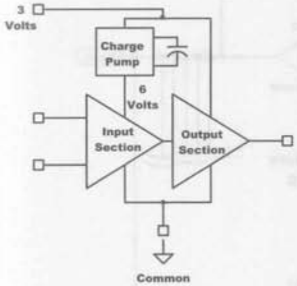
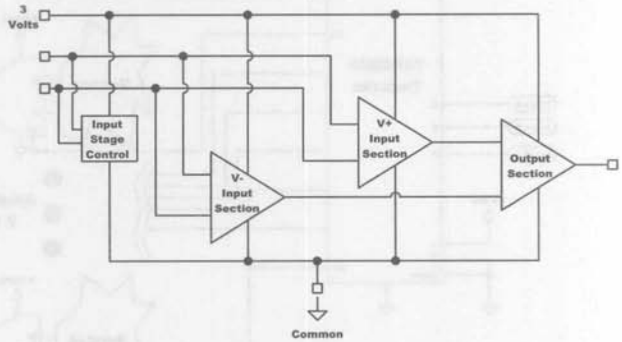
Rail-to-Rail Input Architecture

- **Charge Pump.**
- **Dual input.**

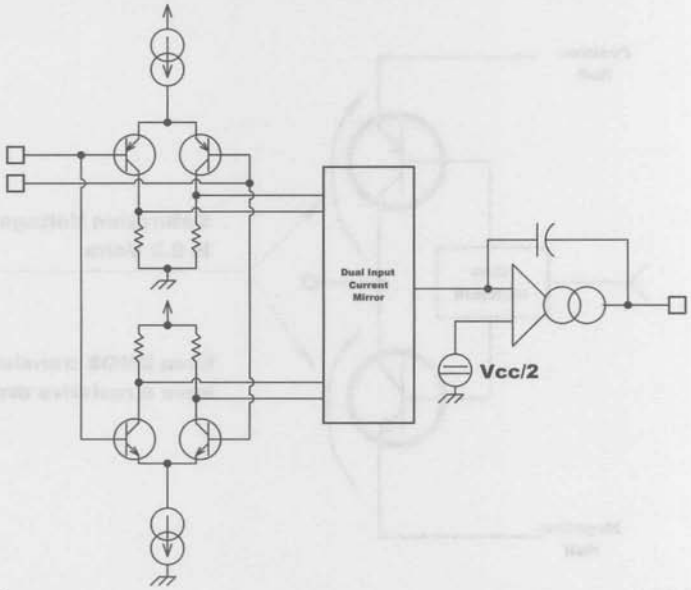




Low voltage amplifiers are often made with rail-to-rail input stages. These stages allow the inputs to work as long as they are kept within the supply rails. There are two fundamental ways to achieve rail-to-rail inputs in an amplifier. The first is to add an internal charge-pump circuit to the part such as shown in the left figure. The currents are low enough on the first stage that the charge pump capacitor can be internal. The charge pump doubles the supply voltage. This allows the use of a conventional PNP input stage like the ubiquitous LM324 uses. This stage is always good to the bottom rail. By powering it from split supply voltage the PNP bases can also be brought to the top rail. The disadvantage to this type of rail-to-rail architecture is that the switching noise of the charge pump may appear at the output of the part. The switching inside the charge pump also consumes power that will increase the supply current.

The second type of rail-to-rail input stage uses a dual input stage. One of the stages can work down to the bottom rail (the PNP stage) and one can work to the top rail (the NPN stage). There needs to be a control stage that smoothly switches the stages as the signal gets close the rail. In general the PNP stage is used for input voltages close to the bottom rail all the way up to about a volt below the top rail. The control section transitions the active input to the NPN stage so the input signals can go to the top rail. The inputs can often go a little beyond the rail, to almost a diode-drop. This means the inputs of a rail-to-rail input stage with this architecture can go from a half-volt below the bottom rail to a half volt above the top rail. The reason the transition is not at the mid-point between the rails is because the stages do have different offsets and other parameters and many operational amplifiers are used with small signals right at half-supply. By having the transition between the stages be a volt below the top rail, the part has consistent parametrics around mid-supply.

Rail-to-Rail...Input Stage



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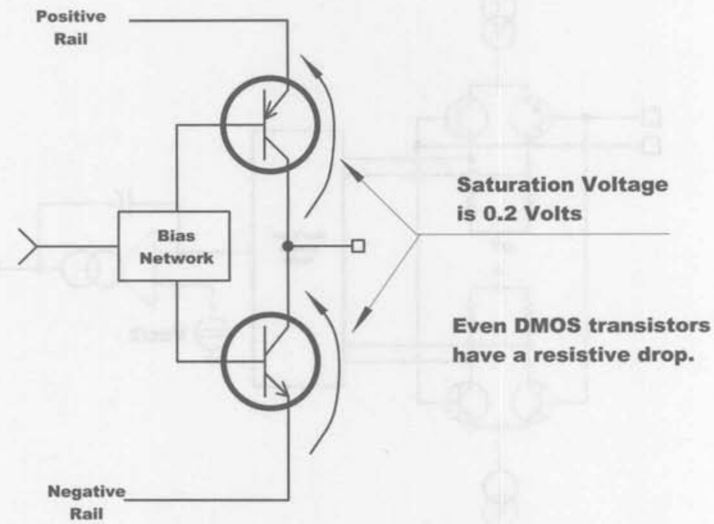
This is a detailed view of a representative rail-to-rail input stage of the dual input type. One can see that one stage uses a pair of differential PNP transistors and the other uses differential NPN transistors. It is important to note that this type of amplifier has two different sets of input parameters depending on which differential pair is active. As explained earlier, the usual setup is for the PNP pair to do the work until the common-mode voltage gets to about 1 volt below the upper supply rail. Then control is passed to the NPN stage, which operates the rest of the way to the upper rail. Since there are two different differential pairs it should be obvious that there will be two different offset voltages for the amplifier, depending on the common mode value of the input pins. Small signal bandwidth and other AC parameters are also different for the two. If the amplifier is used to buffer an input to an A-to-D converter one must be aware of the offset error change as the part transitions between input stages.

Rail-to-Rail...Output Stage



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The Art of Analog 10

Conventional output stages have a voltage-follower totem pole output, with an NPN transistor on top and a PNP on the bottom. The problem with this is that even if the internal circuits in the amplifier could bring the bases of these output transistors to the supply rail, the V_{BE} diode drop from the base to the output means that the output can never be driven closer then 0.6 volts to either rail. By flipping the transistors around, as Bob Widlar did in the LM10 in 1978, the base drive problem goes away. The bias network becomes far more complicated but that is inside the part and National's problem, not yours. If you remember your transistor physics you may know that the saturation voltage (the maximum "on" condition) of a transistor is about 0.2 volts. This means that a rail-to-rail output still can never really reach the rails. It can get even closer then 0.2 volts when using DMOS FET transistors, since they are resistive in the on state, but even then, as soon as you draw current out of the part, the a voltage drop will be created that pulls the output away from the rail. A special problem should be noted at this juncture. If the rail-to-rail input is actually at either rail and the part is configured as a voltage follower, the output will never be able to reach the rail.. This means that the feedback loop stops working and the amplifier does everything it can to try and bring the output even closer to the rail. "Doing everything it can" means that the amplifier will start shoveling base current drive into the associated output transistor. Most amplifiers are designed with clamp circuits around this base drive so that base current does not become excessive but you can see from the diagram that this base current is not delivered to the load like with a voltage follower stage. It is sourced or sunk into the respective rail. One should be aware that when a part is driven so hard that the loop can't close, the supply current will go up until that base-clamp circuits kicks in. This might explain why your micro-amp class amplifier is sucking up a few milliamperes when the output bangs against either rail.

Rail-to-Rail Outputs...Definition

So can a rail-to-rail output REALLY ever reach the rail?

Does this mean semiconductor companies are all a bunch of liars?

(Hint: Marketing people are involved.)

Definition: Rail-to-Rail outputs simply means closer than 0.6 volts (and that's all it means)

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The Art of Analog 11

Now that we've explained that rail-to-rail outputs really can't reach the rail you might wonder why they are called rail-to-rail and not close-to-the-rail amplifiers. Well, the marketing people got involved that's why. And not National's marketing people. The entire industry has adopted this nomenclature. You have to admit that "rail-to-rail" sounds a lot better then "close-to-the-rail". And the performance implied by rail-to-rail is not necessarily the same either, as we noted with the DMOS versus bipolar output transistor issue. So what does rail-to-rail mean? All that can be said generically is that "rail-to-rail" means that the outputs can get closer then 0.6 volts to the rails. Sometimes it can get a lot closer but it can never reach the rail. And remember, just because the inputs may work when they are a half-volt past the rail, there is no magic that can make the outputs get past the rail. (Unless you add a pull-up resistor! Cheater!)

Who Really Needs Rail-to-Rail Inputs?

- ***You rarely need a rail-to-rail input amplifier***

What is the fundamental application where you do?

- ***The Buffer***

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Our applications manager has a valid conjecture concerning rail-to-rail input amplifiers. His conjecture is that: "Rail-to-rail inputs are rarely needed". Think about a system with any appreciable gain, say, a gain of two. Well, the inputs will only have to go one-half the excursion of the rail-to-rail voltage in order to drive the outputs all the way to the rail. And any inverting amplifier has the input pins biased up at one place, usually mid-supply, and certainly won't need the inputs to go anywhere near either rail. Remember, there are many amplifiers that can work to either the positive or negative rail. If you wanted to sense current high-side or low-side you could use one of these with no problem. In fact there is only one application that can really take advantage of the rail-to-rail input: The non-inverting voltage follower, also known as a buffer. Here the plus pin (and the minus pin if the amplifier is working) will be swept across the entire range of supply voltages. This is most commonly used when needing a low impedance input to an A to D converter or when buffering a DAC to give an output that can swing from rail to rail.

Things That Can Go Wrong

- *Different pin-outs*
- *Power supply sequencing*
    - *Latch up*
    - *Power through ESD diode*
    - *Slow power-up or power-down*
- *Temperature issues*

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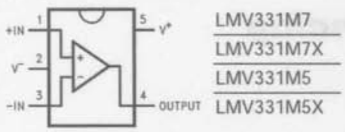
The Art of Analog 13

Every designer wants to know the "gotchas" of designing with a given parts family. As most of us have learned, analog design is full of "gotchas". Low-power, low-voltage parts have their own peculiarities. One of the most basic is that there are different pin-outs for the small packages such as SC70 and SOT23. The proliferation of micro SMD (solder-bump) packages will only make this worse. Another headache is the sequencing of the power supply, how the power is applied relative to the input signals. A final concern is temperature. We'll assume you know the issues of high temperatures, especially with theses tiny packages that can not dissipate anywhere near the power of a DIP or SO package. There are also problems that can occur at cold temperature. Stability suffers and the common-mode range or output drive can suffer. The following few slides details these problems and explains what National is doing to help you.

Watch Those Pin-Outs!

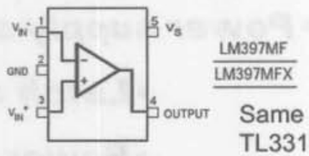
There are FOUR SC70/SOT23 pin-outs possible.

5-Pin SC70-5/SOT23-5



Top View

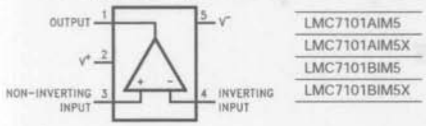
SOT23-5



Top View

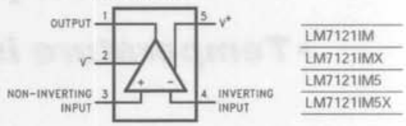
Same as TL331!

5-Pin SOT23-5



Top View

5-Pin SOT23



Top View

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Since low-power and low-voltage amplifiers are often used in handheld applications, these amplifiers are offered in very small packages. SOT23 and SC70 are two common package sizes used by many manufactures. Unlike DIPs and the SO8 package, there is no standard pin-out for the SOT23 and SC70. This can make selecting substitutions for existing applications difficult. This slide shows the 4 different pin-outs National uses. Note the two parts on the bottom of the page have seemingly identical pin-outs until you notice that the power pins are reversed. Also note that Texas Instruments has a part called the TL331 that is in a different pin-out then National's LMV331. The TI part is a comparator; the National part is an amplifier. All this means you have to be very careful when substituting parts intended for an SOT23 or SC70 package. Having the same specs is not sufficient, you have to insure the pin-outs are the same. There is an equally diverse set of pin-outs possible in the micro-SMD package. What's worse is that the footprint for these die-size packages may be different—the center-to-center distances between the solder bumps is a function of the die layout, not any formal industry standard.

Power Supply Sequencing

- **Latch-up**
- **Power delivery through ESD diode**
- **Unstable/unpredictable outputs on power-up or power-down**

Engineer with bad Supply sequencing

Engineer with good Supply Sequencing

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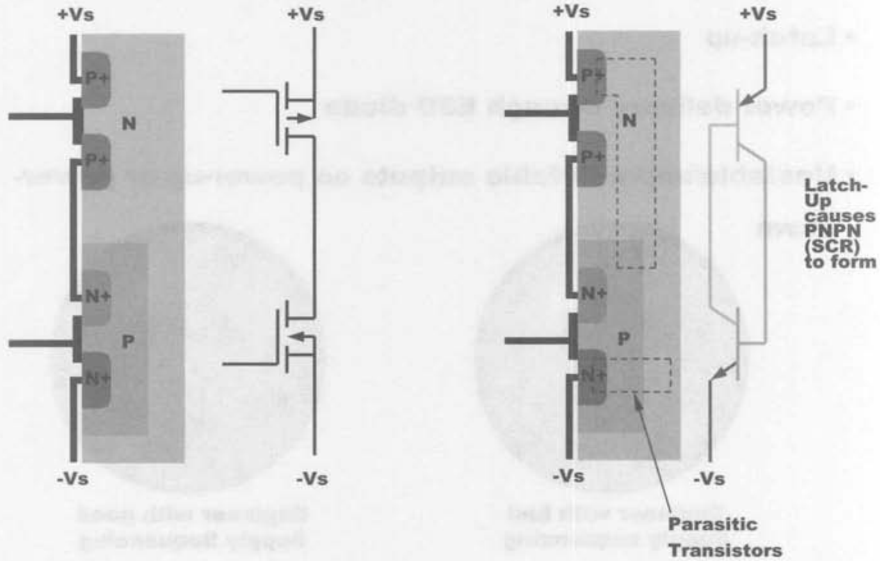
The Art of Analog 15

As power conservation becomes more and more important many electronic systems utilize power management schemes that turn off various sections of the circuitry until they are needed. This is reasserting the need to understand power supply sequencing issues. In general it is desirable to first make sure the part has a suitable ground, then apply power to the part, and then activate the input circuitry that presents voltage to the input pins. Now the ground side is usually pretty easy, most times it can just be left connected. Applying power is straightforward too, although sometimes applying the power too fast or too slow can cause problems. The real headache is often insuring that there is no voltage on the input pins until after power is applied. There are three common consequences of having energy on the inputs when power is applied to the amplifier. Latch up is primarily an issue with CMOS amplifiers. The other two, power delivery through the ESD diode and unstable outputs, can plague any type of amplifier.

Latch-Up



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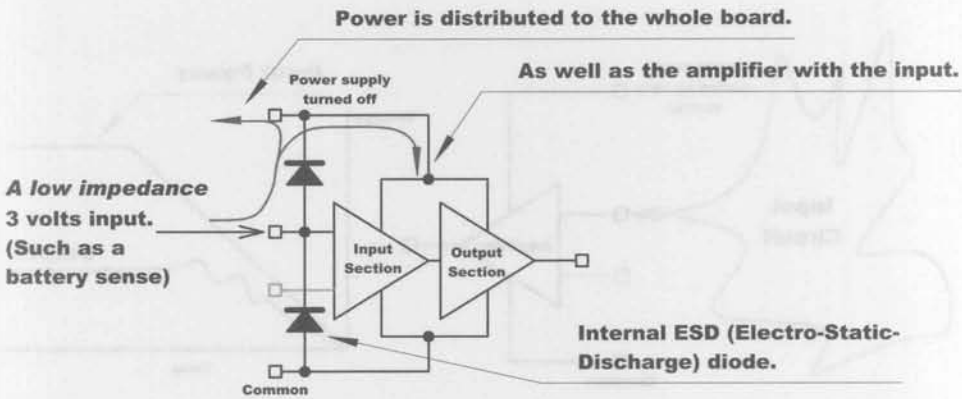
Latch up occurs when the P-N junctions between transistors and the die substrate they are laid out on create a parasitic SCR device. As you may remember, SCRs are four layer (PNPN) devices that once triggered, stay on until power is removed. You can see from the diagram of the interconnected PNP and NPN transistor above that once any current begins flowing in the base of either transistor the current will self generate and latch the structure "on". The current usually stops when the bond-wire melts or the part explodes. This is primarily a problem in CMOS parts. Bipolar parts rarely exhibit latch up and dielectrically isolated processes that put each transistor into their own little glass tub (such as our VIP10 process) also are impervious to latch up. If you can limit the current into the input pin you may be able to prevent latch up with CMOS parts. Try putting a high-value resistor in series with each input pin. Be sure to evaluate the circuit over temperature and supply variations as well as supply turn-on speed to insure that latch up won't occur. You can also limit the current into the power supply pin but that will not prevent the latch-up, it will only save the part from destruction. In order to get the part to work, power will have to be removed from the supply pins and the inputs and then the part turned on again.

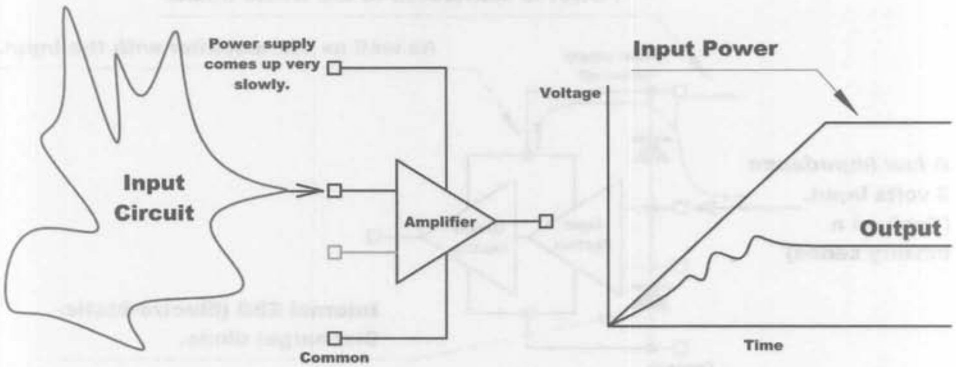
Power Delivery Through ESD Diode



National Semiconductor — *The Art of Analog* 17

This slide shows a problem that can affect any amplifier from any manufacturer. All modern amplifiers have a pair of ESD (Electro-Static Discharge) diodes on every pin. These diodes protect the delicate internal circuitry of the part from static discharges in handling and assembly. If the discharge is positive into the input pin shown, the high side diode conducts the energy to the positive rail and if the discharge is negative the low-side ESD diode is forward biased and clamps the input pin to the bottom rail. In this fashion all the pins are clamped to values no further than 0.6 volts from the supply pins. Looking at the diagram above one can see that having a low-impedance voltage on one of the input pins when power is turned off to the amplifier is sure to cause problems. The ESD diode on the input pin will conduct and the input will be connected to the supply pin by a diode drop. That is why it is low impedance inputs that cause a problem. If there were a meg-ohm resistor hooked to the pin, there would be enough to current available to forward bias the ESD diode but 3 micro-amperes of current isn't going to power up very much of anything. Now imagine that some input is directly connected to a battery. That low impedance source can deliver plenty of current. Enough current to forward bias the diode and then flow into the entire power node of the board, powering up the whole system. If enough current flows (100 milliamperes or so), the ESD diode will melt and short out, ruining the part. As with latch-up, the solution is to add series resistance to the input pins to insure that the there is not enough current available to power the system through the ESD diode. The ESD diode can take tens of milliamperes of current but it is usually more of a problem that current is being wasted. If at all possible, try to insure that everything in the circuit, power as well as inputs, are disabled by the power management scheme. If something is drawing power you can't explain, this is a good place to look first.

Unstable / Unpredictable Outputs on Power-up or Power-down



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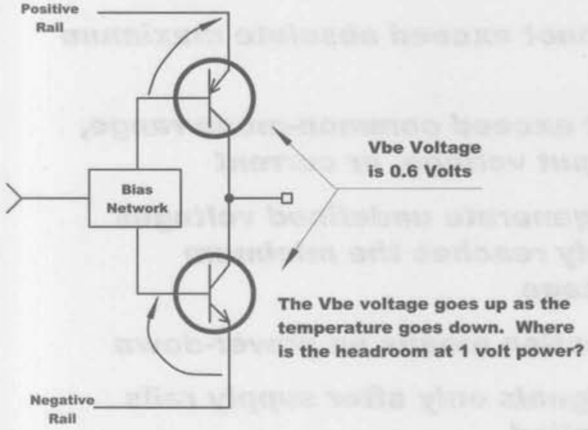
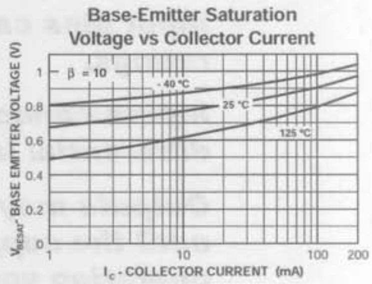
The above slide shows the problems that can occur if the power comes up too slow in a system. When amplifiers are below their specified voltage there is no guarantee what the outputs will be doing. Very often the outputs will oscillate mildly or bang into the rails until the amplifier reaches some minimal voltage. If this output is hooked to something critical, that critical function won't be stable until the power is established above the minimum need by the amplifier. You may make the best slitter-degutter in the entire cattle industry, but please insure it doesn't start slitting and degutting until it is supposed to. It should be noted here that supplies that come up too fast can sometimes cause problems. The fast rise-time may couple to the output and cause a problematic glitch. In all cases be sure the amplifier is tested in a system that uses the same power system as in production. There are many stories of disasters that occurred because the analog system was developed and tested with laboratory power supplies and then things go very wrong when they are hooked to a noisy soft-starting switcher in the real product.

Temperature Issues

- ***Watch those low temperatures***





Most system-level designers regard high temperatures as the enemy. We all know that getting a part too hot will waste power, cause performance to suffer and ultimately, melt the part. You should also realize that semiconductor physics is not kind at cold temperatures either. With regards to transistor physics, one of the disturbing things that happens is the V_{BE} voltage goes up as the temperature goes down. If the V_{BE} of the transistors is 1 volt it's going to be pretty hard to design a part to work at a power supply voltage of 1.2 volts. There can also be stability issues at cold temperatures. Oscillations can form into moderately difficult (i.e. capacitive) loads that don't show up at room temperature. There is a reason the charts section of the datasheet has charts that deal with temperature effects. Be sure to test and evaluate the system at low temperatures as well as high.

Power Supply Sequencing Summary

- ***Power supply sequencing:***

  VIP10 and Bipolar devices resist latch-up

  Input pins cannot exceed absolute maximum ratings.

  Inputs cannot exceed common-mode range, differential input voltage, or current

  Outputs may generate undefined voltages until the supply reaches the minimum operating voltage

  Shutdown function means no power-down

  Apply input signals only after supply rails have been applied

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The Art of Analog 20

Most of you know National's web site sets the standard for the entire industry. Our manufacture of LAN chips spurred our early adoption of intranets and it only followed that our internet presence would be world-class. When sifting through product data the National web site can help you call up the information such as pin-outs and package options in a speedy and accurate way. Power supply sequencing issues can be ameliorated by our VIP10 process as well as our other bipolar processes. You can utilize our parts having the shutdown function to allow power to be present at the amplifier to minimize latch-up and ESD diode power delivery problems. We specify our low-voltage parts at several voltages that can indicate the stability of the output as the power supply comes up. We specify most of our parts at –40 degrees C which can assure you of the part's functionality at severe low temperatures.