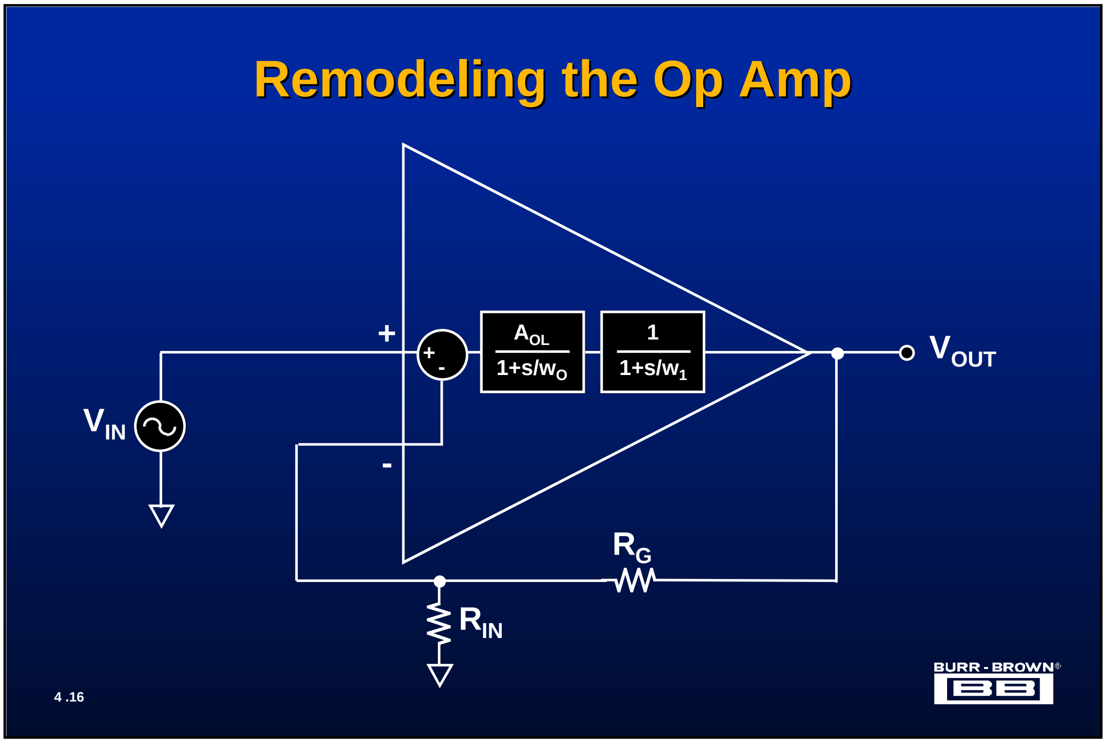
The components R_N and C_N are used for compensation and will be discussed later. For the moment assume that they are not connected in the circuit.

For a successful stability investigation we need to look at two plots of the op amp application.

1) The magnitude of the Open-Loop Gain plot of the amplifier as seen by the feedback element(s) of the circuit. In our example, the point of feedback is the juncture of C_{LOAD}, R_O and R_G. If we move the load capacitor into the amplifier model and open R_G, the open-loop gain is easily visualized and plotted.

2) The amount of output voltage seen by the amplifiers input terminals. That is the amount of differential voltage between the positive and negative terminals. This quantity is referred to as β. In the case of the above application circuit, without the inclusion of the components R_N and C_N, β is simply the ratio of voltage at the summing junction over the output voltage or,

$$\beta = \frac{R_{IN}}{R_{IN} + R_G}$$



The above diagram shows a first order model of the power operational amplifier which includes the effect of output impedance as it reacts with a capacitive load.

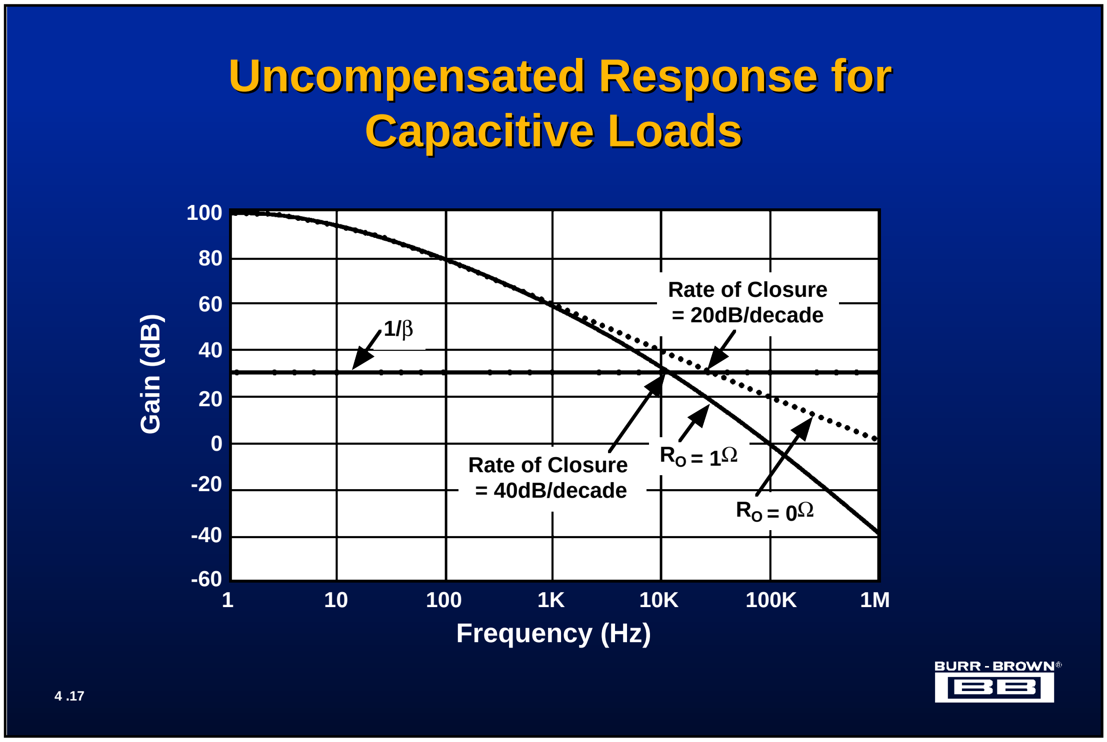
Generally, the frequency characteristic on gain is modeled as a single pole response. When some output impedance is included in this model the “apparent “ open-loop gain now has an extra pole, w_1, given by the equation

$$w_1=1/(R_O*C_{LOAD})$$

The amplifier will no longer exhibit the typical 20dB/decade frequency response above the frequency w_1. In fact it will role off at 40dB/decade above this frequency.

The model has been changed in this slide to include the load capacitance, C_{LOAD} inside the original model as a second pole. This approach can be generalized to say that all load elements between the original output of the op amp, the point of feedback, and ground should be moved inside the ideal op amp model. While this does not result in any circuit simplifications it makes the point of analyzing this application easier to understand.

If straight resistive feedback is used in this application, and the gain set via this resistive network is not of sufficient magnitude, a stability problem will occur.



A well known test for the stability of an operational amplifier is to plot the inverse of the feedback factor β versus frequency on the same graph as the apparent open-loop gain curve of the amplifier in use.

If the the output impedance of the amplifier is not zero for voltage control of a capacitive load, the open-loop gain of the amplifier will have more than a 20dB/decade roll off above a certain frequency. In the graph shown above, the feedback factor for a typical capacitive load on a power op amp is shown. In this case the circuit values have the following values. R_O=1Ω, R_G= 3Meg, R_{IN}=100kΩ, C_{LOAD}=16µF, the open-loop gain is 100dB, and the pole frequency of the op amp is 10Hz.

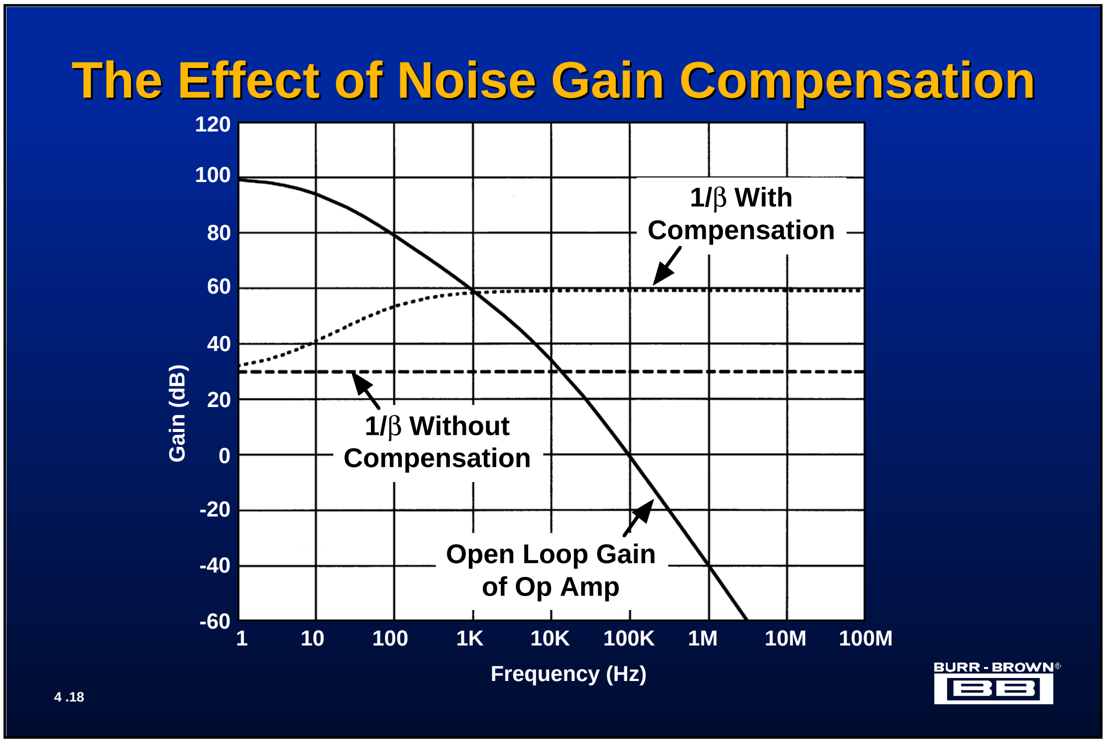
From the graph it is seen that at the point of intersection of the 1/β and open loop gain curve of the operational amplifier with an output impedance of 1Ω, the rate of closure, or difference between the two slopes is 40dB/decade. The conclusion that can be drawn from this is that this amplifier circuit will be unstable and will in fact oscillate at this frequency.

In order to make this circuit stable, the 1/β curve will have to be modified, via some added circuit elements, to achieve stability. The most universal way of doing this is by adding a series combination of a capacitor and resistor between the two inputs of the amplifier. This technique is known as noise gain compensation because the noise gain of the amplifier is modified. The component values, designated R_N and C_N are chosen as follows.

1) After determining the DC gain required of the circuit, R_{IN} is known. Make R_N equal to 0.1 of the value of R_{IN}.

2) Choose the value of C_N such that the corner frequency of the noise gain circuit is a decade below or 0.1 of the value of the intersection frequency between the uncompensated 1/β curve and the open-loop gain curve of the op amp.

This graph also shows the theoretical intersection of the 1/β curve with the open-loop gain curve if the output impedance of the op amp is zero. Note that this intersection occurs at a slope difference rate of 20dB/decade. It is this type of intersection characteristic that is achieved with noise gain compensation.



The 1/β and open-loop gain characteristics for the capacitive loading application are now shown using the following noise gain components R_N = 3.4kΩ and C_N = 0.46µF.

Note how the 1/β curve begins to increase a decade below the 3kHz intersection point. Also a pole in this response flattens the 1/β curve as it intersects the A_{OL} curve. It is for this reason that the noise gain circuit values are chosen to be a decade below so that their effects are dominating the feedback effects at the point of intersection. When the proper values of R_N and C_N are added to the circuit, the 1/β curve intersects the open-loop gain curve at a 20dB/ decade difference and the circuit is stable.

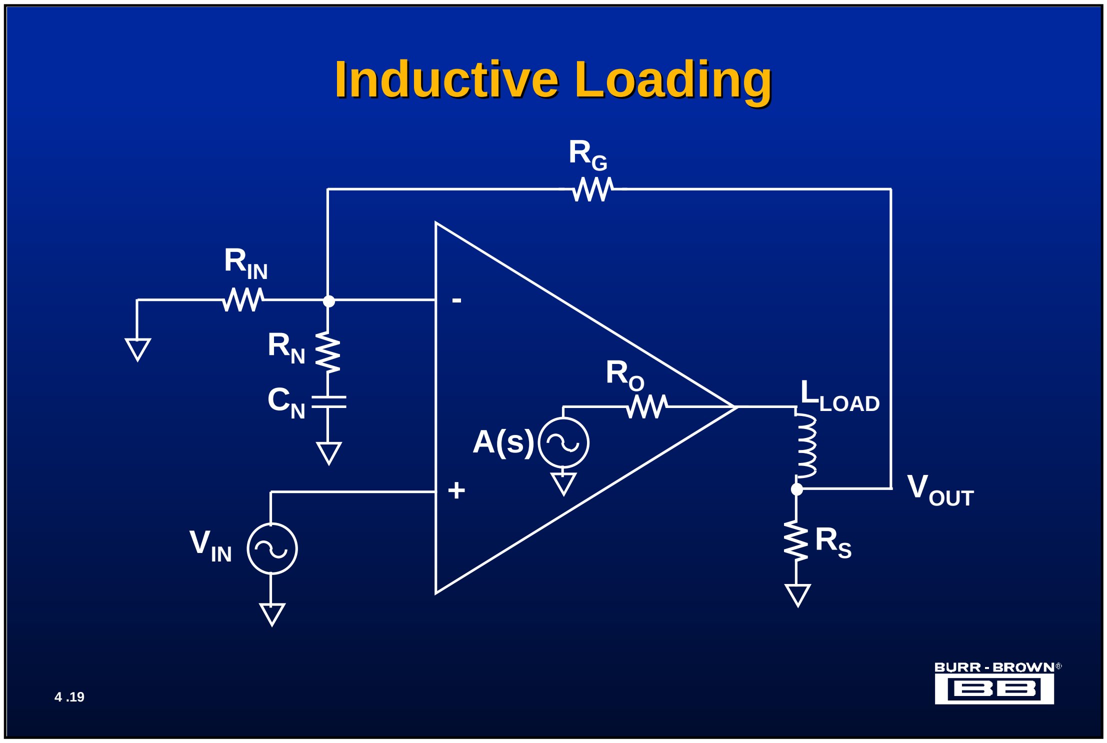
Intuitively the circuit values are chosen such that the R_N value dominates at high frequency i.e. once the C_N becomes a short circuit the equivalent impedance seen by the amplifier is the parallel combination of R_N and R_{IN}. Since R_N is chosen to be 1/10 the value of R_{IN}, R_N will dominate. The value of C_N is then chosen to make sure that the R_N dominates the noise gain equations at least one decade before the intersection frequency, making the circuit always be stable.

The formula for the zero formed in the 1/β response is given by,

$$f_Z = \frac{R_G + R_{IN}}{2 \bullet \pi \bullet C_N \left(R_G R_{IN} + R_G \bullet R_N + R_{IN} \bullet R_N\right)}$$

And the formula for the pole in the 1/ β response is given by,

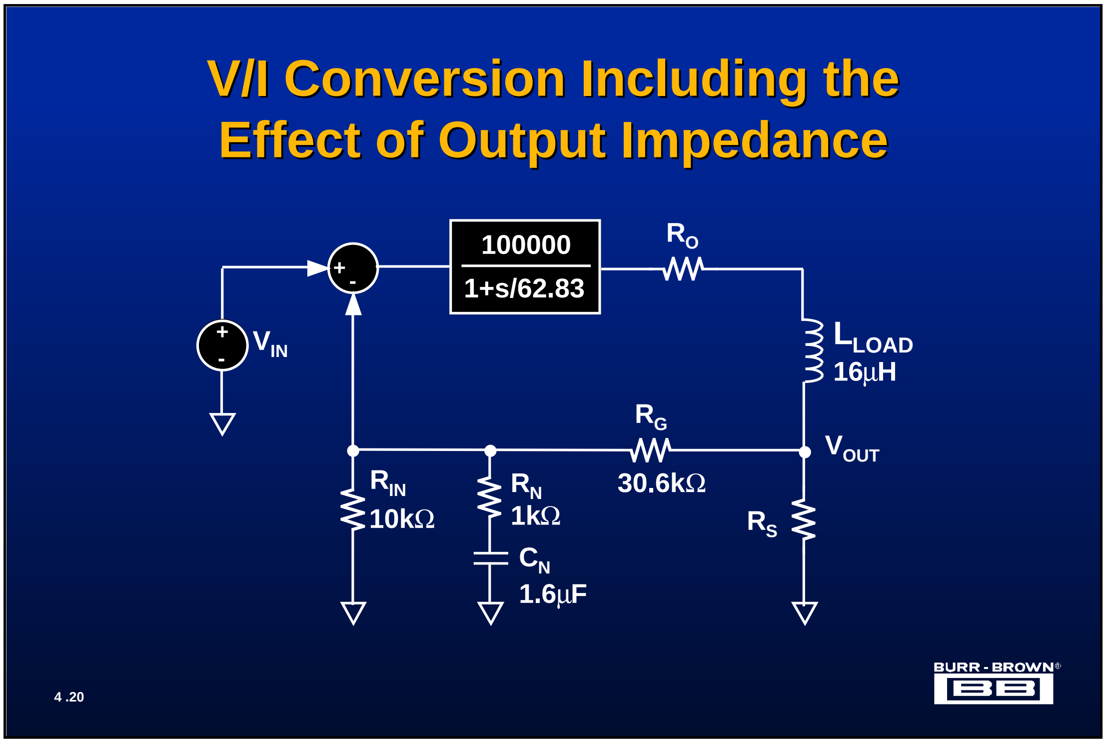
$$f_P = \frac{1}{2 \bullet \pi \bullet R_N \bullet C_N}$$



The above schematic shows a typical application for a power op amp when driving an inductive load. Normally the inductor is driven with current as the controlled element. The reason current instead of voltage is controlled is that at DC an inductor is a short circuit and any output voltage would cause the POA to drive a short circuit. Using current control protects both the inductor and the POA from this condition.

As before this circuit will be analyzed with both zero (ideal) and non-zero (real world) output impedances for the op amp. Instead of relying on symbolic analysis, Spice can be used to show how these circuits can be analyzed and designed to be stable.

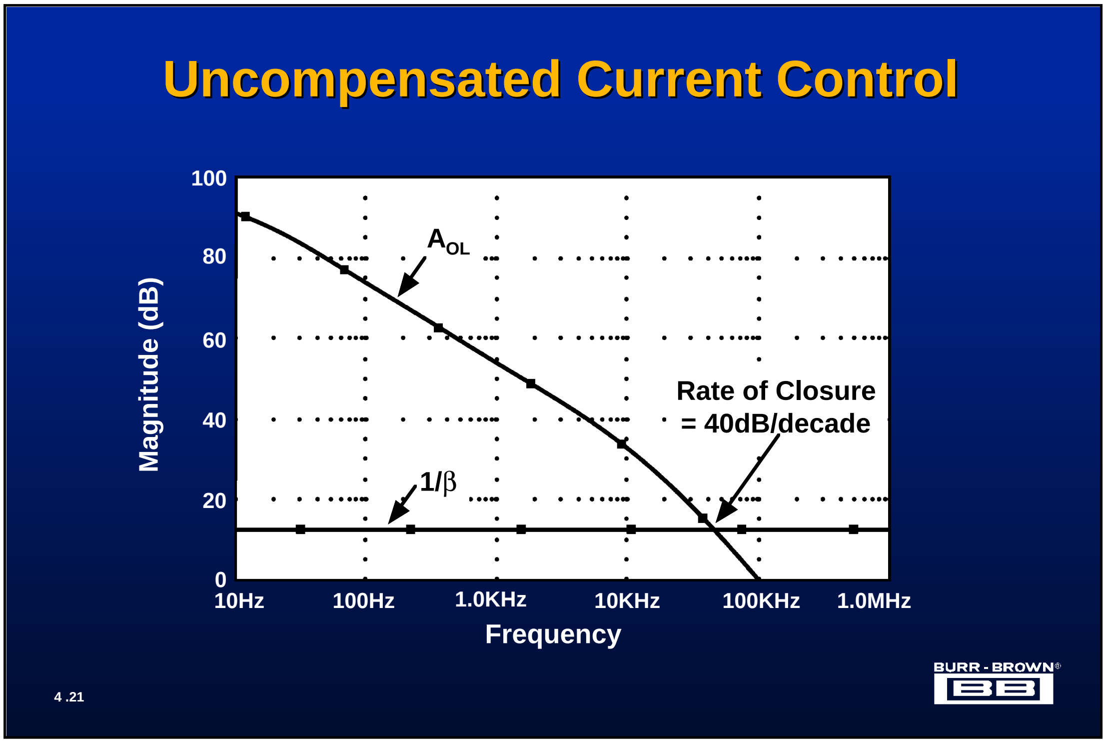
For AC analysis the op amp can be modeled as a summing junction and a Laplace transfer equation. The same model for the power op amp has an open-loop gain of 100dB and a pole frequency of 10Hz. When it is necessary to model the output impedance it will be modeled simply as a 1Ω resistor. The inductor will be assigned a value of 16µH. R_{IN} is set to 10kΩ, R_G as 30.3kΩ, and R_S is set to 1Ω. The compensation components R_N and C_N are selected with values of 1kΩ and 1.6µF respectively.



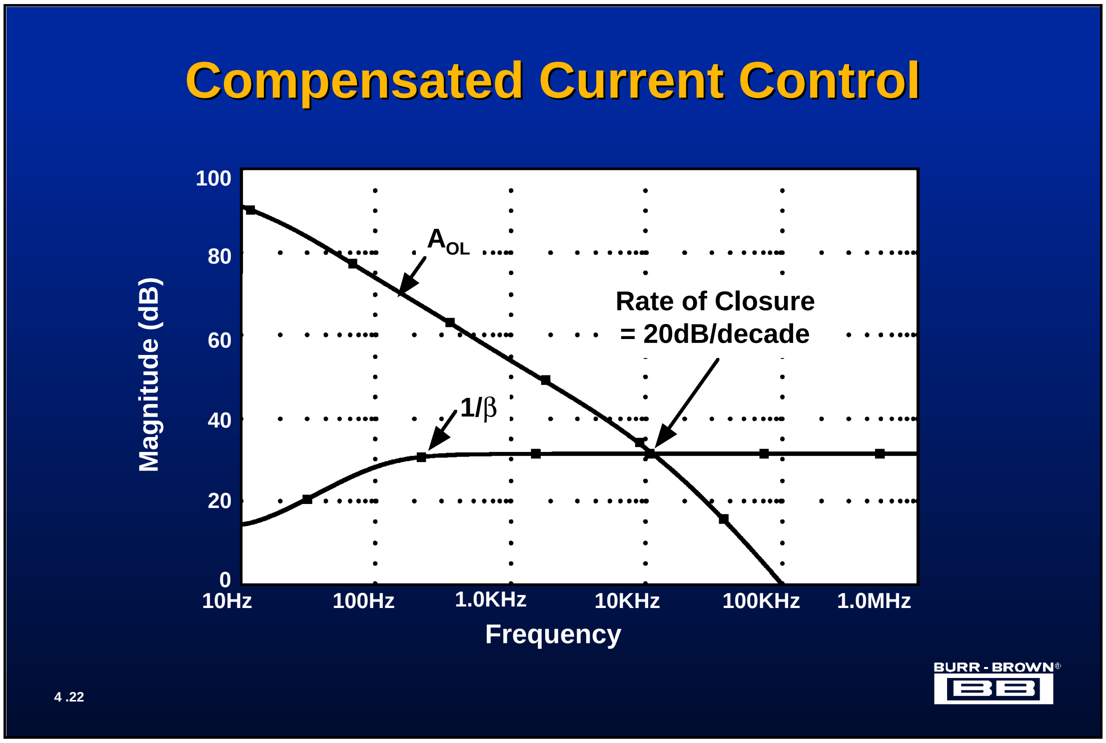
Just as with voltage control of a capacitor, current control of an inductor modifies the apparent open-loop gain of an operational amplifier as seen by the load. Again an additional pole is formed by the reactive load and the output impedance of the amplifier. The apparent open-loop gain of the amplifier is that A_{OL} curve that we would measure at the point of feedback, in this case the juncture of L_{LOAD} and R_S.

The schematic above shows the POA with the load inductor plus the output impedance of the amplifier forming a second pole in the apparent A_{OL} response. We have thus taken the load inside the POA. Unlike the Voltage driven Capacitor application there is still access to a node before this second pole and in fact feedback can be taken around the inductive load for some applications.

Stabilizing such a circuit relies on RC compensation of the inductive load. This is similar to the compensation used for capacitive loads when driven in a voltage mode. In this case instead of shorting the inputs of the amplifier together, as was done with the voltage driven capacitor case, the feedback signal is shunted to ground via C_N and R_N above a certain frequency.



The above plot shows the intersection of the modified open-loop gain characteristic of the current controlled inductor and its 1/β plot. As was seen with the uncompensated voltage amplifier, when driving a capacitive load, the rate of closure is 40dB/decade and this circuit is unstable.



With the addition of the components R_N and C_N, the $1/\beta$ plot has been modified to make it rise with frequency before the intersection of the 40dB/decade slope of the open-loop gain of the amplifier. Rate of closure is now 20dB/decade and stability is assured.

POA Application Circuits

- Piezo Driver
- Paralleling POAs - More Amperes
- Stacking POAs - More Volts
- Howland Current Pump - V/I Conversion
- Building a POA

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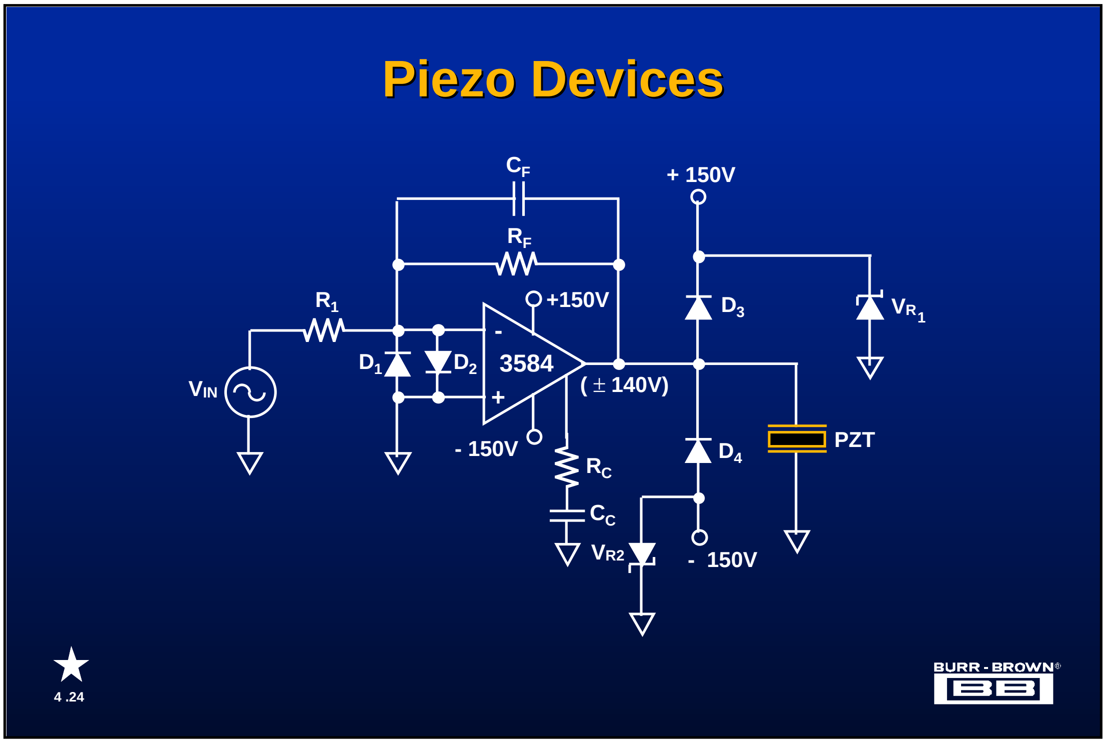
Power amplifiers can be used in a variety of applications such as the ones listed above. In all cases the amplifiers used in these applications are required to drive high currents or high voltages to the load. For each circuit thermal and stability considerations will be discussed as appropriate.

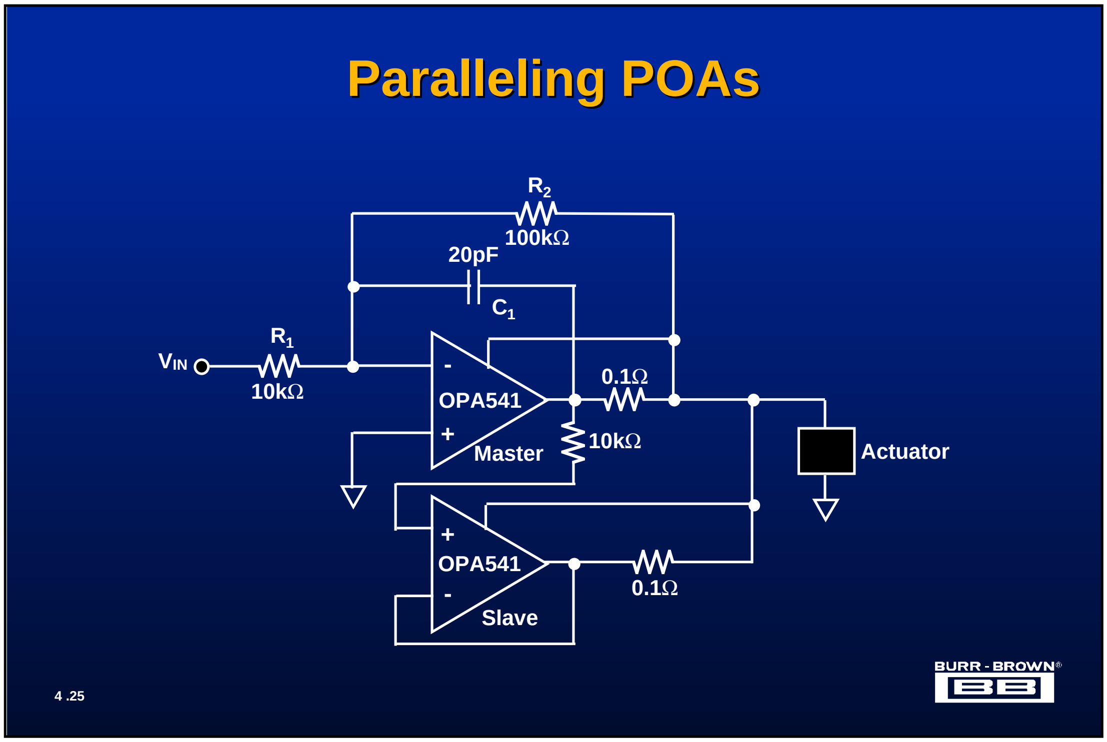


Piezo transducers are used for micro-positioning functions found in surface profiler, scanning tunneling microscopes, and mirror positioning for laser applications.

PZTs (Piezo Transducers) require relatively high excitation voltages, > 100 Vp-p, for large mechanical dynamic ranges. High voltage operational amplifiers like the 3584 are very useful for these applications.

The above schematic shows the recommended circuit configuration for driving the predominantly capacitive load of the PZT. Also shown is another approach to stabilizing the op amp for this type of load namely the addition of a capacitor, C_F, in parallel with the gain setting resistor R_F. This compensation technique forces the gain of the op amp to drop with frequency. The compensation components, R_C and C_C modify the open-loop characteristics of the 3584 and are another way to compensate the system.

Diodes D_1 and D_2 protect the input stage from receiving the full output of the op amp during a transient. Transzorbs V_{R1} and V_{R2} protect the op amp and the power supply itself. Since the PZT can either be displaced with electrical excitation it can also generate a voltage if it is mechanically displaced. Thus if the PZT is accidentally displaced, and this would result in a larger voltage than the op amp could safely handle, the transzorbs would clamp this PZT voltage to the supply rails and provide protection.



One of the more common application problems that come up when selecting a Power Op Amp is that the manufacturers line does not offer a device that has sufficient current for the application. It is possible using the scheme shown above to parallel like op amps for more output current.

Some amount of degeneration or ballast resistance must be added to the output of the POAs to limit the amount of current that would flow between these two devices. Thus, for the example shown above, for every 1 amp of output current 100mV of available output voltage is lost.

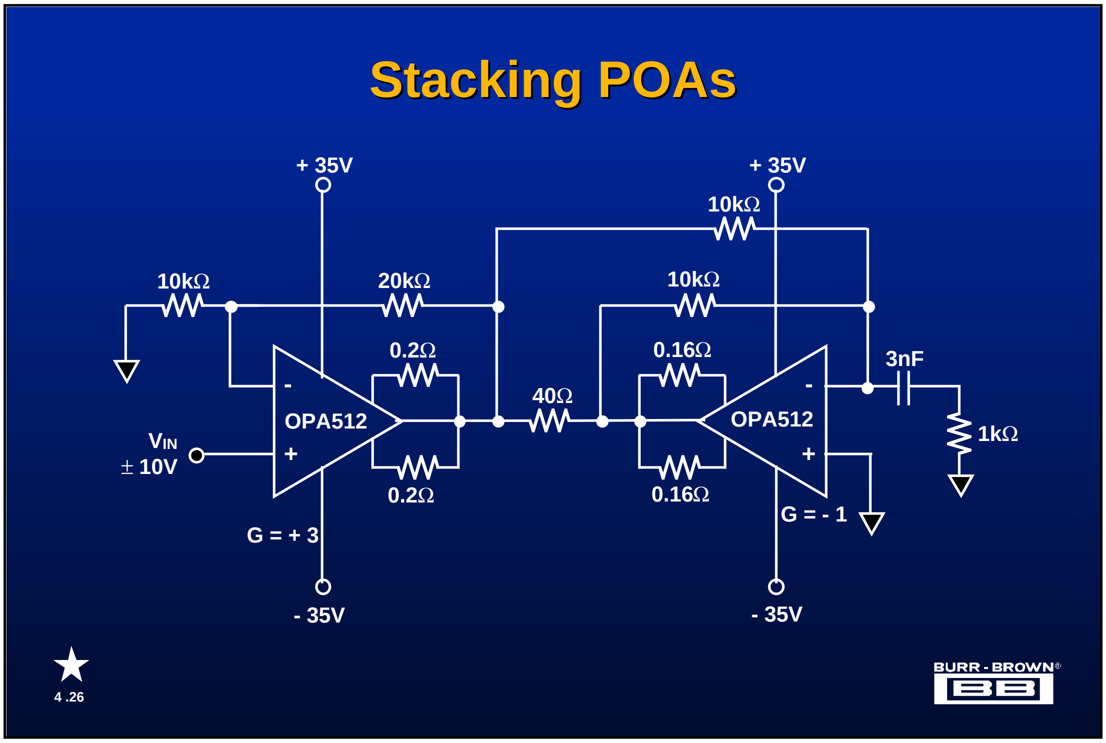
The 0.1Ω ballast resistors minimize the circulating current that will always flow between the two devices due to V_{OS} errors. The circulating current is equal to the worst case mismatch in offset voltage divided by twice the value of these resistors or

$$I_{CIRC}=\Delta V_{OS}/\,(2\bullet 0.1\Omega)$$

which results in 50mA of waste current in this case. This current must be added to the normal quiescent supply current for power dissipation or heat sink calculations.

The configuration used has one device operating as a master device with the bottom amplifier simply following the master's output. The point of feedback for the master is the voltage at the load itself and the slave's feedback is taken from the actual output of the master. The reason this is done is to force the slave to follow the actual output of the master, a signal which includes errors due to offset voltage differences between the two amplifiers.

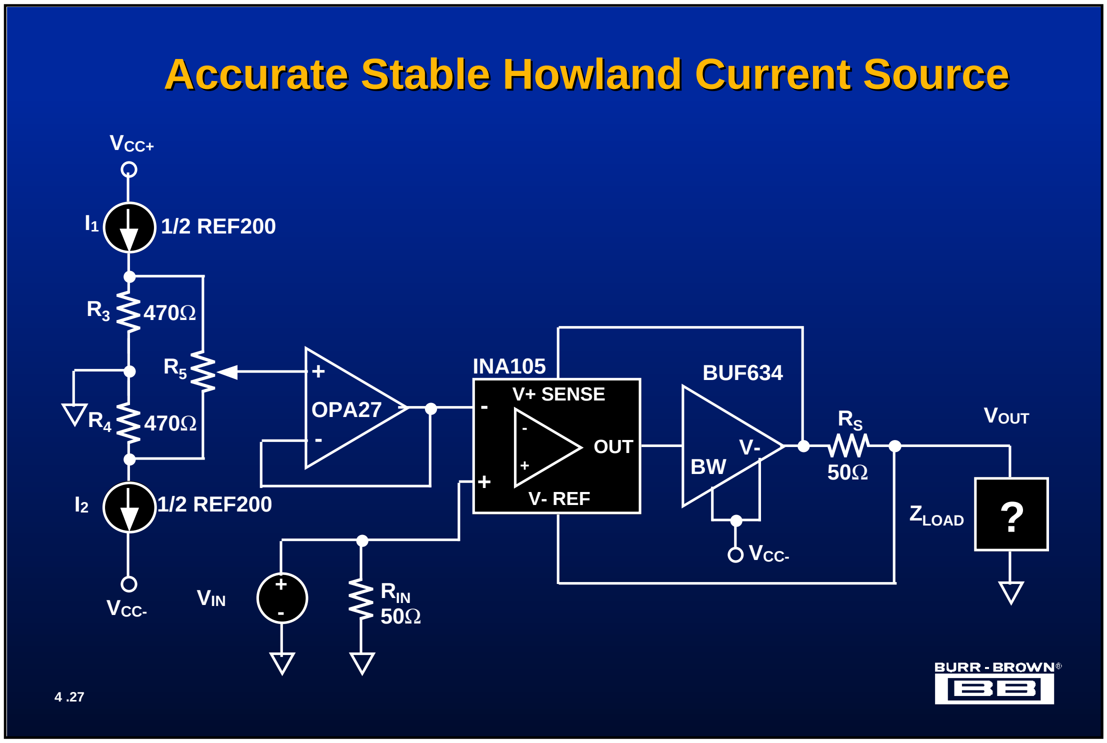
Finally the master device must be slew rate limited. This is done with R_1 and C_1, the value of which is determined by the minimum specified value from the data sheet. This avoids current limiting and sharing errors during transients.



Using a similar master/slave scheme that allows for increasing load current two POAs can be connected as shown above to increase peak-to-peak voltage to a load. The master op amp, on the left, is set for the desired gain and gain polarity while the slave is set for a gain of -1V/V so that its output is the inverse of the master or system gain. This technique not only doubles the available output voltage but also increases the slew rate by a factor of two.

Also similar to the parallel application some sensitivity must be taken to keep the devices from violating the thermal or electrical constraints imposed by the SOA curves. It is for that reason that the current limit of the master device is set to a level 20% less than the slave. Thus during an overload condition the master will limit first. This will result in a large error voltage on the slave, the slave will follow.

This guarantees that during a short circuit condition both devices will share, although not equally, the power dissipated. If the slave were to current limit first, the master would respond by forcing the majority of the power dissipation to occur in the slave.



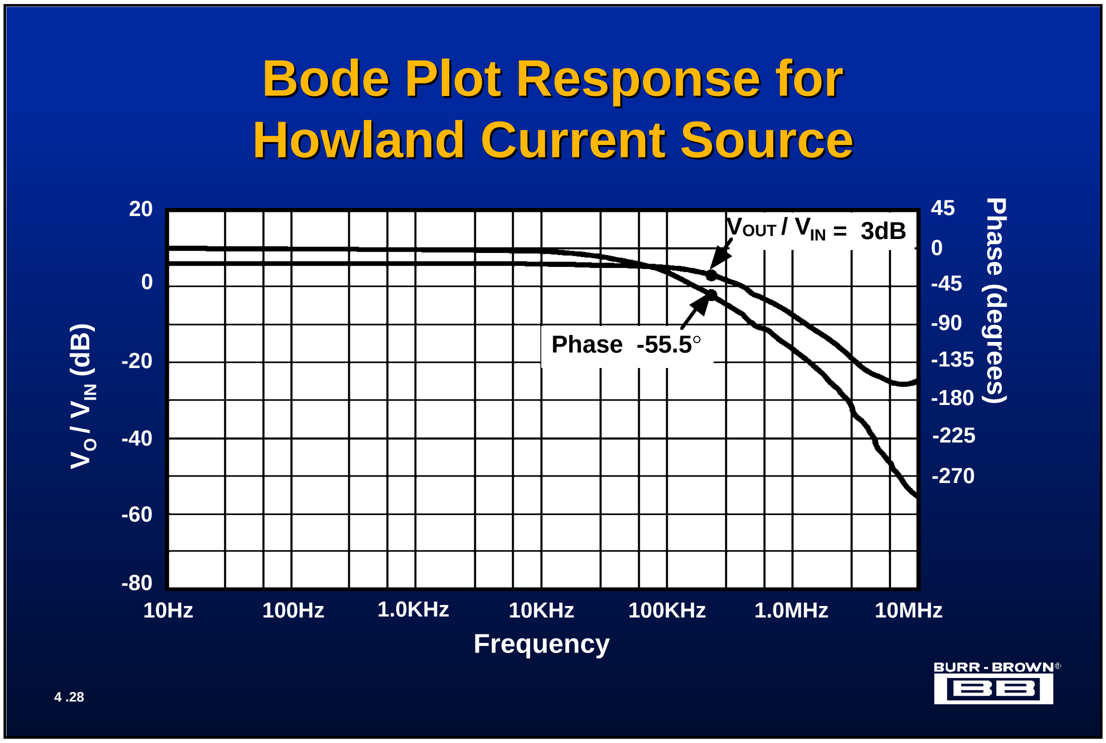
Another application for a POA is the conversion of voltage into an equivalent current. Quite commonly this converted current is used to drive a reactive load. If a POA was used in this configuration with discrete resistors it would be quite common to have stability and accuracy problems. The accuracy problem could be solved with expensive matched resistors. The stability problems could be overcome by noise gain compensation.

This circuit avoids these problems by using the INA105 as an accurate front end which then drives the BUF634 to the correct output voltage to maintain the desired flow. This technique avoids the problem of output impedance interaction with the load by relegating the device which has all of the open-loop gain, the INA105 to driving the high impedance input of the BUF634. Also this circuit takes advantage of the fact that the BUF634 has a much higher bandwidth than the INA105. Thus the overall frequency response of the circuit is only dependent on the INA105 and in fact exceeds 250kHz.

Accuracy is maintained using the INA105, a precision differential amplifier with four well matched (< 0.01%) resistors built in. In an ideal application the sum of R_S and the resistor going into the V-REF pin 1 (25kΩ) of the INA105 would be equal in value to all the other resistors in the differential op amp. However, for R_S values of less than 50Ω, the accuracy of the system is better than 0.1% over the full scale output range.

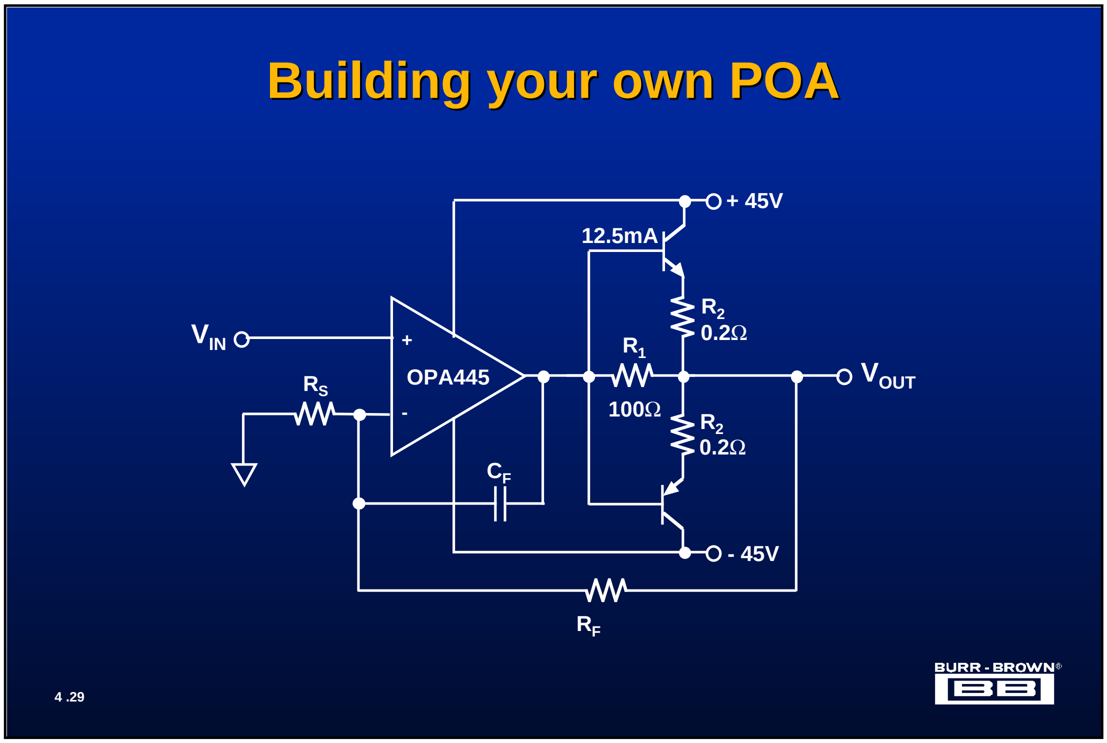
Finally the REF200 and OPA27 allow for offset voltages that would normally be turned into error currents, to be trimmed out.

The entire circuit is fairly inexpensive and can change any voltage out function generator into an equivalent current out device.



The above graph shows the actual measured closed-loop response of the V_{OUT}/V_{IN} gain characteristics of the Howland current source.

The load being driven was chosen to be a 100Ω resistor so that the closed-loop bandwidth of the circuit could be examined. The I_{OUT}/V_{IN} response of the circuit is simply $1/R_S$ or 0.02(1/Ω). A 100Ω resistor load is being driven, making the low frequency or DC voltage gain of this circuit should be $(1/R_S)$*100Ω, (2V/V or 6.02dB). The 3dB bandwidth of this circuit is approximately 250kHz. The phase shift at this frequency is -55° and can be very closely modeled as a single pole system, which would have a -45° phase shift.



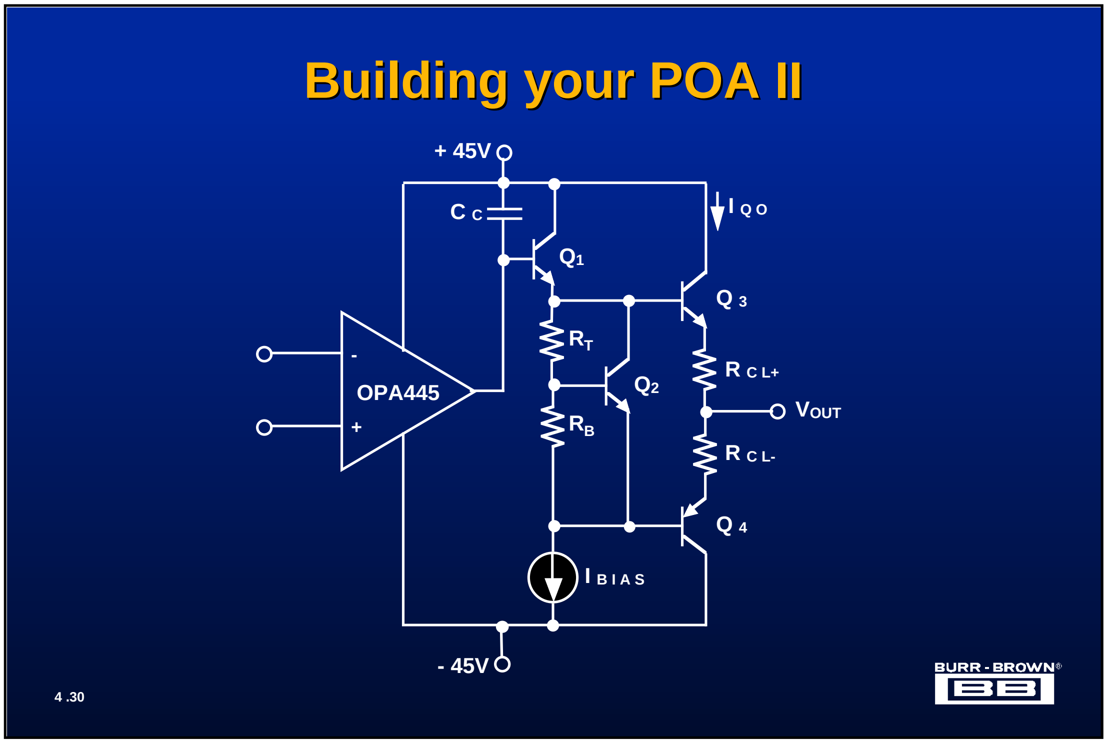
Most of the discussion about POAs so far has been about amplifiers that can supply high current and high voltage. There is a class of POAs that are not capable of delivering high currents at any supply voltage like the OPA445. This amplifier is capable of sustaining high power supply voltages up to ±45V. Using the scheme shown above it is possible to get 1 amp out of this op amp which by itself is only capable of 26mA. This amplifier circuit is only good for applications where low distortion is not a concern since the output stage is not designed for low distortion.

Resistors R_F and R_S set the DC gain of the circuit and C_F attenuates the gain at high frequency. Resistors R_2 provide current limit for the transistors Q_1 and Q_2. The resistor R_1 provides current limit for the amplifier and allows the amplifier to drive the load when the output from this circuit is between 0.7V and -0.7V.

This is the source of the distortion mentioned before. The transistors provide output to the load only when the output is above or below one diode drop from ground. As the output is transitioning from positive to negative, the load is supplied from Q_1 to the OPA445 and finally to Q_2. Hence this circuit has inherent cross-over distortion.

The output impedance of this amplifier is also dependent on where the output is with respect to ground. When the OPA445 is driving ±0.7V, the output impedance is rather high, 100Ω. When Q_1 or Q_2 is in conduction the output impedance will drop and depending on the actual devices used. The stability of this circuit is best analyzed using 100Ω as the output impedance.

Most of the power dissipation of this circuit is in the power transistors Q_1 and Q_2. Their θ_{JA} and θ_{JC} thermal resistances will govern the heat sink selection for the system. If the output of this circuit will be required to spend a lot of time around ground with the OPA445 in conduction then its power dissipation should be closely monitored.



Solving the cross-over distortion problem of the previous circuit can be done with the addition of a class A-B output stage to the OPA445.

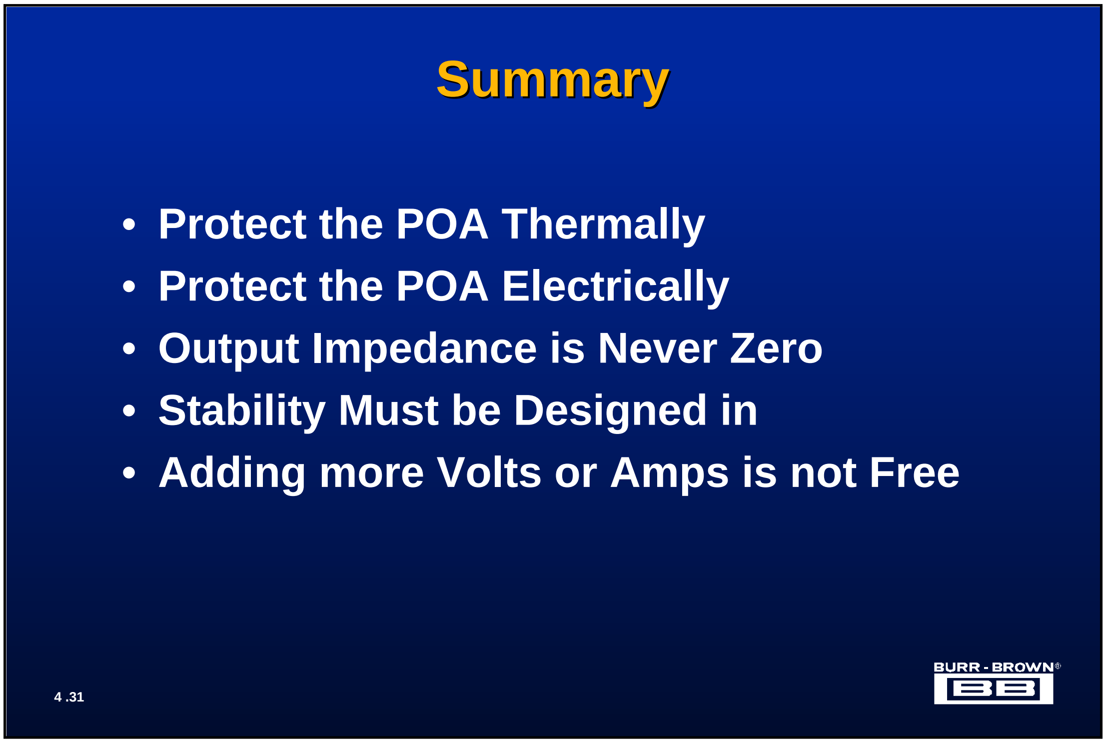
Transistors Q_3 and Q_4 are power devices that will always supply current to the load. Transistor Q_2, R_T and R_B form the V_{BE} multiplier stage that establishes the bias current I_{QO} in the output stage. The current source $I_{BIAS,}$ biases the V_{BE} multiplier stage. Q_1 is used to couple the output of the op amp to to the output stage and thus off loads the OPA445. Finally C_C can be added if necessary to roll of the high frequency gain with frequency.

The ratio of the multiplied V_{BE} voltage of Q_2 to the V_{BE} voltages of Q_3 and Q_4 establishes the bias current I_{QO}. If for instance the output devices are Darlington type, at least four diode drops must be placed between the collector and emitter of Q_2. Normally the current I_{QO} is selected to be in the 2-4mA region.

A word of caution about the ratio of the currents I_{QO} and I_{BIAS} is warranted. The ratio of these two currents, as well as the types of transistors used, govern the temperature drift of the output stage bias current. There is no simple way to simulate or design this ratio, but normally the current, I_{BIAS}, is 4 to 10 times less than I_{QO} for output stages that do not drift appreciably with temperature. Also transistor Q_2 needs to be thermally coupled to the output devices so that its temperature closely matches the power devices. In addition, the current source I_{BIAS} should be designed not to drift with temperature.

Finally, the transistors Q_1,Q_3,Q_4, the capacitor C_C, and the current source I_{BIAS} must be designed to withstand the full supply voltage $+V_{CC}$-($-V_{CC}$), of 90V in the above example.

As with the previous circuit, the emitter resistors are used to limit the maximum output current.



Power Operational Amplifiers represent the best choice for any op amp application that must drive a low impedance load. The POA represents a significant cost investment and this investment should be protected.

Not every POA application calls for a heatsink but the calculations should always be done to verify this. Just because the amplifier is in a TO-3 package this does not guarantee that it will never get too hot.

Modern POAs often have built-in protection devices that protect against over current and over temperature conditions. It is wise not to count on these features to protect a load. If these fault conditions are occurring on a regular basis, the design should be revisited.

Stability should always be considered when using a POA. There are very few POA applications that drive purely resistive loads and these are the only loads that do not affect the Open-Loop gain characteristics of an op amp.

By following the guidelines in this section most of the common Power Operational application problems can be avoided.