# Temperature Measurement

Pressures and temperatures play important roles in tracking performance of flight systems. In fluid dynamics, temperature and pressure are interdependent - as fuel and air are compressed in a cylinder, temperature of the mixture goes up markedly before the spark plug lights a real fire. Pressure differential across a partially closed throttle plate causes a corresponding drop in temperature; perhaps low enough to freeze any moisture present. Increased ambient temperature at the airport makes air less dense; depriving wings of lift and engines of power.

Temperature has a profound effect on many materials. The strength of aluminum alloys drop markedly at rather ordinary temperatures of 450°F. At temperatures of -60°F, some alloys that are normally quit durable become brittle and will break like glass. Oils that lubricate nicely at 200°F lose necessary qualities at 300°F. Wear rate of rings against cylinder walls goes up rapidly if head temperatures exceed 500°F. Materials physically expand as their temperatures rise - rates of expansion are a function of the material. So when different materials are used in contact with each other, their mode of attachment and quality of fit become issues affected by temperature. Temperature cycles alone may contribute as much working stress to aluminum parts as do mechanical loads. Temperature cycles may cause accelerated, sometimes mysterious failure of an otherwise lightly loaded part.

## WHAT IS "TEMPERATURE?"

Temperature is easily measured and we probably use or at least hear the word several times a day. But what are we measuring and what do the numbers mean? Is a cylinder head at 415°F 4.15 times warmer than air at 100°F? We know a thermometer attached to a piece of aluminum over a burner on the stove will show an increase in temperature as burning gas heats the metal. But if a fuel/air mixture in a cylinder gets hotter just because it has been compressed, what causes the temperature rise? Yeah, I know. Some of you just want a couple of instruments on the panel to deal with a few engine parameters and get on with it. Feel free to skip on ahead folks. But if you will indulge me a few pages, we just might change some ways you think about a machine to which you entrust your body!

Temperatures we discuss every day are stated in degrees Fahrenheit or degrees Celsius. There are other temperature measurement systems with names like Rankin and Kelvin. Every temperature measurement system must have a definition to make it understandable to any who would use the system. For example, the Celsius temperature scale is based upon the freezing and boiling points of water: water was said to freeze at 0°C and boil at 100°C. Converting these two temperatures to their Fahrenheit equivalents gives us water freezing at 32°F and boiling at 212°F. Obviously, these two systems have different **offset** and **scale factor**. The freezing point to boiling point spread in the Fahrenheit system is 180°F; in the Celsius system it is 100°C. Further, we know that "zero degrees" in either system is not as "cold" as it can get . . . both systems permit one to speak of "degrees below zero."

Indeed, we could create our own system of measurement. Let's see . . . I propose the Phramesh system where 0°P is the temperature at which 95% of all squirrels tails fracture in a 40 knot breeze; the upper calibration point will be the melting point of a Hershey bar (with almonds). Now, for scale, how about one gross of degrees? 0°P to 144°P . . . okay. In the Phramesh system, I suspect water would freeze at about 60°P and boil at 300°P. Anyone interested in instruments calibrated in °P? Unlike volts, amps and ohms that are pretty much standard with around world, temperatures, lengths and volumes can be and have been described by many users over the years with resulting differences in offset and scale. However defined, all temperature measurement systems describe the same physical phenomenon.

## MEASUREMENT SYSTEMS COMPARED . . .

Figure 14-1 illustrates four commonly used temperature measurement systems. Couldn't come up with enough squirrels for calibration so we'll set the Phramesh system aside for another time. Degrees Rankin and Fahrenheit

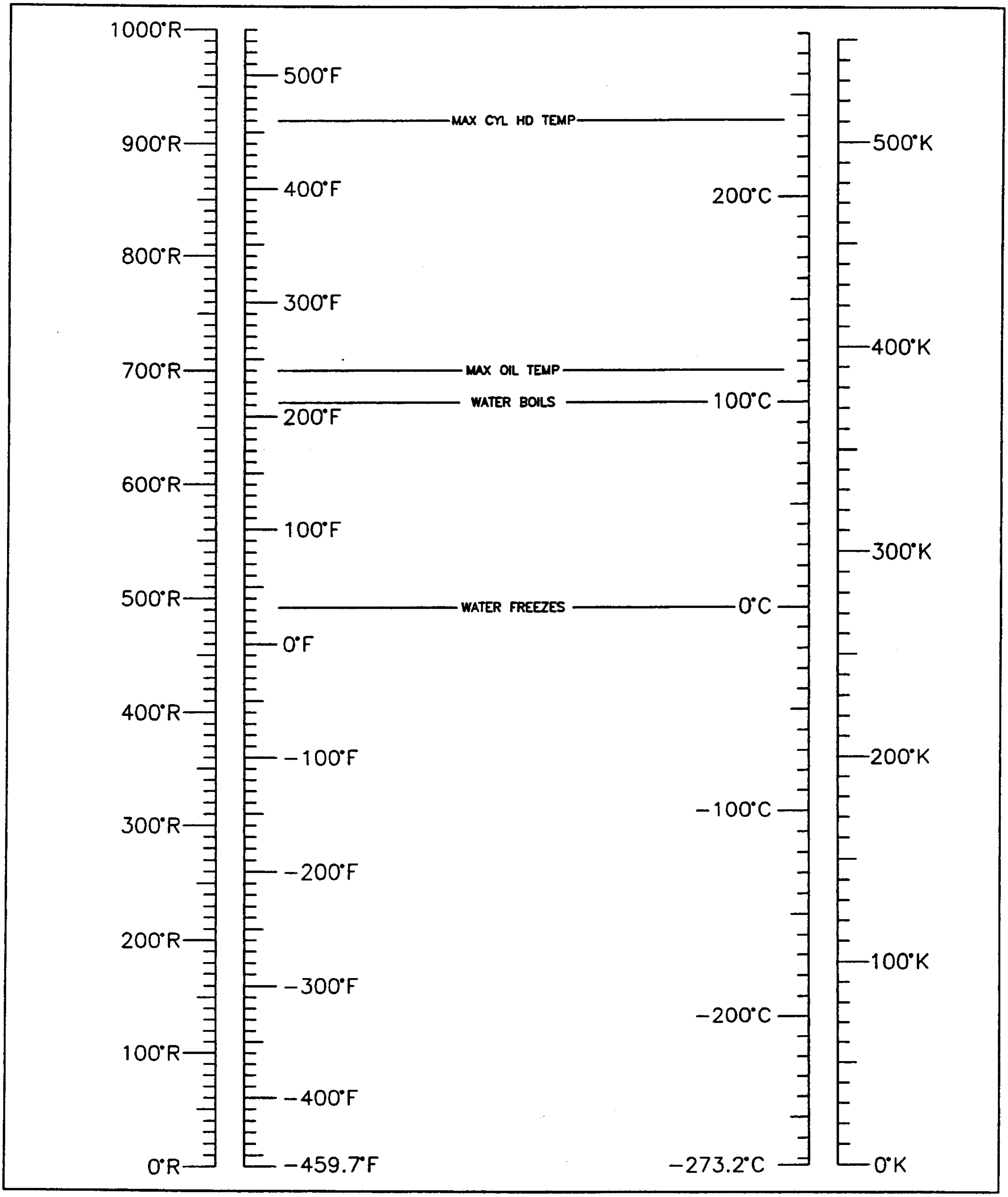


Figure 14-1. A Graphical Comparison of Four Temperature Measurement Systems.

are on the left; degrees Celsius and Kelvin are on the right. Note that °F and °R are the same size, they just start counting from a different point. They may be said to have the same **scale factor** but one is **offset** from the other by 459.7 degrees. A similar situation is illustrated on the right side. A °C and °K are also the same size; their scales are simply offset by 273.2. How cold can we go? Note that both Kelvin and Rankin systems illustrated in Figure 14-1 do not go below zero. That's because 0°K is as cold as you can go . . . **absolute zero.** Is there an upper bound on temperatures? Don't know. There are objects in the universe with densities so great that light and other forms of radiation cannot escape their gravitational attractions. You can bet that if an upper bound on temperatures exists, it's probably there. But let's talk about the lower bound. -459.7°F seems quite cold for a walk in the park but it's still a rather ordinary temperature in the laboratory. Scientists have achieved temperatures within a few tenths of a degree of absolute zero; the very low temperatures are where super-conductivity was first discovered. Figure 14-1 also depicts a few temperatures for things on and around airplanes.

Absolute zero is where all molecular motion ceases. Motion? Yes, in spite of our mortal perceptions of solidness or rigidity, molecules in a piece of steel or aluminum have some motion. The degree of motion describes its temperature. Adding heat energy to an object causes its molecules to become more agitated and raises its temperature. A temperature we perceive by touch would be described as warm or cold depending on its absolute temperature relative to our own; a block of aluminum at 40°F might feel rather "warm" if your skin temperature were down around 20°F! So, for the purposes of scientific studies, most temperatures are described on absolute scales like Kelvin or Rankin. On these scales there is no "cold", just variable degrees of "warm." Recall that I asked a question earlier if an object at 415°F was 4.15 times hotter than an object at 100°F? Referring to Figure 14-1, we may deduce: No, it is only 1.56 times hotter. Kelvin and Rankin scales are based at absolute zero. Temperatures on these scales are proportional to the **absolute** quantity of heat energy born by the object. To calculate the answer to my question:

(1) 415°F = 874.7°R
(2) 100°F = 574.7°R.
(3) 874.7 / 574.7 = 1.56.

Of course, one may repeat the exercise with °K and get the same answer.
Now the reason for absolute zero scales becomes apparent - many laws of physics are interdependent with effects of heat energy. The mathematics required to deal with these relationships are much more convenient to work with if one uses temperature systems based upon absolute zero . . . you don't need to add 459.7 or 273.2 to every temperature before its real effects can be quantified. So much for the physics lesson . . . let's get to the mechanics of temperature measurement. Indeed, some very common temperature measurement systems are purely mechanical. In spite of the very electric nature of this book, I would be remiss if mechanical temperature measurement techniques were not discussed also.

Unlike meters, feet, quarts and liters, temperature is not something that can be measured directly. Like volts and amps, temperature is described and measured by quantifying external effects that can be measured. For example, a voltmeter is really displaying the torque moment of a fixed and variable magnetic fields against a spring (see Chapter 7). In one breath we've described three or four areas where the calibration of a voltmeter can drift . . . and all of them may be affected in some undesirable way by temperature! Designers of precision voltmeters take great care to insure that temperature effects are eliminated or compensated for so that the instrument will be accurate at any temperature.

## MECHANICAL THERMOMETRY

One well known temperature effect can be readily observed: most materials will expand when warmed and contract when cooled. Careful accounting must be made for this phenomenon when designing closely fitted parts that operate over wide temperature ranges. Bearing fits to shafts and piston fits to cylinder walls of engines are good examples. Design tasks become still more challenging when you discover that materials do not all expand at the same rate! For example, any good physics or mechanical engineering text will tell you that iron has an expansion coefficient of .0000066 per °F while aluminum and copper have coefficients of .00001244 and .00000900 respectively. These numbers tell us that a block of aluminum that measures 1.000000" at 0°F will measure 1.000124" at 10°F, 1.001244 at 100°F, etc. Obviously, measuring very small changes in length requires a device that is NOT itself sensitive to temperature change. Note that for 100 degrees shift in temperature, a 1-inch object made from aluminum will grow by only .0012 inch. However, consider that an aluminum piston, 4" in diameter that is raised in temperature by 200°F will grow a total of .0096. If cylinder bore expansions are not carefully considered and matched as needed, I suspect a 0.009" inch growth of a piston would pretty well jam it in the bore!

Since most materials do expand as their temperatures increase, a thermometer could be devised by attaching a pointer to the end of a metallic rod . . let's make it out of copper. My machinist's handbook tells me that copper has an expansion coefficient of .00000900 per °F. Here's how temperature coefficient works: Temperature coefficient of expansion is a dimensionless number that states a ratio of measurements taken at two temperatures. Its used simply as a multiplication factor. Length change due to temperature equals total length at old temperature times expansion coefficient times difference between the two temperatures in °F. Example: A copper rod having a length of 10.000 inches at 0°F will grow to 10.018 inches in length at 200°F. 10.000 times .000009 times 200 equals .018 inches expansion. Add .018 back onto original length yields 10.018 inches. Hmmmmmm . . . now all we need to do is install a pointer and scale so that the .018" long scale can be graduated with a range of 200°F. That's pretty tiny. Even with my new bifocals on, I don't think I'd be able to read anything useful on the dial. There are ways to utilize expansion coefficient to devise a thermometer, but we need two different materials.

## BI-METAL THERMOMETRY

There is a simple experiment that you can do for a kid (or yourself) that illustrates the principals of bi-metal thermometry. Take a strip of aluminum and a strip of steel, each about 1/2" wide and 10 inches long. Fasten them together with a row of rivets or screws down the middle as shown in Figure 14-2. Clamp one end of the assembly in a vise with the aluminum side up. Apply heat with a torch or heat gun and observe that the free end moves down. If you allow the assembly to reassume room temperature, it will straighten out. If you pour ice water on it, a curl in the opposite direction can be observed.

This simple experiment illustrates a temperature measurement technology that has been with us for many years. The temperature sensing element in a BI-METAL thermometer or thermostat uses a special material wherein metals with different tempcos are intimately bonded to each other by welding or electroplating. Long strips are then coiled into more compact shapes. The bi-metal experiment previously described used 10-inch lengths; most bi-metal temperature sensors will be 3-6 inches total length, wound into a spiral shape. Figure 14-3 shows how the coil may be supported in the center and carry a mercury switch on the outside (peek inside the round heat-cool thermostats used in your home). Or, it may be fastened on the outside and used to rotate a shaft connected at its center (outdoor, big display thermometers do this). Almost any thermometer that displays with a pointer on a dial uses bi-metal technology temperature sensing. This would, of course, include the familiar outside air temperature indicators commonplace on lightplanes for years.

## VAPOR PRESSURE THERMOMETERS

One of my favorites is another purely mechanical temperature measurement tool. The technique features a simple elegance that has to appreciated by anyone who designs instrumentation systems. You've heard the term "vapor pressure" applied to blends of fuels being considered for use in airplanes. Virtually all liquids can be vaporized to a gas if heated beyond a certain temperature. Under ordinary atmospheric pressures, water will be totally boiled away at temperatures exceeding 100°C. However, we also know that water will evaporate into the atmosphere at temperatures considerably below 100°C. Of course, if one cools water below 0°C, it will freeze into a solid. What's going on in the region between 0°C and 100°C?

In several places throughout this book, we've mentioned the fact that various materials have different abilities to hang onto electrons whizzing about the outer shells of their atoms. We've stated further that temperature can have an effect on electron mobility. Liquids exhibit similar temperature effects. The effect can be quantified by measuring a phenomenon called vapor pressure. In Figure 14-4, I've illustrate a container with three ports. One port is connected to a vacuum pump, a second connected to a reservoir of water, the third to an absolute pressure measurement device (like an engine manifold pressure gauge or altimeter). First, with the valve leading to the water supply closed, we'll pump all the air out of the container (manifold pressure equals zero inches of mercury; altitude will be clear off scale). Now, let's close off the pump port and carefully open the water valve. We'll allow the container to fill only half full of water. Now, what happens to the pressure in the space above the liquid? Recall that no atmospheric gases previously existed in this space . . . we pumped them all out. Therefore, if anything exists in the volume above the liquid now, it must be water vapor. Suspicions are confirmed by the fact that our pressure gage no longer reads zero. Data tables in physics books predict how

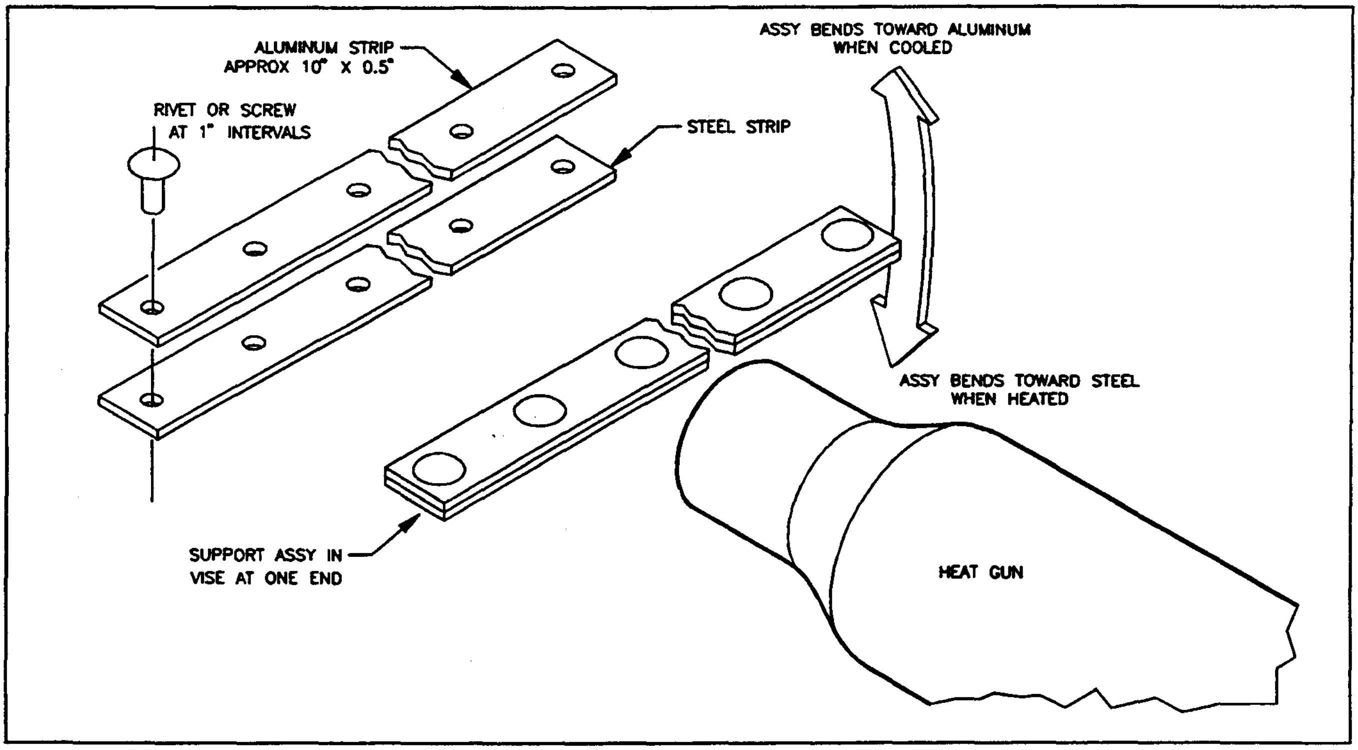


Figure 14-2. Bi-metal Thermometer Demonstration.

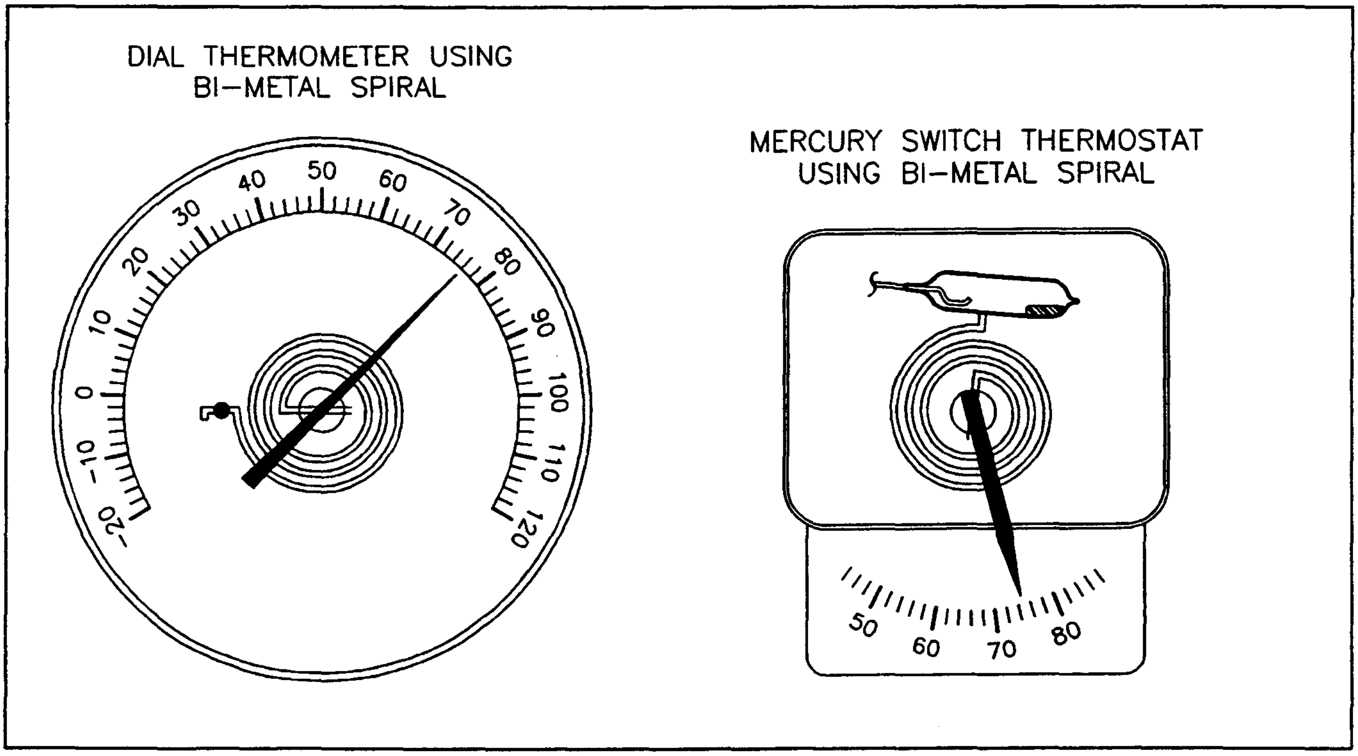


Figure 14-3. Examples of Bi-Metal Thermometers.

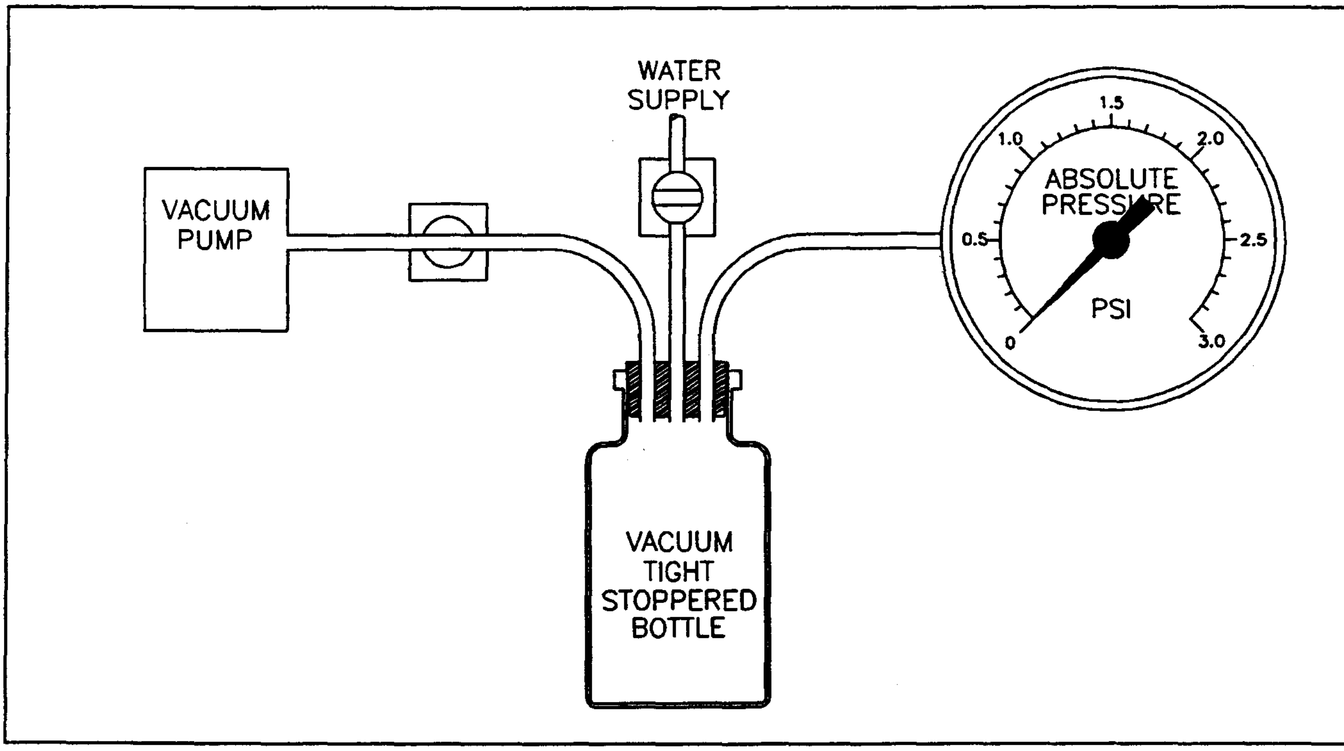


Figure 14-4. Vapor Pressure Demonstration.

how much pressure to expect depending on temperature and type of liquid. Vapor pressures for any liquid will increase with temperature. This is a practical demonstration of molecular mobility with respect to temperature. When water is introduced into a space that initially contains no other substance (absolute pressure equals zero) and allowed to fill only partly with any liquid, then molecules will begin to jump off the surface causing pressure in previously empty space to rise. As pressure continues to rise, a certain number of the liquid's molecules begin bumping into the liquid surface and becoming recaptured. As the pressure rises the rate of molecules jumping off the liquid will the equal rate of molecules being recaptured; pressure will stabilize. Pressure observed at this time will be equal to the vapor pressure for that particular liquid (in this case, water) at its present temperature.

If the water temperature is increased, the observed pressure will go up; conversely pressure will fall if the temperature is decreased. Table 14-1 illustrates vapor pressures for several common liquids. Note that while mercury does have a vapor pressure, it is small compared to other liquids. Mercury's low vapor pressure combined with a high density (13.5 times heavier than water) makes it an ideal liquid for fabrication of atmospheric barometers and pressure manometers. If we were to repeat the vapor pressure experiment using mercury instead of water, the evacuated container would have to fill completely before a rise in pressure would be observed! Note that water's vapor pressure at 100°C is 760mm of mercury or 1.0 atmosphere . . . . .

Table 14-1. Approximate Vapor Pressures of Common Materials

| Temperature °C | Vapor Pressure in mmHg | | |
|---|---|---|---|
| | Water | Mercury | Benzene |
| -50 | tiny | tiny | .0001 |
| 0 | 4.5 | .0001 | 25 |
| 50 | 93 | .01 | 300 |
| 100 | 760 | 0.4 | 900 |
| 150 | 3,570 | | |

That is what **boiling** is all about. When vapor pressure equals or exceeds ambient pressure, all the liquid molecules will evaporate (boil) away. Note that Benzene's v.p. exceeds atmospheric pressure at 100°C. Therefore, we should expect Benzene's boiling point to be well below 100°C. Further, the table doesn't show a temperature of 20°C but my physics handbook says water will have a v.p. of 17.5 mmHg at 20°C. That's about 0.3 Psi. Therefore, at room temperature we may expect our v.p. demonstrator gage to rise to about .3 PSI when the vacuum space is partially filled with water.

Another item of interest in the table is that water at 0°C has a vapor pressure of 4.5 mmHg. How can ice have a vapor pressure? *(Actually it does but very tiny.)* Did you know that water may exist in either liquid or ice phase at 0°C? As you suck BTU's from a quantity of liquid, its temperature will stop dropping when it reaches the freezing point. You need to remove an additional quantity of heat called "heat of fusion" from the mass of liquid just to convert it to ice. Once all the water is frozen, the temperature will begin to drop again. If this heat of fusion phenomenon didn't exist, ice wouldn't be worth a hoot for cooling a six-pack or making ice cream.

Now, let's take this principle and build a practical thermometer like that shown in Figure 14-5. Water could be used as the working liquid except for two things. First, water will readily absorb gases from the atmosphere making it depart from laboratory derived vapor pressure values. Second, it freezes at 0°C and boils at 100°C. Our water based thermometer would have to operate over a limited temperature range. Further, it would require a rather sensitive and less robust pressure gage. How about propane as a working liquid? The graph in Figure 14-6 illustrates vapor pressures for propane, a common bottle fuel. Consider a pressure gage with a measurement range from 0 to 300 psi plumbed with a capillary (very small bore) copper tube to a hollow metal bulb. Our bulb is fitted with a service port with which we first evacuate the system followed by introduction of a small amount of propane and finish with a permanent seal. Now, according to the vapor pressure graph in Figure 14-5, if our pressure gage reads 132 PSI, we know the liquid filled bulb is at 20°C; if the gage reads 257 psi, then the bulb must be at 50°C. Obviously, the final step in our manufacturing task is to replace the pressure gage dial plate with a new one calibrated in temperature instead of pressure.

The final feature of this instrument to be discussed is the tubing that connects bulb and gage. Obviously, this type of instrument will display a temperature of the hottest liquid present anywhere in the system. I recall a conversation between an uncle and the proprietor of a grocery store in Medicine Lodge, Kansas, about 1950. Large, sub-zero temperature freezers for homes were still some years away from commercial practicality. The store had just added new walk-in freezer space behind the store. From time to time, Grandpa gave us a side of beef to butcher so my family rented a locker in this frigid room to store family foodstuffs.

The big dial thermometer on the outside wall of the freezer was giving the store owner fits. Seems it worked for awhile and then decided to display temperatures far above what existed inside the freezing room. For whatever reason, this thermometer had been built with a rather large interconnecting tube. Instructions told installers to place the sensing bulb below the indicator. Further, slope of interconnection tubing was to be downward from indicator to sensing bulb. Instructions had not been followed; working liquid migrated into the pressure gage whereupon temperature indicated was for the wall outside the freezer, not inside. A rearrangement of the installation fixed the problem. It was about 10 years later, in high school physics that I came to understand what I had witnessed!

This becomes a problem only if the temperature being monitored is below ambient temperature for the indicator. It can be prevented by building a pressure gage with a small volume and making interconnection of the sensing bulb and gage with capillary tube. For liquid to migrate from bulb to gage, an exchange of vapor space (bubbles) and liquid must take place. If the tubing is small enough, liquid and bubbles cannot pass each other going opposite directions. Therefore, the working liquid is kept in its proper place.

The vapor pressure temperature gage was very common for displaying water and oil temperatures on engines (both gas and steam) for nearly 100 years! Obviously, a higher gage pressure range and temperature scale would have to be developed to make a practical oil or water temp gage using propane as a working liquid. However, there are literally hundreds of liquids that are suitable for building vapor pressure thermometers over a range of temperatures. You won't find a simpler, more elegant method of remote temperature measurement and display. Modern trends are toward electronic sensing methods. The sense bulb, capillary tube and gage has been traded for simplicity of installation. Wires can be cut and spliced while copper capillary tubes cannot be opened or modified in length. Further, new system designs require both traditional panel displays and digital engine data monitoring. Unless you are building a very simple airplane or restoring and old one, you are not likely to encounter this form of temperature gauging system.

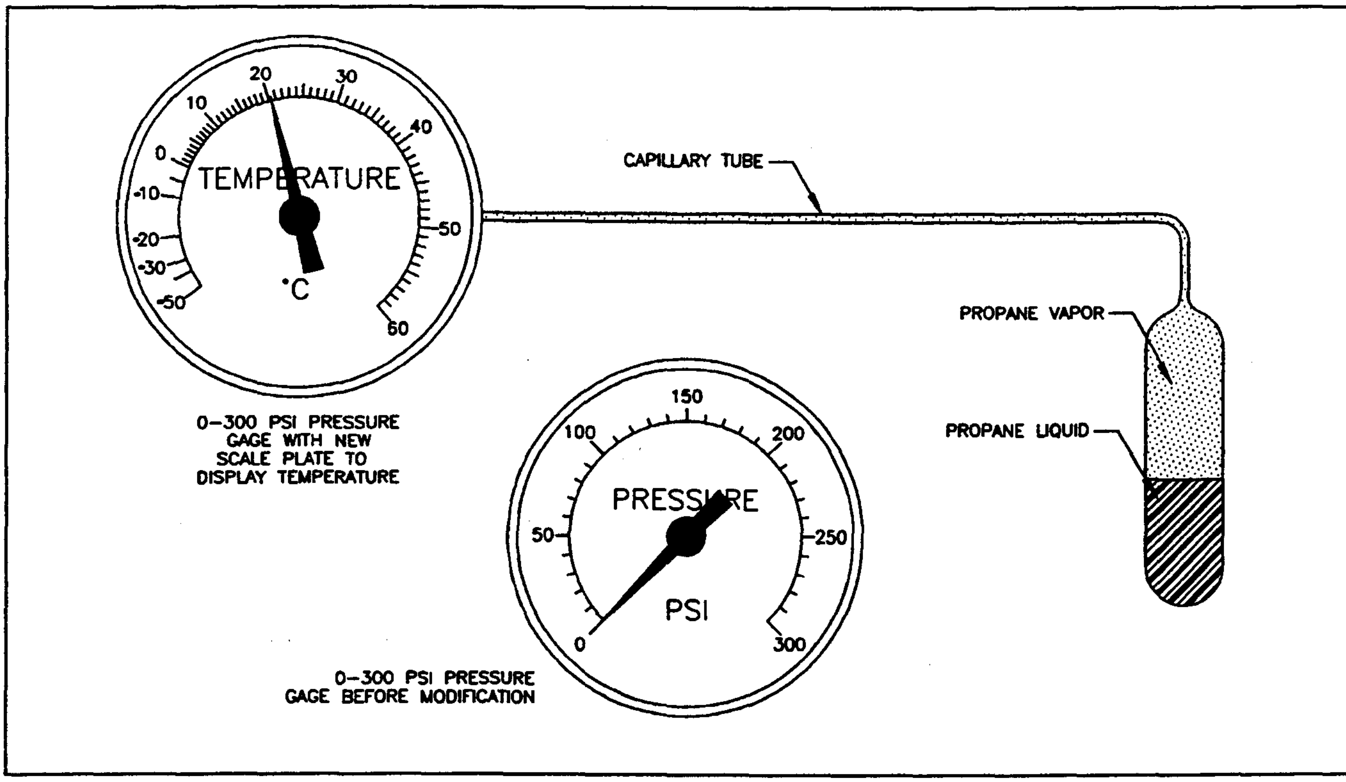


Figure 14-5. Propane Based Vapor Pressure Thermometer.

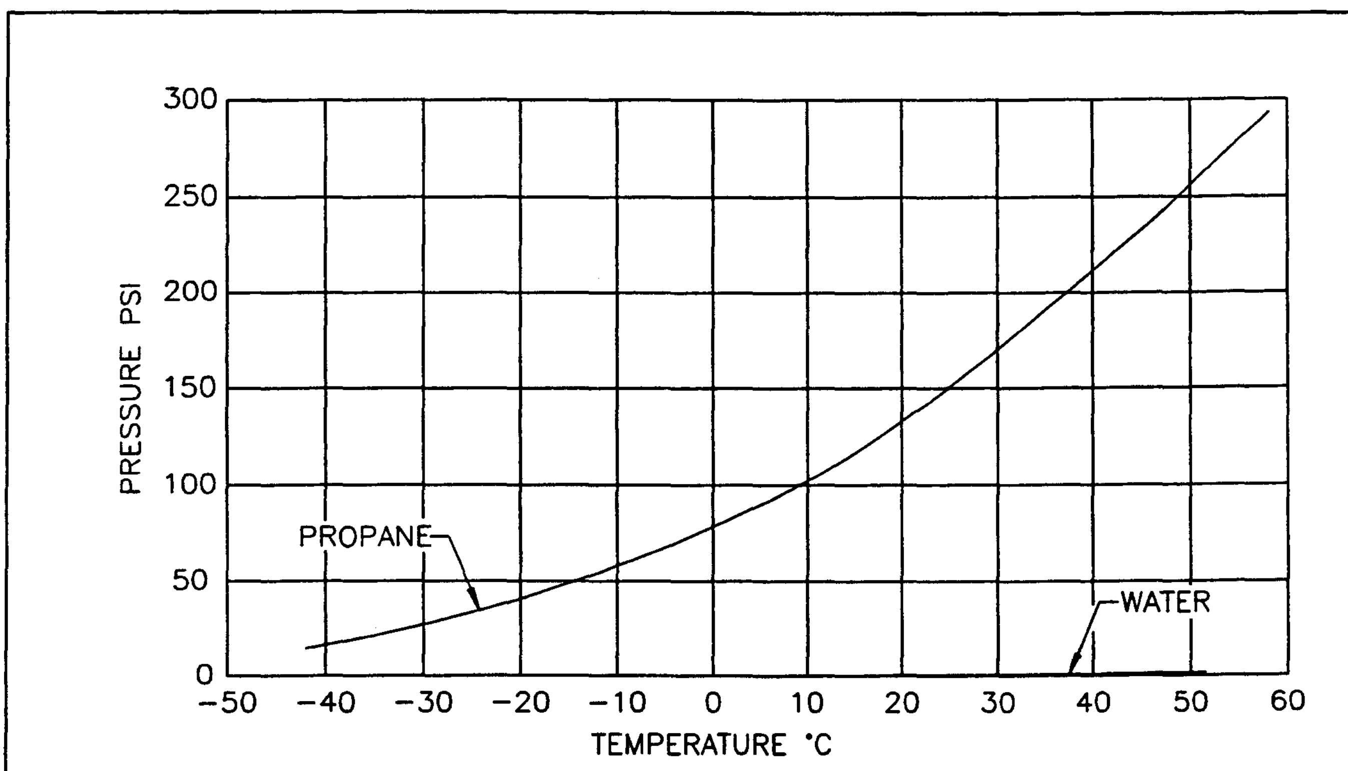


Figure 14-6. Cmparison of Vapor Pressures for Water and Propane.

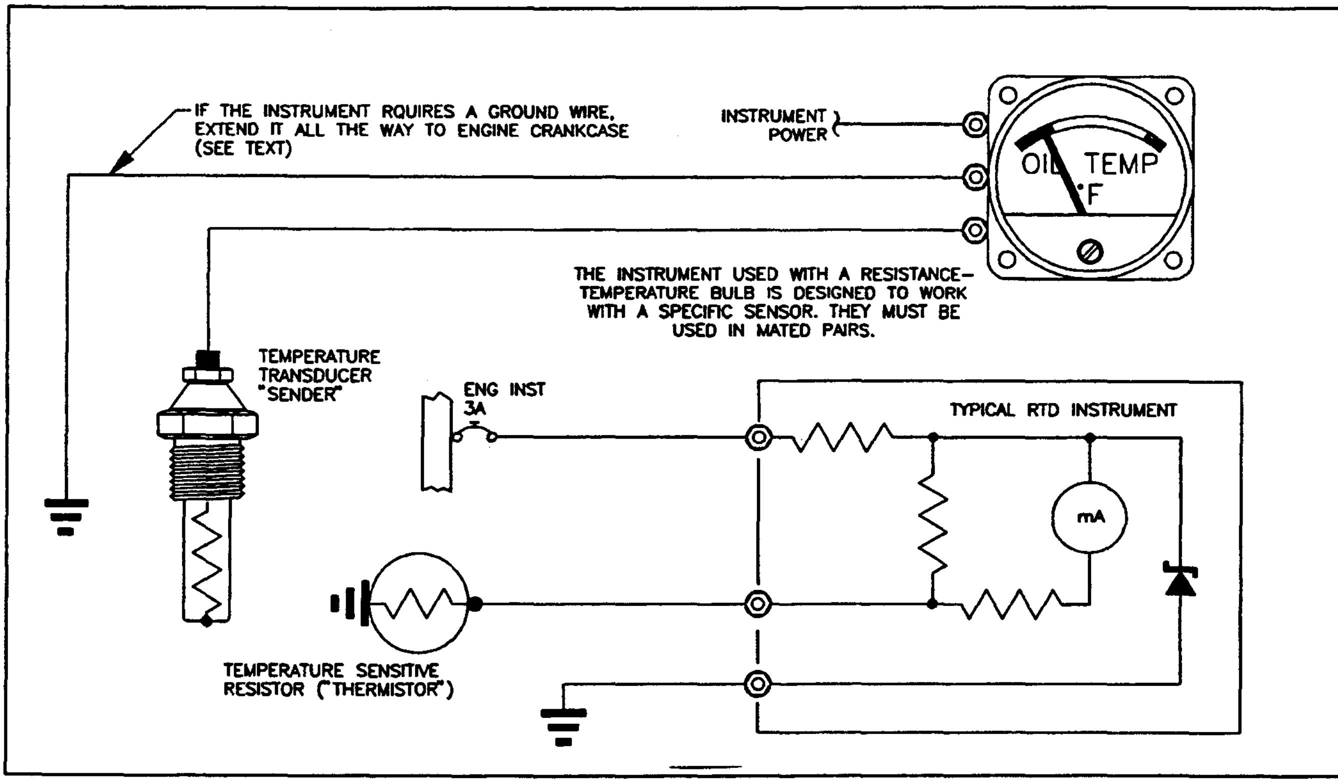


Figure 14-7. A Basic RTD Thermometer System.

## ELECTRICAL TEMPERATURE MEASUREMENT SYSTEMS

The first practical motive power engine was steam driven. Development of the machines along with engineering understanding of fluid and gas dynamics went hand-and-glove with development of pressure gages and vapor pressure thermometry. The first gasoline fueled engines used magneto ignitions and had no generator or starter so vapor pressure temperature gages were technology-of-choice for measurement and display of water and/or oil temperatures. However, as soon as rechargeable batteries, generators and starter motors took hold, systems engineers had a whole new box of "tinker toys" to select from. Refer to Chapter 7 for background on basic instruments with which to display electrical phenomenon. We'll explore one of the earliest versions of an electrically driven, temperature measurement system.

## RESISTANCE-TEMPERATURE DEVICES

There are a number of ways to measure and display temperature electrically. The oldest and one of the most common technologies utilizes a temperature dependent resistor called a thermistor. These are commonly referred to as an RTD: resistance-temperature device. Thermistors are a special class of semiconductor. The room temperature value of resistance and the percent of resistance change per degree of temperature are controlled by the mix of materials used to fabricate the device.

Figure 14-7 illustrates a simple temperature gaging system utilizing an RTD (thermistor). This system is typical of electric measurement systems used in automobiles for the past 60 years or more. The gage is nothing more than a milliammeter that reads change in current through a thermistor as its temperature changes. Both accuracy and stability of this system are interdependent upon the applied voltage, hence the need for a voltage regulator between system bus and the temperature gage. In early cars, the voltage regulator was a mechanical-thermoelectric device; modern systems use integrated circuit voltage regulators. Any stand-alone RTD thermometer you encounter may have some form of voltage regulation built into the indicator.

The primary disadvantage of this system is its rather non-linear calibration characteristics. For an indicator to be calibrated with a linear looking scale, it must be designed for equal but opposite non-linearity matching its companion transducer (sometimes called a "sender"). On the positive side, RTD thermometers are easy to install. Interconnecting wires can be any desired length and may be modified at will.

## TAMING THE VICIOUS "GROUND LOOP"

This type of thermometer is commonly used for oil, cylinder head and water temperature gaging. Transducers are almost always single wire devices which ground to the engine crankcase by way of a metallic, threaded housing. This usually means the companion instrument has a ground connection. With any single wire transducer mounted on an engine, it's a good idea to extend the instrument ground to the crankcase or firewall ground bus. This is especially important on pusher airplanes where alternator ground wires have long runs.

Alternator charging currents can produce a small (tens of millivolts) drop in the alternator ground conductor. The panel mounted instrument is displaying a temperature that is represented by a voltage drop across the transducer. If the transducer grounds at the engine end of the alternator ground and the instrument grounds at the panel end, the small drop in alternator ground lead will introduce errors in the displayed temperature reading. If more than one instrument uses single wire sensors, the instrument cluster may share a single ground. It doesn't matter that the instruments are a mix of pressure and temperature indications. Tie all the instrument grounds together at the panel and run a single, 22AWG conductor from the instruments directly to the engine crankcase.

## RTD INSTRUMENT SYSTEMS COME IN SETS

Unlike other transducer/indicator combinations which will be presented later, RTD transducers and their companion indicators are not mix-and-match devices. Each part number of indicator must be paired with a specific transducer. This is because RTDs come in a tremendous range of materials and technologies. Each instrument part number has been designed to compensate for any non-linear characteristics of the transducer. Further, an instrument may have internal voltage regulation to prevent errors due to bus voltage variation. The automotive industry has used RTD systems effectively for years and has produced hundreds of combinations of gage and transducer. Resist the urge to salvage any form of transducer/indicator combination from an old, certified airplane . . . getting spares for these devices has always been difficult, expensive and it's getting worse! If you're working with a set of 2.25", individual instruments, finding modern replacement for complete gaging systems isn't difficult. But if you're committing to a custom cluster gage and a single gage or its transducer goes belly up, you may have problems getting it fixed. Thermistors are not the only form of RTD. A common form of Mil-Spec OAT sensor uses a coil of very fine platinum wire as the sensing element. As you might suspect, this critter isn't cheap! Unless you stumble across one in a surplus store somewhere, you are not likely to encounter anything other than the relatively inexpensive thermistor type transducers.

This class of electric thermometer is rapidly disappearing from all new product designs having been replaced by newer, more designer friendly products. The quality of most RTD gages used in certified airplanes hasn't really been all that impressive in terms of absolute accuracy. However, any given transducer/instrument combination is rather repeatable. That's important - you're more interested in changes from the norm as opposed to knowing exactly any given temperature. So if you've got a set of gages in place that seem to be working, leave them in until you're forced to change the technology for whatever reason.

## THERMOCOUPLE TEMPERATURE MEASUREMENT

I've got a special place in my heart for simple, elegant solutions. The vapor pressure thermometer must surely find a home there along with **thermocouples.**

We're going to spend more time and words discussing thermocouples than any other temperature measurement method. The reason being that compared to all other measurement technologies, thermocouples are easiest to fabricate and put in place. During initial fly-off testing for your project consider the following list of temperatures to be investigated:

- Oil
- Voltage regulator
- Alternator stator winding
- Alternator diode array
- Fuel pump(s)
- Gascolator
- Vacuum pump
- Magneto housing(s)
- Cylinder heads (checks baffling)
- EGT each cylinder (checks fuel mixture distribution)
- Top radio in stack

Dimmer heatsinks
Electro-hydraulic power pack motor

Some of these items will be part of your permanent instrumentation. However, most airplanes have one or more equipment items that may be damaged or rendered inoperative by temperature extremes. Each item should be instrumented and investigated for worst case scenarios that may induce adverse temperatures under ordinary flight conditions. These include low-and-slow pattern work (touch and go landings), hot day best angle climb (work'n hard - minimum cooling), heat soak after shutdown, maximum electrical load, etc. The first few hours of flight on a new project are crucial; use mandated fly-off time to assure yourself that heat stress on critical components and systems are within acceptable limits.

## IT TAKES GOOD INFORMATION TO MAKE GOOD DECISIONS

This kind of temperature survey is routine during certification work on production airplanes; it's a simply a good idea. Technology historians have suggested that in spite of Russian ability to build bigger and stronger launch vehicles, more than one Russian rocket scientist was fearful for his future when development programs suffered from many, very big disasters. Scholars theorize that US ability to instrument prototypes and operational vehicles made analysis and correction of problems a breeze by comparison; US scientists read tens of thousands of data points on a space flight vehicle while the Russians recorded very few.

In a later chapter, we'll discuss failure mode effects analysis (FMEA) as a tool for enhancing reliability of a flight system. Comfortable outcome of an FMEA assumes that parts are going to fail because they've reached end-of-life (no matter how short). When parts fail because they are not properly installed or operated, the benefits of an FMEA are severely compromised. So when in doubt, **measure** it!

Thermocouples make it relatively easy to do. Thermocouple wire is sold in spools of various sizes and types of insulation. Thermocouples are easy to fabricate and attach to equipment items you wish to monitor. A single readout instrument may be switched to an array of thermocouples; surveys can be conducted with a minimum of expense and cockpit clutter from test hardware. Thermocouples are the ultimate engineering and flight test temperature research tool. I'd bet that US space flight vehicles have more thermocouples on board than any other sensor.

## THE SEEBECK EFFECT - ELECTRONS ON THE LOOSE:

As we've observed in our daily lives and as I've discussed here, temperature affects materials in a variety of ways. We know that all materials are made of atoms; atoms have electrons whizzing around their nucleus and atoms consist mostly of empty space. It is less commonly known that the atoms within any solid are constantly exchanging electrons to a certain degree depending on the makeup of the material *and its temperature.* Some materials are less capable of hanging onto their rambunctious electrons than others. So, if you put differing materials in contact with each other and if the materials are otherwise reasonable conductors of electricity (metal) then a voltage difference will appear between the two conductors. The material with the stronger grip on its electrons will steal a few from the other material and acquire a more negative potential (voltage) with respect to the other conductor. The amplitude of the potential (voltage) depends both on the type of metals used and upon the temperature which exists at the junction of the dissimilar metals. We've already discussed the concept of absolute zero, a place were all molecular motion stops. It's no leap of faith to understand that the voltage generated by a thermocouple goes to zero volts at $0^{o}K$. Okay! All we gotta do is hook a voltmeter to the two conductors and convert the resulting reading to temperature.

One may fabricate a thermocouple from any two, ordinary metals. This concept is illustrated in Figure 14-8 where I show an iron wire twisted together with a copper wire. There's a just a couple of very tiny problems: First, the voltage generated between the two materials is small. A typical thermocouple generates a voltage between 20 and 60 **microvolts** per $^{o}C$. So even though we've heated the copper/iron junction very strongly with an open flame, the generated voltage is small - a few tens of millivolts. Until a few years ago, dealing with the tiny voltages was a real challenge. I was first introduced to thermocouple measurement techniques in the early '60s. Back then, tiny thermocouple voltages were measured with a cumbersome device called a millivolt potentiometer. It was housed in a box about 10 inches on a side. Voltage measurements were made by rotating a range switch and a large dial until a needle on a meter was centered. Each measurement could take 10-15 seconds. Measured voltages were recorded by hand onto a datasheet and later converted to temperature measurements by referring to charts. It was easy to make

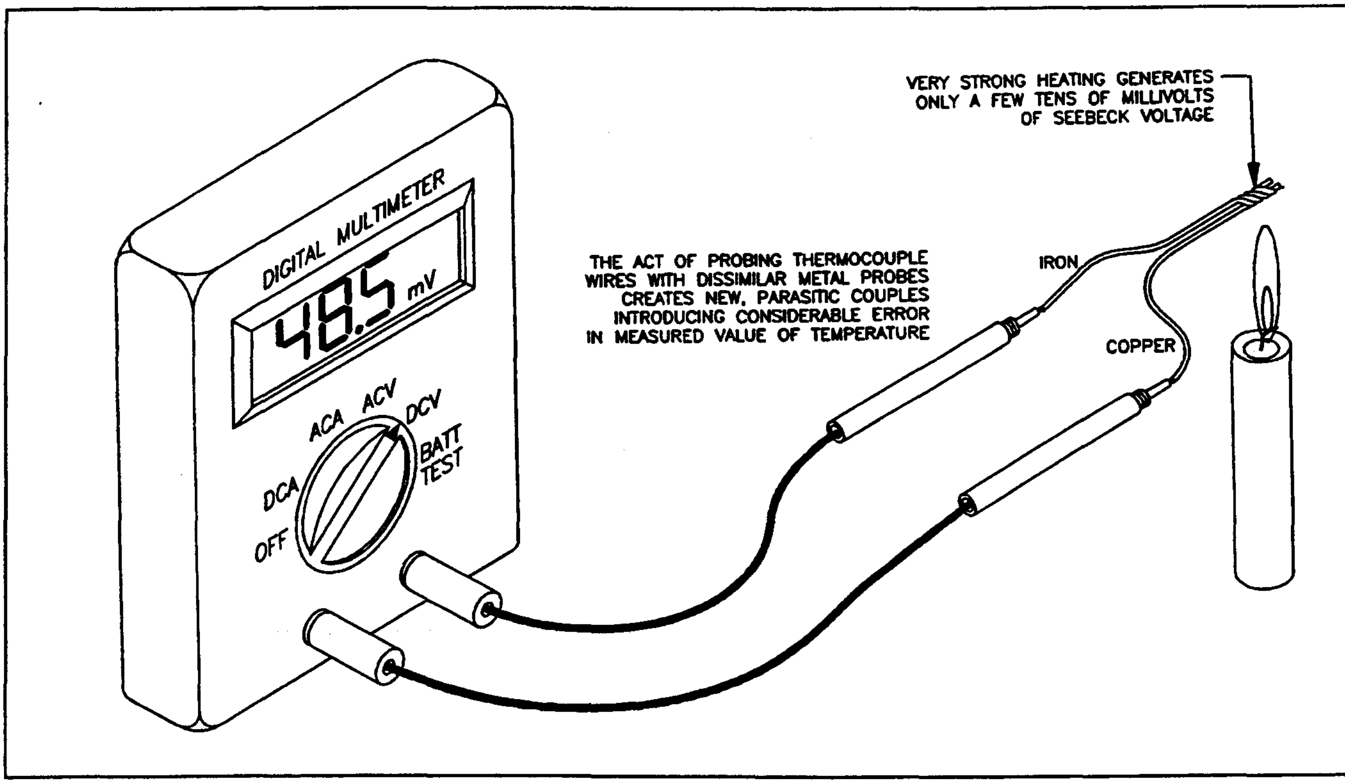


Figure 14-8. Basic Thermocouple.

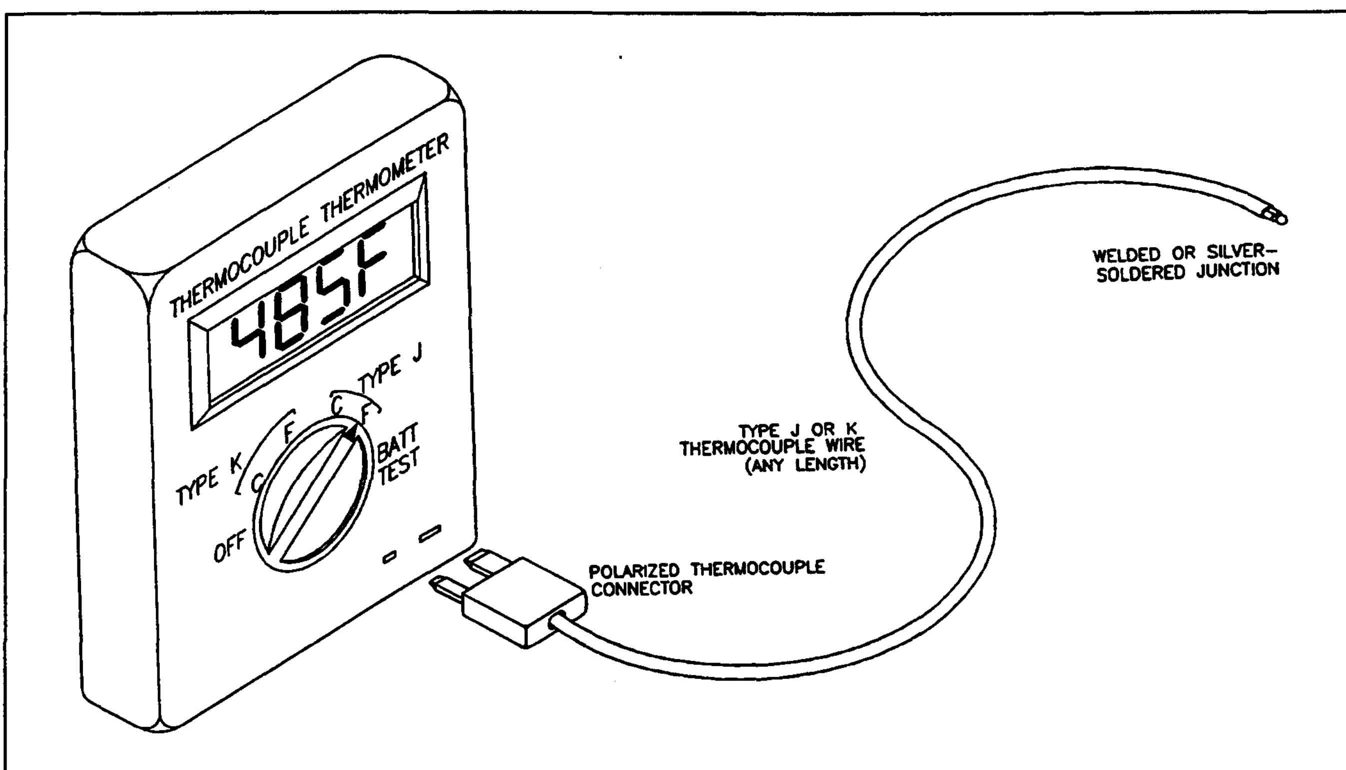


Figure 14-9. An Off-the-Shelf Digital Thermocouple Thermometer.

mistake in taking a reading especially when taking a lot of measurements in flight.

The second problem with thermocouples arises from installation logistics. Recall that **any two dissimilar metals will form a thermocouple.** In the illustration of Figure 14-8, I've shown plated brass probes making connection to the iron and copper thermocouple wires. These points of contact create two new, parasitic thermocouple junctions. Further, as you advance up the voltmeter lead wires, into and through the instrument's internal wiring, more parasitic thermocouples may be found; each couple contributing or detracting from the reading of interest. Fortunately, dealing with parasitic couples is easy.

Nowadays, one may purchase direct readout thermocouple thermometers for as low as $80 (see Figure 14-9). These handy instruments have internal cold-junction or "ice-bath" compensators. They are also programmed to compensate for small non-linearities in voltage vs. temperature curves. Further, even the low cost instruments will utilize either type J or K thermocouple wire. Finally, one may choose to read either °F or °C. Some low cost, hand held instruments have two jacks to allow switching between two thermocouples. I don't recommend paying extra for a dual thermocouple device. In my experience, every time I've needed to measure more than one temperature at a time in an airplane, it was always more than two. Invariably, I have to rig a multipole thermocouple switch which I will describe later in this chapter.

Before we discuss practical applications of thermocouples let's explore their operation in more detail. Further, let's define several new terms: "type J" and "type K" wire along with "ice-bath" and "cold-junction." There are dozens of thermocouple wire types - each was developed for a specific task. The two most common thermocouple wires for aircraft instrumentation are fabricated from some pretty strange sounding stuff: iron-constantan (type J) and chromel-alumel (type K). Constantan, chromel and alumel are special alloys designed specifically for thermocouple use. Their characteristics are carefully controlled and agreed upon by international industry standards. Any spool of thermocouple wire marked type J or type K will yield consistent, predictable results according to Table 14-2. When designing a useful thermocouple one must consider Seebeck voltage (some combinations of alloys generate much higher voltages per degree than others), operating temperature (you don't want the thing to melt!) and resistance to materials in the environment to be measured (strong acids, oxidizers, caustics, etc., may dissolve the sensor). Finally, one must select an insulation suited to the operating environment.

Type K alloys are suitable for any kind of measurement on an airplane including exhaust gas temperatures. Type J has a recommended upper limit that suggests it not be used in exhaust stacks but it is fine everywhere else. As

Table 14-2. Thermocouple Voltage (mV) versus Temperature (Reference to Ice-Bath).

| Temp °C | Temp °F | Type J Wire | Type K Wire |
|---|---|---|---|
| -40 | -40 | -1.96 | -1.50 |
| -30 | -22 | -1.48 | -1.14 |
| -20 | -4 | -1.00 | -0.77 |
| -10 | 14 | -0.50 | -0.39 |
| 0 | 32 | 0.00 | 0.00 |
| 10 | 50 | 0.50 | 0.40 |
| 20 | 68 | 1.02 | 0.80 |
| 30 | 86 | 1.54 | 1.20 |
| 40 | 104 | 2.06 | 1.61 |
| 50 | 122 | 2.58 | 2.02 |
| 60 | 140 | 3.11 | 2.43 |
| 70 | 158 | 3.65 | 2.85 |
| 80 | 176 | 4.19 | 3.26 |
| 90 | 194 | 4.73 | 3.68 |
| 100 | 212 | 5.27 | 4.10 |
| 110 | 230 | 5.81 | 4.51 |
| 120 | 248 | 6.36 | 4.92 |
| 130 | 266 | 6.90 | 5.33 |
| 140 | 284 | 7.45 | 5.73 |
| 150 | 302 | 8.00 | 6.13 |
| 160 | 320 | 8.56 | 6.53 |
| 170 | 338 | 9.11 | 6.93 |
| 180 | 356 | 9.67 | 7.33 |
| 190 | 374 | 10.22 | 7.73 |
| 200 | 392 | 10.78 | 8.13 |
| 210 | 410 | 11.34 | 8.54 |
| 220 | 428 | 11.89 | 8.94 |
| 230 | 446 | 12.45 | 9.34 |
| 240 | 464 | 13.01 | 9.75 |
| 250 | 482 | 13.56 | 10.16 |
| 260 | 500 | 14.12 | 10.57 |
| 270 | 518 | 14.67 | 10.98 |
| 280 | 536 | 15.22 | 11.39 |
| 290 | 554 | 15.77 | 11.80 |
| 300 | 572 | 16.33 | 12.21 |

you can see from voltages in Table 14-2, Type J wire has a little more output for a given temperature than does Type K but for most purposes, either is satisfactory. The most universal insulation is a woven Fiberglas which is not very neat to work with but it has very good high temperature characteristics. My favorite is Kapton covered wire. It's smooth, strips nicely and has temperature characteristics that work everywhere except in the exhaust gas stream - no big deal; you need special, shielded probe for EGT work anyhow. Here's how you identify type J and K wires:

Table 14-3. Thermocouple Conductor Identification.

| Conductor | Insulate Color | Polarity | Magnetic (?) |
|---|---|---|---|
| Type J Wire: Iron/Constantan | | | |
| Iron<br>Const. | White<br>Red | Positive<br>Negative | Yes<br>No |
| Type K Wire: Chromel/Alumel | | | |
| Chromel<br>Alumel | Yellow<br>Red | Positive<br>Negative | No<br>Yes |

Spooled thermocouple wire has a unique appearance and usually conforms to marking conventions that make it easy to identify. First, any thermocouple wires you are likely to encounter are always paired. The outer jacket may be any color. Insulation over the inner conductors usually follows industry standards: For type K wire the positive conductor is made of chromel, insulated in yellow and identifiable as non-magnetic. The negative wire is made of alumel, insulated in red and will be attracted by a magnet. In type J wire, the positive conductor is made of iron, insulated in white and magnetic. The negative conductor is constantan, insulated in red and is non-magnetic. These identifying attributes are summarized in Table 14-3.

An aforementioned consideration for working with thermocouple wire is the issue of parasitic couples - all electrical circuits are fabricated from some kind of metal (conductor). There's no way to get electrons to flow from point A to point B without bringing two pieces of metal together. So, making the transition from thermocouple wire to instruments requires special attention. One of the neat things about working with thermocouple is that parasitic couples don't have to be eliminated, they just need to be accounted for. For every parasitic couple in one side of a thermocouple lead, you need one of equal potential but opposite polarity in the other lead.

In Figure 14-10, View -A-, I show two chromel-alumel thermocouples hooked in series with their alumel wires brought together. This means that the "hot" junction generates a voltage opposite in polarity to the "cold" junction. If both couples were at the same temperature, the net voltage at the instrument is zero. Now, let's place the "cold" couple in a known temperature environment, say a bath of crushed ice and water. We know that while any ice exists, the bath is 0°C. Now the voltage measured between the two couples is proportional to temperature difference between the "hot" and "cold" junctions. Further, note that our voltmeter is now connected to two constantan wires. The two parasitic couples at the voltmeter terminals now have equal but opposite effects on the voltage of interest. In other words, irrespective of their voltage, they are opposing polarities and equal to each other - they cancel each other out. Now our instrument need be concerned only the calibrated difference voltage between hot and cold junctions. Further, the hot junction's temperature will be represented by the voltages described in Table 14-2.

View -B- shows a two-junction ice bath. This setup is useful if you have a very long run between thermocouple and instrument - it's less expensive to do the long run in copper wire. In this case we may transition from any thermocouple wire into copper. Now we have two parasitic couples: one is chromel-copper, the other is alumel-copper. It turns out this system works fine when **both** transition junctions are referenced in the ice bath.

Needless-to-say, an ice bath isn't a convenient temperature reference to carry around in an airplane *(although years ago, I did it - had a special Thermos bottle with a cork that had a number of reference junction thermocouples sealed in it)*. Fortunately, electronic replacements for a reference junction are possible. There are a number of instruments flying in airplanes that appear to be no more than a meter with a thermocouple attached. Common examples include exhaust gas temperature (EGT), cylinder head temperature (CHT) and a smattering of carburetor air temperature gages. If you find one of these indicators separated from its companion thermocouple you need to know that the thermocouple is matched to the instrument. The instrument contains a special, low voltage movement along with reference-junction compensation. Low voltage movements tend to draw quite a bit of current - perhaps as much as 100 milliamps! Therefore, resistance of the companion thermo-

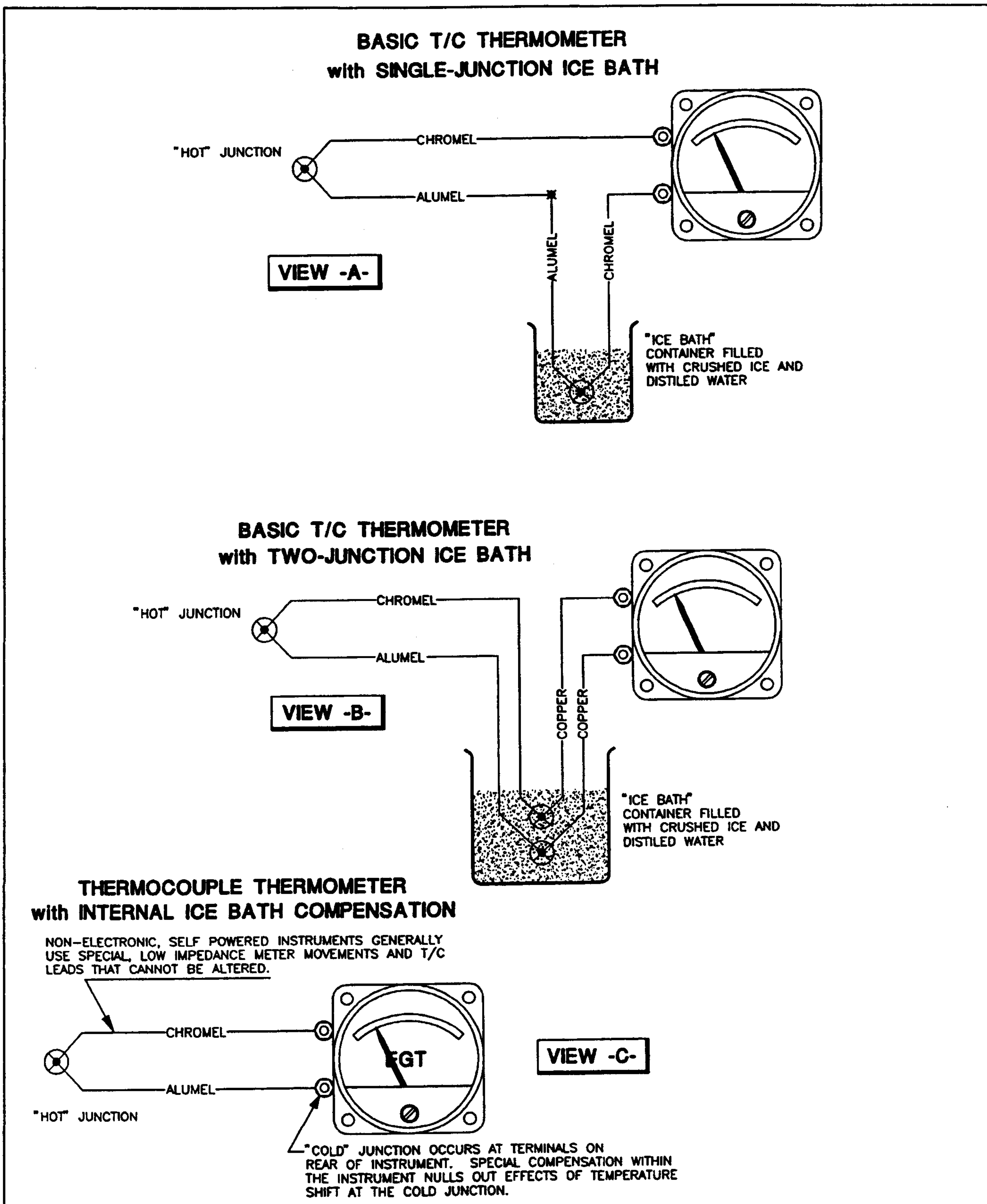


Figure 14-10. Generic T/C Thermometers and Various Reference-Junction Techniques.

couple assembly is part of the instrument's calibration. As a general rule, un-amplified instrument thermocouples cannot be shortened or extended. When Smiley Jack's Almost-Good-As-New Airplane Parts Emporium offers you such an instrument, be sure to check its calibration just be sure that the thermocouple supplied is really the one that belongs with it. Boiling water is a good calibration bath at 212°F (100°C); an ice bath is 32°F (0°C); etc. If in doubt, any instrument shop can take a quick look at it to be sure it's working properly.

Except for a few cautions, the unpowered thermocouple gage is quite attractive. It can be accurate and requires no wiring to ship's dc power. Such an instrument is illustrated in View -C-. Obviously, the reference-junction for this instrument exists right where the thermocouple wires bolt to the back of the instrument. Reference-junction compensation doesn't have to look like a 0°C ice bath. The reference-junction compensator just needs to know what the temperature is at the studs on the back of the instrument case; no problem since the compensation circuitry is right inside the case!

The basic tenets of thermocouple measurement are: (1) use two couples in series opposing so that the voltage to be measured is a function of temperature difference between the two couples and (2) design the measurement system so that all parasitic thermocouples exist in opposing pairs. With these concepts in place, we can discuss techniques for switching multiple thermocouples to a single instrument.

Let's suppose you wish to log a bunch of temperatures during your fly-off hours. Consider building your own thermocouple selector switch. Purchase a 12-position, 2-pole rotary switch from one of the catalogs listed in Appendix-A. Mount the switch on one side of an aluminum box and along with two, 13-position terminal strips. Figure 14-11 illustrates the right and wrong way to configure a thermocouple selector switch. You may use ordinary hook-up wire (22AWG aircraft wire is fine) to wire it. It is true that considerable **error** is introduced by each joint of non-thermocouple metal introduced in each leg of a thermocouple. The secret is that errors of **equal** and **opposite** amplitude are created in pairs - one on each side. By observing the second law of thermocouples, errors induced by our switch box cancel each other out.

Readers have called to ask what was wrong with their modern, digital display for CHT or EGT where they were attempting to switch a single instrument between multiple thermocouples. The first question is, "Are you using a two pole selector to switch **both** sides of the thermocouple?" There are expensive, commercial equivalents to the thermocouple selector switch just described. If you can find a used one for a reasonable price (like 30-50 dollars), buy it and donate it to your local EAA chapter. Every new airplane should be surveyed for a variety of temperatures during flyoff hours or after some kinds of major modifications to the power plant. After that, your selector switch and thermocouple readout will sit on the shelf and gather dust. It would be better if your local chapter owned a thermocouple selector switch and indicator for loan to members. That way a few pieces equipment would suffice for many projects as needed.

**CAUTION**

When setting up for multiple measurements with a selector switch, be certain the instrument you use is a **high input impedance** device that doesn't care about thermocouple resistance . . . self-powered instruments mentioned earlier are not good candidates for this task. However, any modern, digital thermocouple thermometer will be fine.

## AMPLIFIED THERMOCOUPLE THERMOMETERS

While on the topic of high impedance instruments for thermocouples, I'll call your attention to Figure 14-12. In View -A- the hot-junction and reference-junction setup is similar to Figure 14-10, View -A- except: an electronic amplifier inserted between thermocouple wires and indicator. Some interesting things happen when you add an amplifier. (1) the indicator becomes a simple, much less expensive, voltmeter and (2) the current flowing in the thermocouple wires is for all practical purposes, zero. Length of thermocouple wire is no longer critical; insertion of a selector switch to manage many thermocouples is feasible. The last inconvenience to eliminate is the requirement for an ice bath . . . .

A company called Analog Devices builds integrated circuits for thermocouple signal conditioning. A sample circuit is shown in Figure 14-12, View -B-. The AD594 integrated circuit is designed to provide amplification, cold junction compensation and linearity compensation for type J thermocouple wire, the AD595 is used with type K wire. The device outputs a voltage of 10 millivolts per °C of thermocouple temperature. These circuits

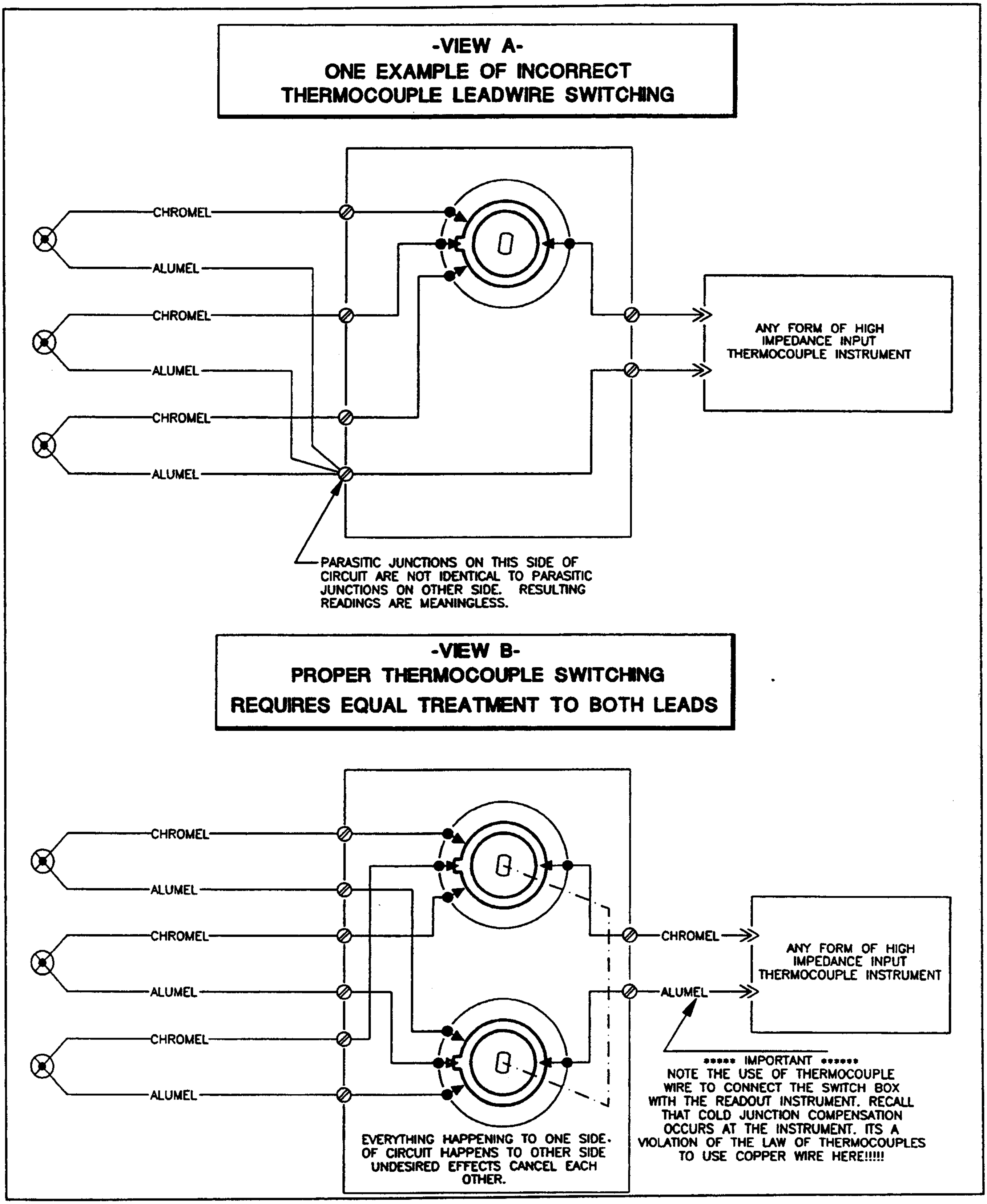


Figure 14-11. Switching Multiple Thermocouples to a Single Instrument.

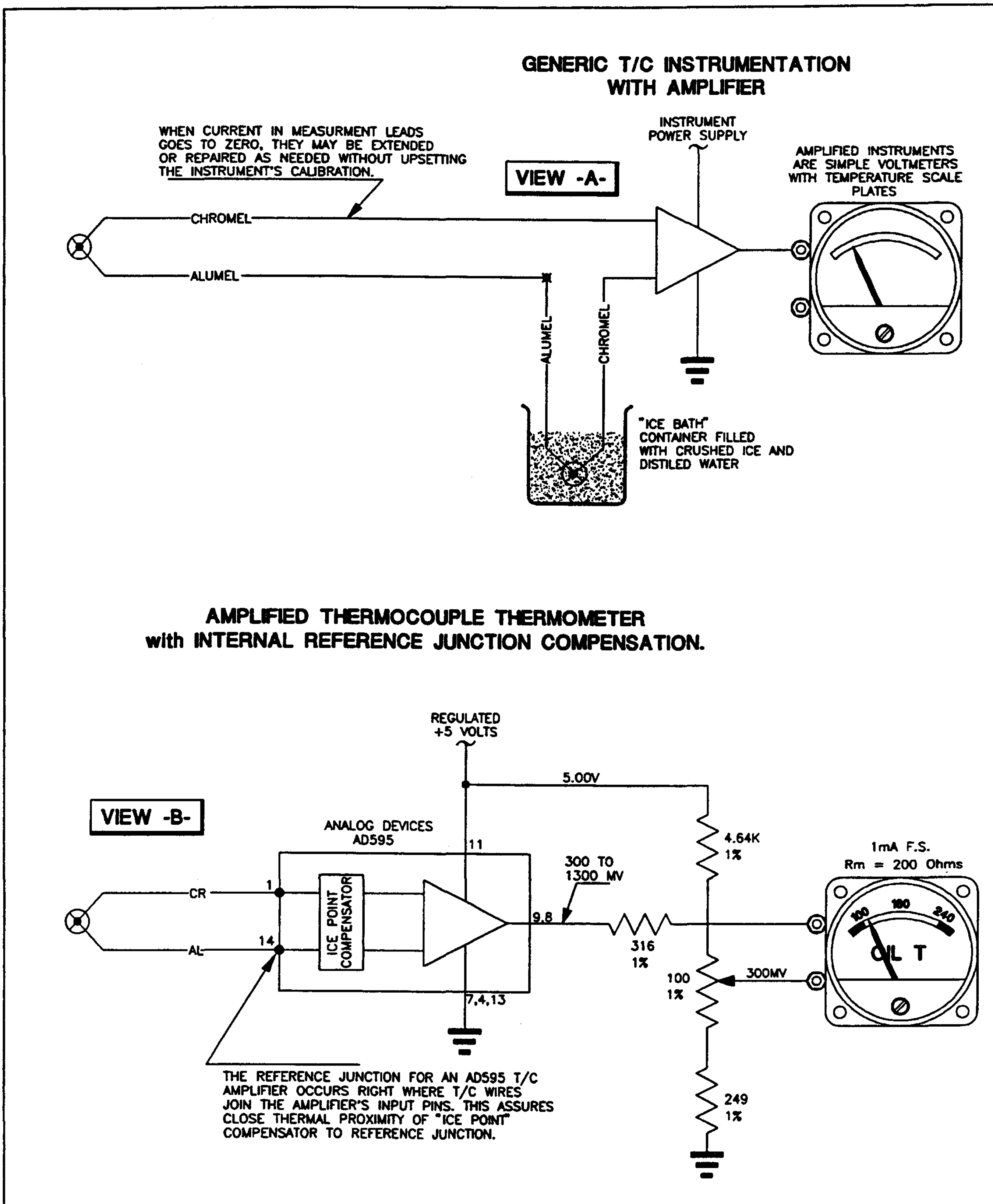


Figure 14-12. Amplified Thermocouple Thermometers.

will work in the minus temperatures if two power supplies (+5 and -5 volts) are provided. Thermocouples work best above 0°C and are quite suited for oil, EGT and CHT measurements. For these parameters, temperatures of interest are well above 0°C. Therefore, a single +5 volt supply works find for measurements between 10°C (.10 volts) and about 300°C (3.00 volts).

For example: Let us suppose you want to display oil temperature over the range of 30 to 130 degrees C (86 to 266 degrees F). The output from the AD595 and type K wire will be 300 to 1300 millivolts over that range (10 millivolts per degree C). So, instead of designing a differential voltmeter for 10-16 volts as in Chapter 7, we're going to design for 300 to 1300 millivolts. The values shown in Figure 14-12 are appropriate for a meter having a full scale current of 1 milliampere and internal resistance of 200 ohms. Resistors for other meters can be calculated using techniques described in Chapter 7 *(OR you can simply use a digital panel meter with the decimal point set in the right place to display 10 mV/°C as temperature.)*

Now, remove the meter's existing scale plate and paste a new scale on having a calibration and label as shown. A similar technique could be applied to cylinder head and exhaust gas temperature indicators. So, you see that one may consider building some instruments that are accurate, calibratable and repairable by you, the builder. I have a variety of scale plates already drawn in AutoCAD that would be easily customized to any basic meter movement. If you'd like to take a whack at building thermocouple driven temperature gages, let me know.

A final note on the AD594/AD595. If you own a decent digital or analog voltmeter you may use one of these devices to build a small adapter for measuring temperatures with thermocouples. You'll need to mentally place the decimal point for conversion of volts to degrees, e.g. 1.000 volts = 100°C; 0.550 volts = 55°C, etc.

## SPLICING THERMOCOUPLE WIRES

Thermocouple wires are easily repaired, carried through connectors or extended by splicing. However, you're now aware that special techniques are required. A number of companies sell splicing devices for joining two thermocouple conductors. One may purchase butt splices that are similar in appearance to those designed for joining ordinary copper wire. If you wish to bring a thermocouple pair through a multi-conductor, bulkhead connector, crimpable terminals of the proper alloys are available but they are not cheap . . . I've paid as much as $25.00 per pin for chromel-alumel pins to fit MS3120 series connectors . . . that's $100 for parts to bring one pair of wires through a connector! I try to avoid bringing a thermocouple through any kind of connector along with other wires. There's a lot of temptation on the part of builders to bring all wires penetrating a firewall through on some kind of connector. For cost, weight and time savings, I recommend fabricating firewall penetrations from ordinary grommets with sheet metal fire shields.

One may purchase small, polarized connectors with molded plastic housings. These are generally attached to the conductors with tiny set screws. I believe they are offered both for semi-permanent splicing and as mated-pair connectors that permit breaking and rejoining a splice for maintenance. These connectors are not outrageously expensive. If you would like to remove an engine without de-mounting oil, cylinder head and/or exhaust gas thermocouples, these low cost connectors should be considered. Vendors of thermocouple joining supplies may be found in Appendix-A.

Occasionally, one simply wishes to permanently join a pair of conductors when a repair or replacement of a thermocouple is done. Other times, a thermocouple wire installation task is made easier by breaking up a thermocouple wire run into two or more segments. Chromel-alumel and iron-constantan conductors may be soldered. Unfortunately, they do not alloy with ordinary tin-lead solder. I prefer silver-solder so a torch is required to achieve adequate temperatures for joining. Further, at silver-solder temperatures, you are going to smoke some insulation on the wires - a condition that does not occur with ordinary electronic soldering operations. The trick is to minimize the damage and to end up with a clean looking splice.

Figure 14-13 illustrates two methods for joining segments of thermocouple wire - solder or install a thermocouple connector. To solder as in View -A-, strip outer jacket of thermocouple pair about 4-inches on each end to be joined. Cut the conductors to be joined so that the solder joints are staggered; one joint about 1-1/2" from the first outer jacket; the second an equal distance from the other outer jacket. Strip inner insulation from each conductor about 1/2". Slip a 6-inch piece of 3/16" heat-shrink tubing over the outer jacket of one pair and 2-inch pieces of 1/8 or 3/32 inch heat shrink over each of the long conductor stubs. If you can find high-temp, Teflon heat shrink for this task, great. However, plain vanilla

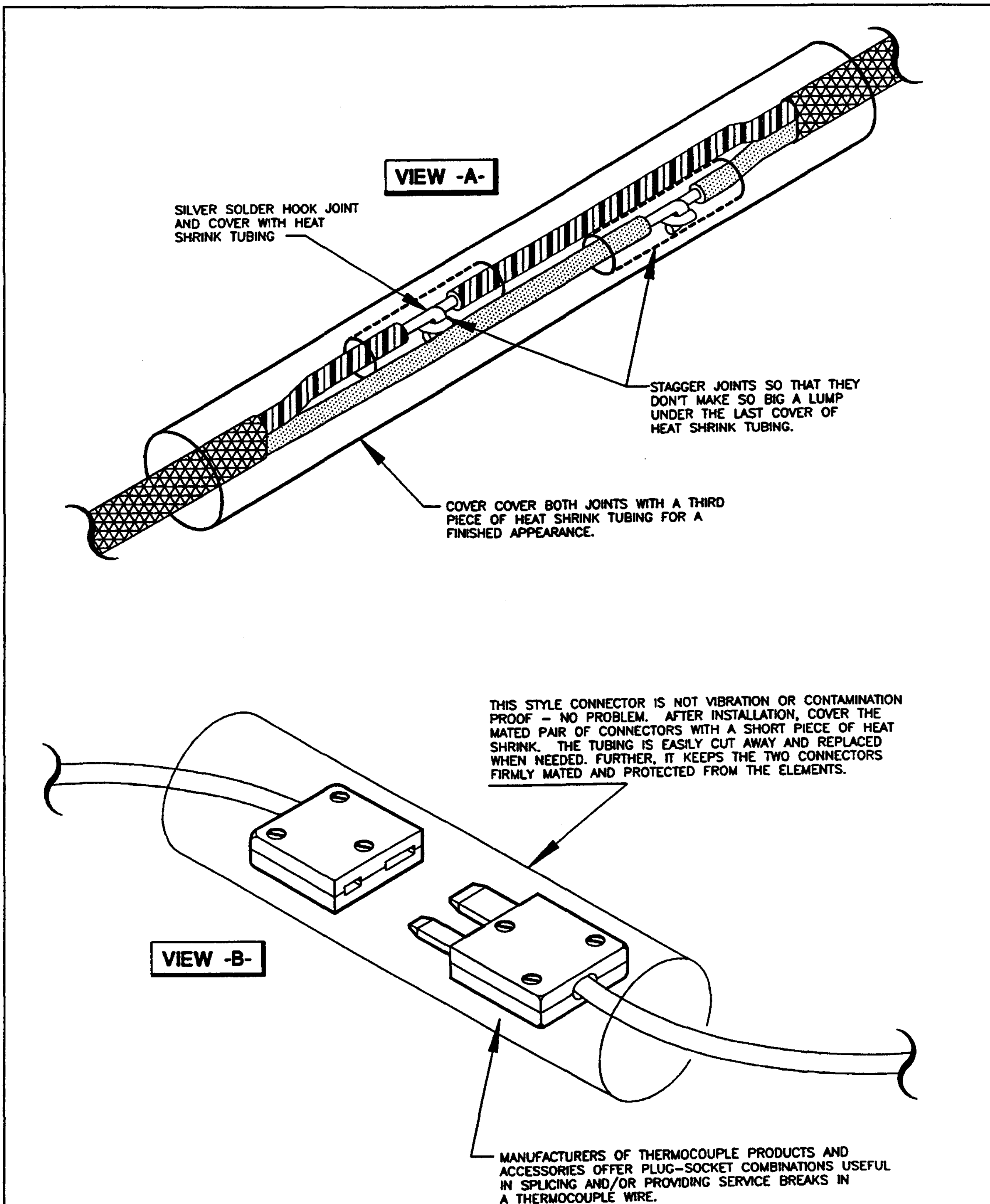


Figure 14-13. Splicing Thermocouples.

variety will do nicely too. Bend a J-hook in the very tip of the first two wires to be joined, interlock them and close the hooks with pliers.

Now, if your propane torch were to be compared with a Star Trek hand-fazer, we're going to set it for "gentle stun" mode; just enough energy to get a humming bird's attention without knocking it off its feet. One-fourth inch of dark blue, inner flame cone extending past the end of the mixing chamber is about right. Some torches I've used for this task wouldn't burn well at this setting until they've burned at a higher setting for a few minutes to warm up.

First, coat the joint of interlocked wires with silver-solder flux. Now, the task is to form a tiny joint with minimal melt-back on the insulation. Success depends on getting solder to melt at the same time the wires get up to alloying temperature. Generally, the solder heats slower than the wires so I try to bring the tip of the inner blue flame tip up to the wires about two or three seconds after putting the end of the solder into the flame tip. If you're really nimble with this process you will be on and off the joint with the torch in about 6-8 seconds. You may want to practice with a few scraps of wire before you climb into you airplane to try this. Be aware that silver solder flows at red-heat temperatures. Further, be prepared for more melt-back than you would really like to see.

In words this probably sounds more difficult than it really is. Further, there is no great sin in smoking a little more insulation than you'd like . . . we're going to cover the dirty deed with two layers of plastic! When the first solder joint has cooled, clean off any flux residue that will now look like a thin coat of glass over your finished joint. Use needle nose pliers to simply crush the fused flux - it will fall away easily. Slip heat shrink over the finished joint and shrink into place. Put another piece of small heat-shrink over the other long stub and interlock two j-hooks. *Electronic stores, like Radio Shack, sell a "third hand" soldering aid that you may find useful in fixturing your victims for this operation. In a pinch, build your own fixture by soldering two alligator clips to a 6" piece of 10AWG bare copper wire and bending it into a U-shape so that the clips can support your wires to be joined on either side of the joint.*

Solder then shrink a cover over the second joint. Finally, position and shrink the large tubing over the whole business and you're done. The judges at Oshkosh will marvel over your clever joining of the "un-joinable" and never know how badly the insulation suffered in the process. Furthermore, instrument panel temperature gauges will read exactly what they are supposed to read: temperature at the far end of the thermocouple pair, unaffected by temperatures encountered along the way.

Figure 14-13, View -B-, shows a small, mating pair of thermocouple connectors sold by virtually every firm specializing in thermocouple products and accessories. Digital thermocouple thermometers often feature a female side of this style connector right on their front panel as shown in an earlier figure. These connectors are inexpensive . . . a few dollars per mated pair. Use these guys to break thermocouple leads when dismounting an engine without having to remove the thermocouples from the engine. Text in Figure 14-13, View -B-, suggests a means for securing these connectors from separation under vibration and protecting them from most environmental hazards.

## FABRICATING & REPAIRING THERMOCOUPLES

The really neat thing about thermocouple wire is that you can make your own temperature sensors at the end of any desired length of thermocouple wire. Simply extend the wire from the instrument to a site where temperature is to be measured. Strip the insulation off the end and twist the wires together. Various laboratories I've worked in were equipped with thermocouple welders. These are nifty little machines that allow one to twist a thermocouple pair of wires together and use an electric arc to fuse them to form a neat thermocouple. The operation occurs so quickly and with so much energy concentrated at the joint that melt-back of adjacent insulation is minimized. Further, no foreign metals are introduced into the joint. Since we're not looking for laboratory grade accuracy in aircraft systems temperature measurements, the silver solder joining technique makes an excellent alternative to the purchase of a laboratory welder and uses inexpensive tools and techniques available to the amateur airplane builder. Just twist the stripped ends of the thermocouple wire together, solder with silver solder, break away flux residue and trim overall length as desired. A thermocouple joint can never be too small to function. Size of wire is purely a logistical consideration. You can buy thermocouple wire in gages (.001" diam) suitable for taking a bumble bee's temperature. On the other hand, hefty wires (18AWG for example) are available for very rough environments. Either wire is read by the same instrument!

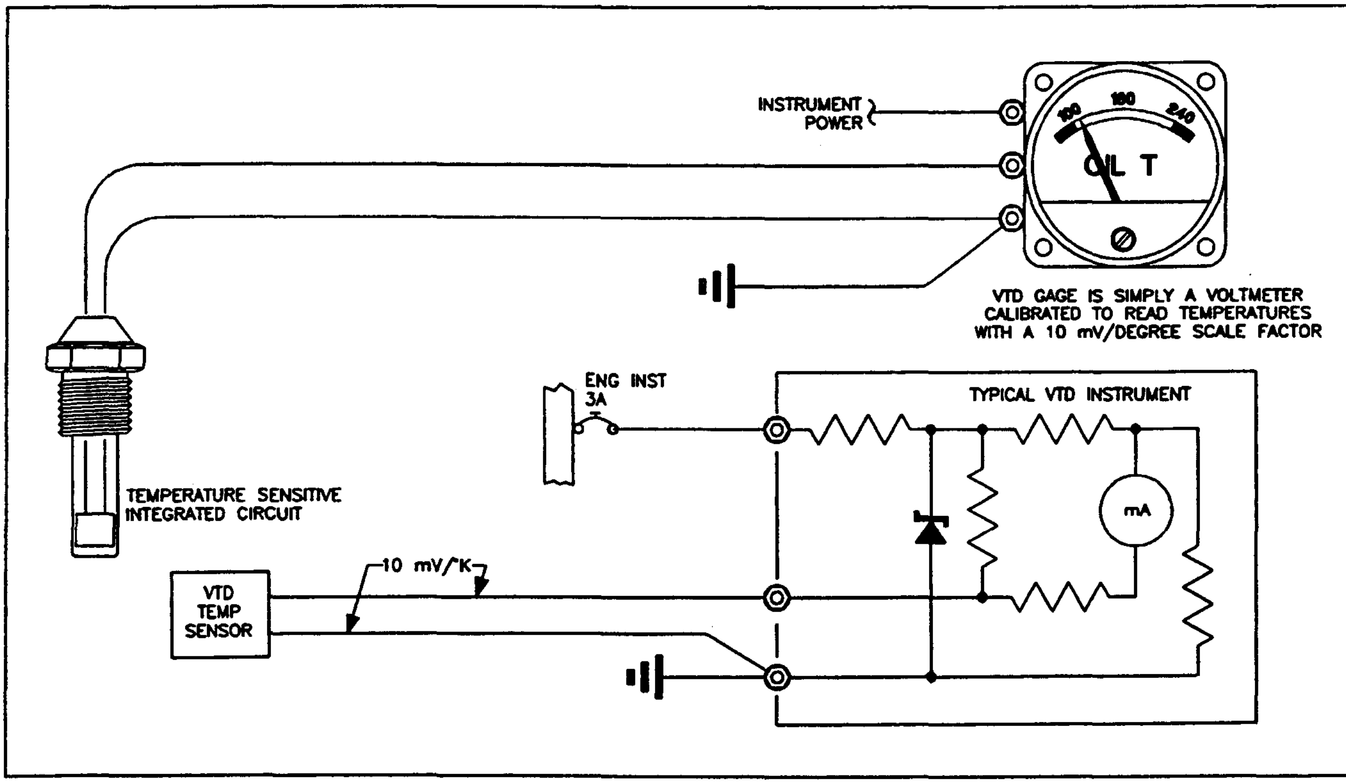


Figure 14-14. Solid State Temperature Sensor.

Insulation becomes the last consideration. Most thermocouples wires found on factory installed aircraft instruments will have a form of Fiberglas insulation on them. This insulation is resistant to most environmental stresses found on airplanes. Thermocouple wires are also commonly insulated with materials like Kapton and Kynar and Teflon. Since thermocouples are most often used to read temperatures well above ambient levels, they are purchased with heat resistant insulations. If you stumble across some thermocouple wire as a surplus item, it's probably suited to measuring about anything found on an airplane. The tough one is EGT which requires type K wire and Fiberglas insulation.

## PERMANENT THERMOCOUPLE THERMOMETERS

There are at least 3 situations where you may wish to install permanent, thermocouple driven instruments on the panel. One each for oil temp, cylinder head temp (hottest one as surveyed during flyoff) and EGT (hottest one as surveyed during flyoff). As illustrated back in Chapter 7, it's not difficult to configure a meter to read any desired range of voltages. With a few more components, you can make the meter read a range of temperatures as well.

## CALIBRATED ELECTRONIC TEMPERATURE SENSORS

Back in the days of germanium transistors, designing solid state circuitry to operate over wide temperature ranges was challenging. We cursed the fact that solid state devices had strong, undesirable responses to temperature. Thirty years later, clever designers of electronic components have capitalized on these phenomena to take advantage of certain temperature effects. In fact, the AD595 integrated circuit described earlier uses an internal solid state temperature sensor to develop a voltage for reference junction compensation. If resistance versus temperature devices are called RTDs, I guess we could call voltage versus temperature devices VTDs.

Several manufacturers build VTDs that look for all the world like a simple, zener diode voltage regulator. However, this "regulator" is very unstable - in fact, it drifts at a rate exactly equal to 10 mV/°K or 10 mV/°R. Hmmmm . . we saw that 10 millivolt figure earlier. That's become a sort of industry standard for temperature measurement devices. Everyone builds parts calibrated for measuring C-size degrees, most also make F-size parts too. Figure 14-14 shows a basic thermometer using a calibrated VTD. The indicator is nothing more than a voltmeter with scale factor of 10mV per degree times total degrees of span and an offset equal to 10mV per degree times the lower end of scale temperature reading. The architectures for expanded scale voltmeters described in Figure 14-12 and Chapter 7 are applicable.

VTDs are **calibrated** devices as supplied from the factory. They are quite accurate, typically plus or minus 1.0°C or better. Their scale factor of 10 mV/°C is the same as the thermocouple amplifier shown in Figure 14-12, but they are somewhat simpler to use as illustrated in Figure 14-14. Their disadvantage is that their operating temperature ranges do not span as far as thermocouples. They are currently unable to measure exhaust gas temperatures; exhaust gases will remain an exclusive domain of thermocouples. Further, few solid state sensors are rated for temperatures experienced on cylinder heads. However, they do work well at low temperatures (below 0°C); actually better than thermocouples. Therefore, VTDs are well suited for OAT measurement. Their large inherent scale factor of 10°C overpowers parasitic thermocouples which exist in the interconnect wiring so leadwires between instrument and solid state temperature sensors require no special treatment.

## BEWARE THE LURKING GROUND LOOP

Solid state temperature transducers can suffer the same installation induced inaccuracies as the single wire RTD transducer mentioned earlier. I design all VTD sensors to bring a pair of wires all the way from VTD to indicator. Any time you encounter a single conductor, engine mounted sensor (temperature or pressure), ground the instrument for that sensor to the engine via its own, dedicated ground wire.

## INTEGRATED INSTRUMENTATION SYSTEMS

Several folk are offering integrated instrument systems, usually with liquid crystal displays, that present one or more temperatures all at once. Virtually all will use either thermocouples or solid state temperature sensors. Unless instructions for your integrated instrumentation system state differently, you may splice and/or extend sensor leads for companion sensors; technique depends only upon whether they are a thermocouple or solid state sensor.

## OIL AND WATER TEMPERATURE PROBES

Most access to water or oil flow in an engine is through tapered, pipe-thread openings. The plumbing department of a well stocked hardware store will yield a brass plug the proper size to fit your engine's oil or water temp sensor opening. Good thermal contact of your temperature sensor (thermistor, thermocouple or solid state) with the fluid being monitored is essential. The usual technique calls for fabricating a "thermowell." A thermowell is illustrated in Figure 14-15. Actually, about every temperature transducer (or sender) is a form of thermowell. The purposes of a thermowell are (1) to extend into a liquid far enough to measure its temperature in the main fluid flow and (2) get as much thermal isolation as possible from the surrounding environment (crankcase, etc.). The thermowell I like to build is illustrated in Figure 14-15. It is fabricated from a brass plug through which I drill a 1/4" hole. A piece of thin-wall, brass tubing is soldered into the plug. The length of the tubing is that which is judged to place the sensor into free flow of fluid inside the engine. The sensor end is squeezed shut and soldered. The sensor is then cemented or soldered into the bottom of the "well." Silicon sealant around the wire as it exits the plug is a good idea to prevent damaging the wire by pressing against the edge of the hole. Sometimes, a close wound spring is cemented into place about the wire to provide radius-relief and reduce stress on wire when tugged.

## CYLINDER HEAD TEMPERATURE MEASUREMENT

Most modern aircraft engines have thermowells built into the cylinder head. These are generally threaded for an adapter which accepts a spring loaded, bayonet-locking retainer for a thermocouple or RTD probe. I've built CHT probes using salvaged hardware purchased from an engine rebuild shop. What you need are the threaded adapter, retaining ring and the spring which is used to keep the sensor pressed against the bottom of the hole.

You can use generic hardware to build your own CHT thermocouples. Find a threaded plug that fits the thermowell on the engine. Drill through the center and chamfer the edges for wire protection. Find a stainless steel compression spring for use under the plug to hold your fabricated thermocouple against the bottom of the thermowell. Even if your CHT instrument displays one cylinder only, consider techniques outlined earlier to build a selector switch to display any desired cylinder on a single instrument.

My favorite CHT sensor is the spark plug gasket type thermocouple. Mechanics don't like these things because they break easy. I like them because they are

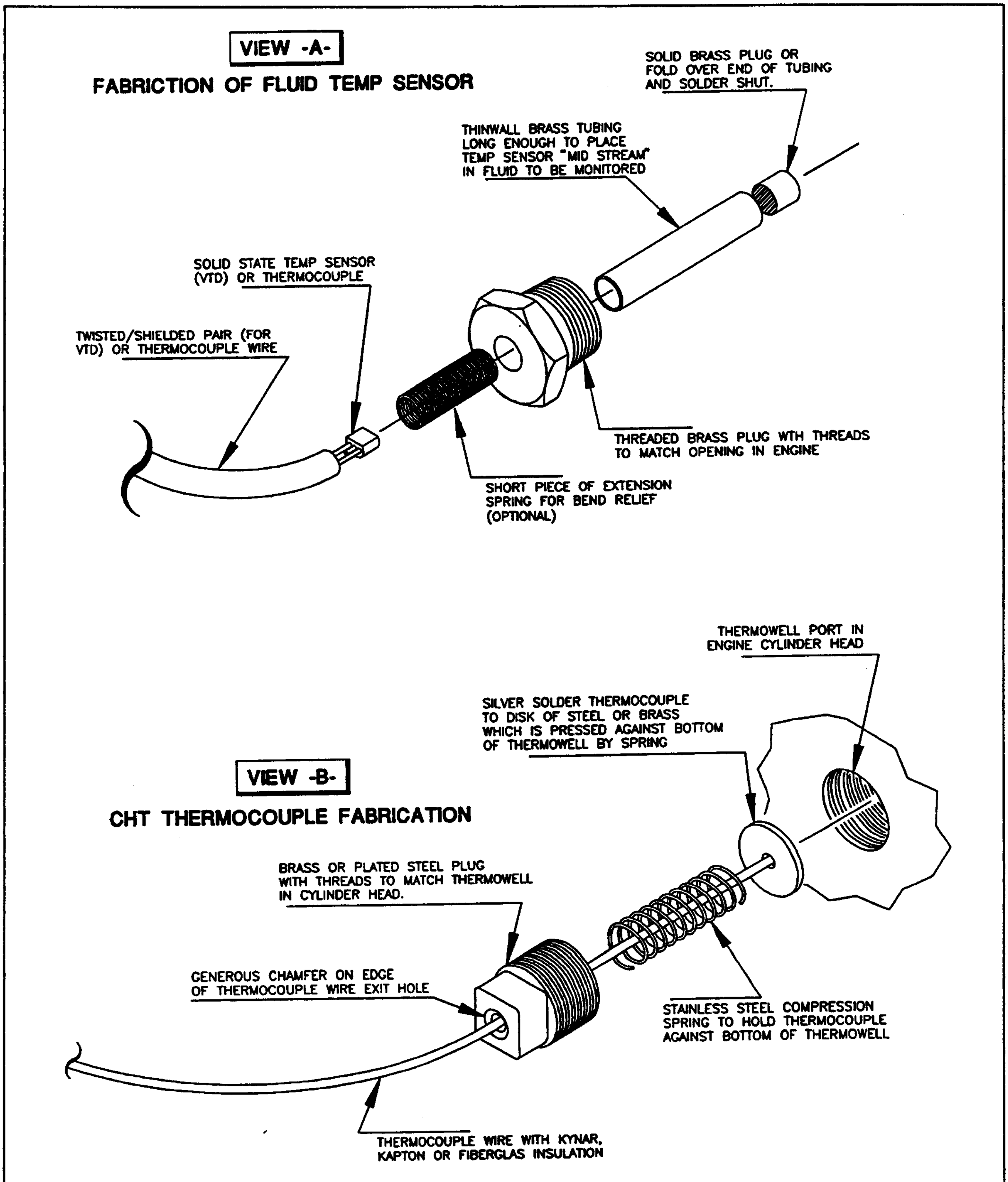


Figure 14-15. "Thermowells" for Temperature Sensing.

inexpensive an easy to repair! A number of manufacturers sell spark plug gasket probes for $12-$20 each. It's probably not worth the trouble to build from scratch. Recall at the beginning of this chapter I mentioned changes to materials from thermal stress? Well, copper work-hardens if you repeatedly stress it. Take a piece of copper wire and start bending it back and forth. You can sense when the worked part of the wire is getting hard, starts to crack and finally breaks in two.

Well, copper gaskets under a spark plug harden from internal stresses cause by temperature cycles. It's standard practice to put new gaskets under the plugs when removing them for cleaning or replacement. When your CHT thermocouple(s) replaces one or more plug gaskets, inexpensive replacement with each plug change is not an option. Use a propane torch to heat the washer portion of a copper CHT sensor to dull red heat and allow it to slowly cool. This single excursion to so elevated a temperature will soften the copper and make it suitable for sealing the spark plug under which it sets.

If the thermocouple wire breaks off a spark plug CHT sensor, you can repair it yourself by opening the copper wrap around the thermocouple. Fabricate a new thermocouple on the end of the old wire as previously described and wrap it back up in the old fitting. Sometimes the tab breaks off the washer. In this case, I use silver solder to tack the old (or newly fabricated) thermocouple back onto the end of the old stub. Yeah, I know, it's going to break off again. Most plug-gasket, CHT thermocouples get broken when plugs are being removed. Tie the thermocouple wire against the side of the plug for vibration support and it will last until next time you pull the plugs. If you do happen to break it during the next maintenance cycle, just think: with a little practice, you can be very quick at repairing it! I personally prefer inexpensive, easily repaired components over expensive and/or non-repairable parts.

## EXHAUST GAS TEMPERATURE MEASUREMENT

Getting into an exhaust stack is a little tougher. Needless-to-say, the inside of your exhaust stack is the nastiest environment on the airplane! I've built some EGT probes but I find that they are not expensive to purchase. Alcor (and competitors) build EGT probes for tractors and other industrial engines with type K thermocouple wire. An EGT probe needs to be fabricated from stainless steel for both thermowell and mounting clamp; temperatures are high and the gases corrosive. The "tractor" parts are identical in performance to the "aircraft" parts. Feel free to use purchased EGT thermocouples with another instrument of your choosing as long as it's designed to work with type K wire. Actually, the wire type and reference junction configuration are not terribly critical for EGT. First, an EGT gage is not calibrated for actual degrees, just degrees per some division of the scale; usually 25°/Division. Offset errors which may exist because of poor or no reference junction don't matter. An EGT gage is used to set mixture so many degrees rich or lean of peak. I suspect that most EGT gages have no, or at best, very crude reference junction compensation.

Very few of you will ever find it necessary or attractive to build temperature measurement instrumentation from scratch. However, I hope that what you have seen and read in this chapter has convinced you that you don't have to be a rocket scientist to deal effectively with installation, troubleshooting and repairing a temperature indication system on your airplane. Further, I hope that I have convinced you that when in doubt about the operating temperature of system components, you'll take the time and trouble to make a measurement to find out for sure.

At the beginning of this chapter I asked a question about temperature versus compression of gases in a cylinder. It does happen. This is the basis for operation of a diesel engine. Air is compressed so hard as to raise its temperature well above the ignition point of diesel fuel. When the fuel is injected into the cylinder, immediate ignition occurs. If gasoline is improperly brewed for the compression experienced prior to complete combustion, spontaneous combustion or detonation occurs. A diesel is designed to run under "detonation" while a gasoline engine will be destroyed by it. Temperature has more influence on the physics of flight and flight systems than any other phenomena. It will serve you well to become familiar and comfortable with its measurement and interpretation of readings.

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