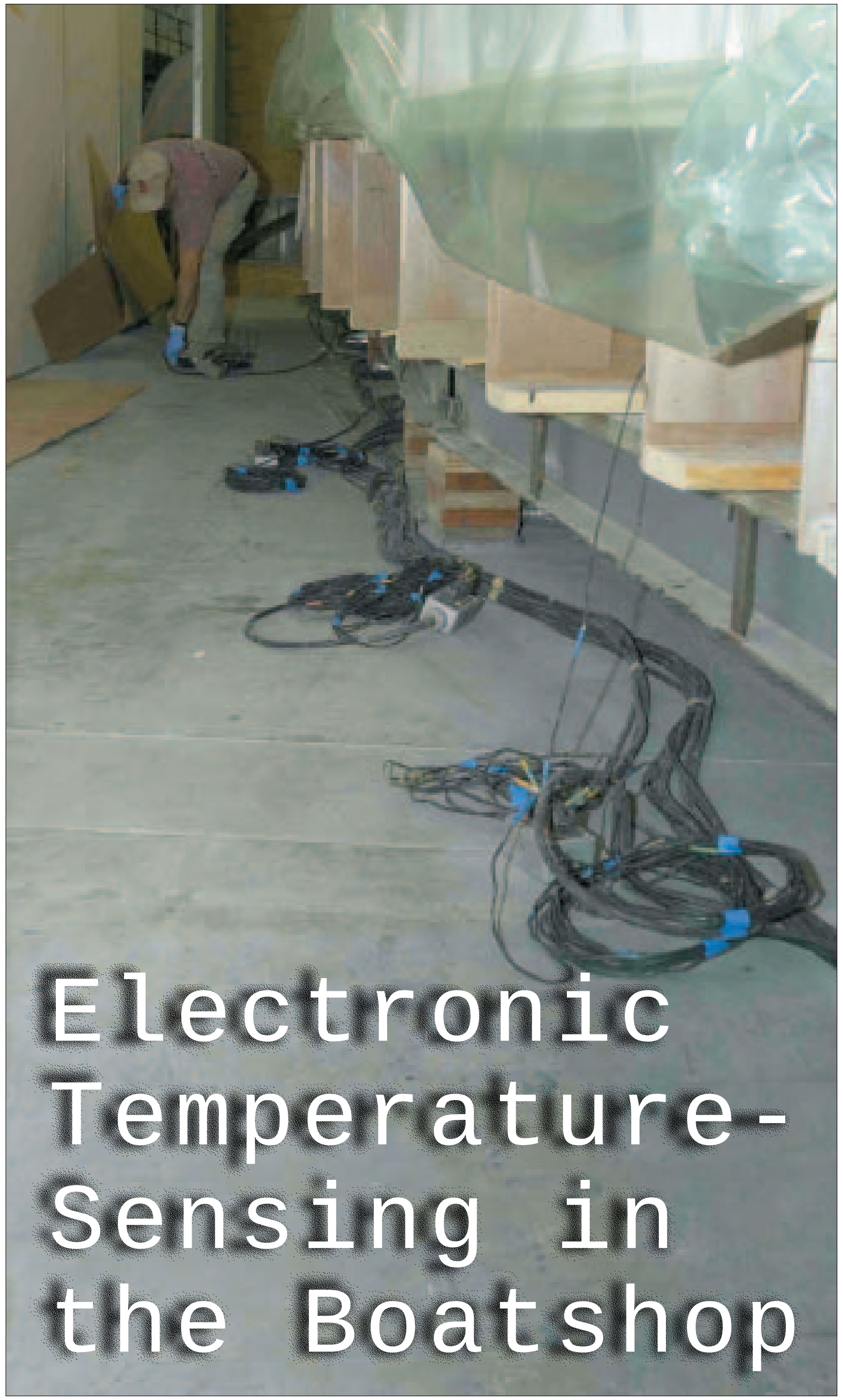


Electronic Temperature-Sensing in the Boatshop

Cost effective and easy to use, thermocouples and related gear are key to temperature control for any composite project. Here's how to set up a basic system.

by Bruce Pfund

Temperature measurement and control is an often-neglected aspect of process control in composite boat shops. You can get away with ignoring this topic during well-executed hand layup, but not during infusion, post-curing, or oven curing. For these more-complex operations, you'll need a clear understanding of how to control material and process temperatures.

Resin working time and cure rates are temperature dependent, whether you're doing open hand-layup processing, infusing resin under a bag, or curing pre-pregs in an oven. Hand layup is by far the most forgiving when it comes to temperature control, because of the relatively low exotherm temperatures for each layer's cure. Infusion or pre-preg processes are much more temperature sensitive, due to the larger volumes of material being cured all at once.

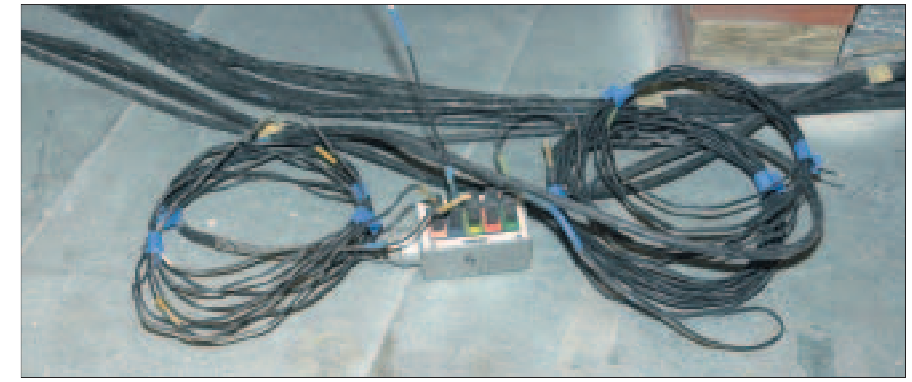
Most hand-layup shops have experienced "runaway" exotherms in large volumes of resin, but these typically occur in a mixing bucket, not on the part. It gets ugly when the last 30 gallons (114 l) of catalyzed resin gels in the supply tank before being inhaled into a laminate during infusion, or when a thick stack of pre-pregs—say, at a sailboat's chainplate regions—gets too hot during the oven-bake cycle. In these two worst-case scenarios, temperature information about the shop, the tooling, and the resin is needed to diagnose what went wrong. It's better to avoid such disasters completely; accurate temperature measurement, recording, and control can help in that regard. In the case of the infused part, variations in the cure-system chemistry and larger, more closely spaced resin-supply manifolding might be required on hot days to increase the resin-delivery rates. For the pre-preg part, adjusting the positions of heaters and air-circulation blowers in the oven could keep the chainplate areas a bit cooler than the rest of the part. Thermocouples (TC) and related electronic temperature-measurement equipment are easy to use and the most accurate and cost-effective ways to detect, record, and manage this critical information.

I have mentioned thermocouples frequently in previous *Professional BoatBuilder* articles, most recently in "Gearing Up for Infusion" (PBB No. 88, page 26), but have never devoted an entire piece to the topic of thermocouples. The aim of this article is to explain how these devices work, what types are available, and how to set up a basic electronic temperature-measurement system in your shop. But first, let me explain the difference between mechanical thermometers and electronic temperature-sensing.

Mechanical thermometers are driven by expansion and contraction of liquids such as mercury or red alcohol, or by bimetallic spiral springs. Electronic temperature-sensing measures changes in a detector's electrical properties and correlates them to temperature. Systems can range from basic to advanced, handheld to fully computerized. In the last decade, the cost of the electronic gear has dropped dramatically.

If you need to detect the temperature of only one or two items that are right in front of you, conventional thermometers will work just fine. If, however, you need to measure multiple objects, and they are more than a few feet or meters away, thermocouples are the way to go. According to John Telfeyan, general manager at Goetz Custom Yachts (Bristol, Rhode Island), "Thermocouples and electronic thermometer displays are functionally just remote-reading thermometers. They're pretty rugged, very accurate, and well suited to temperature measurement in a composite boat building operation." I recently spent a day at the Goetz shop while the crew was curing a 52′ (15m) pre-preg sailboat hull and deck in the shop's huge oven, and will describe below in more detail Goetz's electronic temperature-monitoring setup for that boat.

Although remote-reading mechanical thermometers are available—remember the water- or oil-temperature gauges found on automobiles through the late 1970s—they are impractical for boatbuilding. With this type of gauge, a bulb detector is immersed in the fluid being measured. The bulb contains a high-expansion-rate liquid. When the fluid temperature rises, the liquid inside the bulb expands and is fed to the gauge through a delicate, small-diameter copper tube. At the gauge, a mechanical escapement converts the liquid's expansion into rotation of the needle. Kink the tube just once and the unit is shot. Additionally, the maximum distance between bulb and gauge is usually limited to 10′ (3m) or less.



A crew member at Goetz Custom Yachts in Bristol, Rhode Island, sets up to cure the pre-preg hull and deck of a 52′ (15m) sailboat ***(facing page)*** *in the shop's xx′ x xx′ oven. Accurate temperature measurement is critical to the success of a temperature-sensitive advanced-composite project such as this one. A thermocouple (TC)—two wires of dissimilar metal alloys, deliberately connected, that create a voltage related to the junction's temperature—is the basic unit for electronic temperature measurement. In the photo, each athwartships array of five TCs connects to a junction box* ***(left)****. Each TC lead is color-coded to its specific plug. At every measurement location, four TCs are attached to the hull or deck, and the fifth either hangs down about 6′ (1.8m) from the oven's ceiling, or is secured inside the tool next to the tooling surface.*

How Thermocouples Work

Dissimilar metals below the waterline generate electrical currents and cause electrolysis. Thermocouples work on a related phenomenon. The specialized dissimilar thermocouple alloys—deliberately connected—create a voltage related to the junction's temperature. Thermocouples suitable for boatbuilding applications come in three basic types: J, K, or T specification. All these types will work fine in the temperature range of about 0°F to 400°F (18°C to 204°C). J or K are usually cheapest. Although high-temperature and cryogenic-rated thermocouples are available, they are too expensive to be practical for boatshop use. Here are the three basic types, along with their constituent metals, and color codes for wiring purposes:

	Constituent metal	Color code
J	Iron-constantan	Black
K	Chromega-alumega	Yellow
T	Copper-constantan	Blue

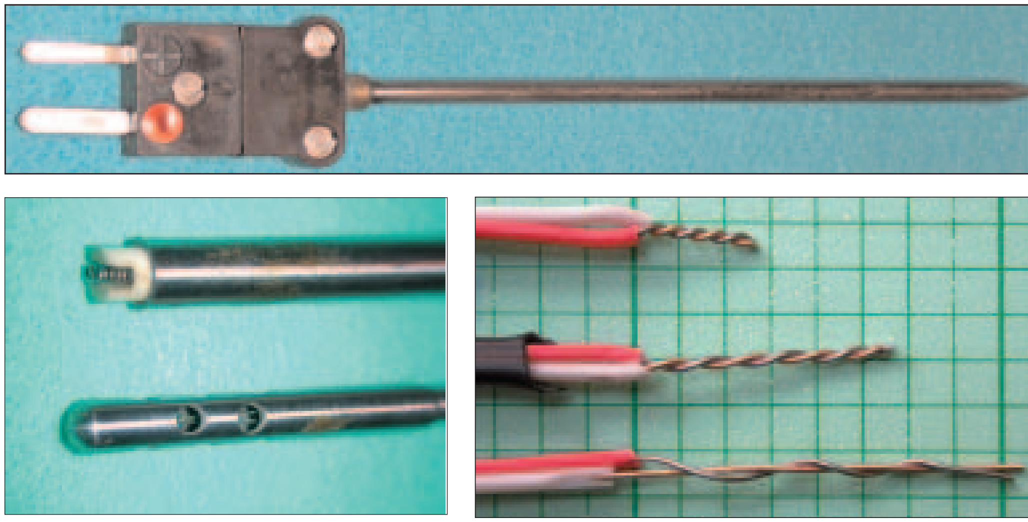
What's most important to know about the different types is that the thermocouple junction and the instrument used to read it must match in order for temperature-sensing to be accurate. In fact, every part of a thermocouple system must match. Each type TC has a specific color code for its wiring, cables, and plugs, so mixing up different types is hard to do. As an example, a simple remote-reading single-channel thermocouple setup might comprise the following:

- J-specification TC
- J-specification solder to attach the TC leads to the cable (Alternatively, a terminal block with matching alloy fasteners and bus bars)
- J-specification male plug
- J-specification meter

Another pitfall in wiring thermocouples, which are polarized devices, is that their wiring conventions are completely opposite from most 12V wiring conventions. On thermocouples:

- the negative lead is red;
- the negative leg of a polarized wire pair is shorter;
- the negative pin, lug, or plug blade is biggest, longest, or widest.

Keep these points in mind if you intend to assemble your own components into a system, or even just to assemble a simple single-channel device. Smoke won't come out of the



__Top—__The needle probe works well for checking the temperature of fluids and soft materials, but is ineffective on flat and dry surfaces. Its response time to changes in air temperatures is relatively slow due to the tube's mass. In the surface-contact probe __(middle)__, a spring-loaded S-shaped thermocouple "foot" retracts into a ceramic insulating block on the head of the probe when it's pressed against a flat surface. A specialized air-temperature-sensing head __(bottom)__ protects a fragile bare-wire thermocouple inside a perforated 316 L stainless steel bulb. Response time to small air-temperature changes is very fast. __Right—__An alternative to purchasing a sheathed probe with soldered wires is to simply twist the wires together. The author ran a simple test to determine whether the tightness or number of twists affected the indicated temperatures. The twists in the middle sample above are about twice as long as those in the top; the bottom sample is deliberately crude, with one wire straight and the other twisted around it. All three pair read within 0.3° when hooked up, and were also within about 2° of the sheathed thermocouples the author used for comparison.

meter or junctions if you reverse the polarity—at least it hasn't for me—but why risk it?

Detector Types

Thermocouples are typically protected by a variety of probe types. Sheathed thermocouples come in a wide range of styles. The three most practical for the boatshop are shown **above**. Stainless steel sheaths are very durable, and a shot or two of wax or polymeric release agent now and then will help prevent resin buildup if you're checking wet processes.

The survival rate for unprotected thermocouples in the average composite boat shop is grim. After you go through a few fights with beat-up and unreliable "naked" thermocouples, you'll end up wondering, "If the TC wires are made of the same alloys as a true thermocouple [in which the two dissimilar metal wires are connected by a dot of special solder], why not just twist the wires together?" You won't be the first to ask this question. In fact, twisted-wire thermocouples will "drive" a meter and display just fine—as long as absolute accuracy doesn't matter.

The Goetz shop, and others I know of, typically do not deploy many soldered thermocouples in their temperature-measurement systems. According to Telfeyan at Goetz, "We don't use individual thermocouples. We use high-quality TC cable, and by stripping and then twisting the two bare wires together we can create an effective junction that generates a strong signal. We don't bother to use the special solder. Twisted-pair, shop-made thermocouples may be off by a degree or two, but in process control during a boat-bake we are more concerned with temperature uniformity than we are with the absolute value."

Both Telfeyan and I initially had reservations about the do-it-yourself thermocouples. He told me that, "In about 1994, I twisted up a bunch and immersed them in boiling water. All read within a degree of 212°F [100°C], and that was good enough accuracy for our purposes. A degree or two high or low isn't critical for the way we measure and control temperatures in our ovens."

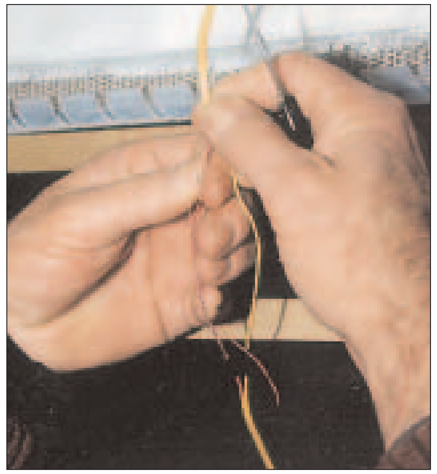
To compare the accuracy and repeatability of sheathed probes and twisted-pair TCs, I put a fresh battery in my TC thermometer and ran a few simple tests. First, I compared the readings from a twisted-pair TC with readings from a variety of sheathed probes—two needle style and two air-temperature-sensor types. Here are the results:

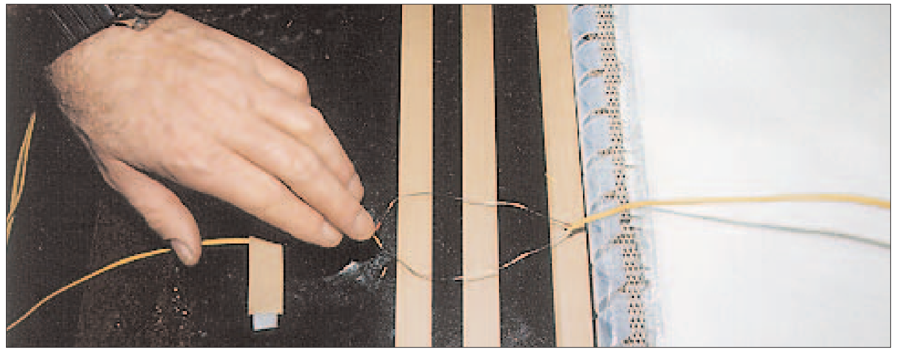
Tube 1	68.1°F
Tube 2	68.3°F
Air 1	68.3°F
Air 2	68.1°F
Twisted pair	67.4°F

Next, I ran a simple test to investigate whether the tightness or number of twists affected the indicated temperatures. With safety-wire pliers, I tightly twisted two junctions together, one approximately twice as long as the other. Then, I made a deliberately crude junction where one of the wires was straight, the other twisted around it—a true embarrassment for this angler, who knows how to make a proper "haywire twist" in #19 trolling wire. Much to my surprise, all three of my experimental twisted-pair TCs read within 0.3° when hooked up, and they were also surprisingly within about 2° of the sheathed thermocouples I used for comparison. I rate that as accurate enough for most composite boat shop applications.

Getting Thermocouples into a Vacuum Bag

The Goetz shop avoids vacuum leaks at thermocouple locations by not bringing the thermocouples under the vacuum bag at all. According to Telfeyan, "There are only a few degrees difference between TC readings from under the bag versus readings taken outside the bag. The consequences of vacuum leaks are so serious that we rarely place TCs under the bag anymore. Instead, we secure them tightly to the bag film with a small piece of tacky tape, and back that up with a short length of blue Mylar tape. Given our conservative cure cycles, the





Right—*The conductors should be separated to prevent a short circuit. The author suggests solvent-wiping the wires where they'll cross the tape, since they are handled quite a bit as the insulation is stripped.* ***Above—****The laminate shown here is being set up for infusion. Two rows of sealant tape secure the bag film to the mold table. Thermocouple cables and wires can produce vacuum leaks; the airflow occurs between the conductors and their insulation, or between the wires and the cable-cover tube. The cure is to strip the cable cover and insulation from the leads, and seal the tacky tape directly to the solid metal conductors. The wires must be effectively sealed at each tape crossing.*

slight differences in temperature readings we get with our method don't really matter. Maintaining the integrity of the process vacuum is far more important."

I asked Telfeyan if they used even one true thermocouple to get a high-accuracy reference temperature. "No," he answered, "we never found it to be necessary. We're using the thermocouples and the computer system to monitor the uniformity of our part's heating during its cure time in our oven. We think purely in terms of BTUs-in and BTUs-out of the oven. We know we have enough heat to get the job done. We use very conservative elevated-temperature oven cure cycles, typically maintaining the peak temperatures for up to 100% longer than the minimum times recommended by our pre-preg and resin manufacturers, then we add an hour. To be extra conservative, we base our timing on the slowest thermocouple to reach the set temperature. Absolute accuracy to within a degree is simply not necessary to develop a complete cure. The extra time takes care of that."

Individual Data Loggers vs. Central Computers

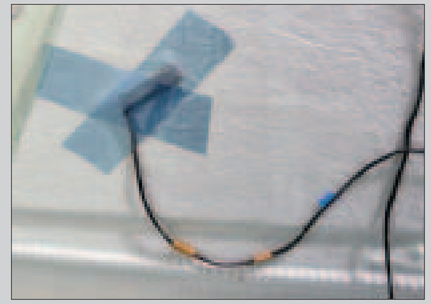
When building a temperature-sensor system (anything more than one thermocouple makes it a system), you face two basic layout choices. In a central system, as shown in the photo **[location]**, all the individual thermocouple cables are run to a central point and wired to the data display or recording equipment.

Left—*The Goetz shop has a substantial inventory of neatly organized thermocouples with standard lengths of wiring and plug terminations, all kept in a box on top of a roll-around storage stand.* ***Right—****Six individual thermocouple cables plug into these junction boxes; the larger multi-connector "jumbo cable" is run back to the interface box. This way, it's easier to keep the channels organized, and there is less cable lying on the shop floor, where it could be damaged.*

What about *not* buying lots of cables? It's expensive. I have monitored an oven, instrumented with six individual thermocouples and 3′ (0.9m) cables, by plugging and unplugging my electronic thermometer into each in sequence—for hours. I know for certain that it was not a brilliant setup. A few years ago, when electronic thermometers were still expensive, a single processor and readout, along with a switchbox for multiple thermocouple inputs, was cost effective. Equipment is now inexpensive enough that switchboxes no longer make sense.

Telfeyan told me, "We started out the same way, plugging and unplugging, recording the data by hand on a simple spreadsheet form. Next, we got a five-position TC switchbox. As the scale and complexity of our cure cycles increased, five channels were not enough, so we got an even bigger switchbox—fifty channels, as I recall. It worked great for a while, but then the selector knob began to slip on the shaft, and that drove us nearly crazy. Was it 65°C at TC number 16, or number 17? It got so bad that we began calling the switchbox 'Dial-A-Prayer.' We really wore out that switchbox, and finally decided that it was a stupid way to monitor so many channels.

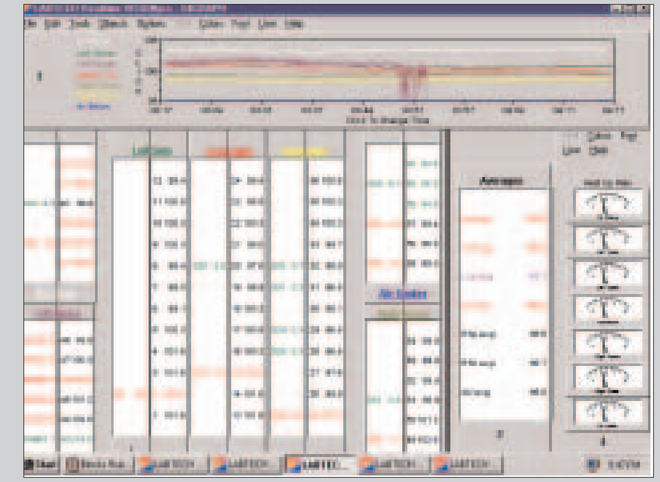
"We were working on Dennis Conner's *America*'s Cup boat in about 1995," he continued. "The campaign had developed hardware and software to monitor rigging loads on the boats. Their consultant, Dr. Milgram from M.I.T. [Massachusetts Institute of Technology], helped us adapt that hardware and software to measure temperatures across multiple channels—32, I believe. It was set up with nice graphical displays that not only showed the current temperature at any given TC, but also the location's



Upper left—_Goetz general manager John Telfeyan demonstrates the shop's dedicated process-monitoring computer, built into a roll-around cabinet with yacht-grade varnished moldings and handles. The keyboard folds down out of the way, the monitor is protected by a Lexan sheet, and the cabinet is equipped with multiple filter-protected cooling fans._ ***Upper right—***_At the Goetz shop, each twisted-pair thermocouple is secured to the vacuum-bag film with a short strip of tacky tape, followed by a crossed pair of 2" (52mm)-wide mylar tapes. The crew secures the long wire runs to the vacuum bag with extra tape crosses. Explains Telfeyan, "The airflow rates are quite high—enough to make dangling wires dance around. If one of the TCs pulls free and I lose a readout on my computer, guess who has to go into the oven."_

temperature history and heating or cooling trend. We upgraded our TC-monitoring computer again when that computer crapped out, and we bought an off-the-shelf data-logger card with 64 TC inputs.

"We have most of the graphical displays on our new system set up the same way," he continued, "and we use the information to move heaters,



Right—_Goetz currently runs a program called Labtech on a Windows 95 operating system. The display has been optimized for monitoring the baking of big parts. According to Telfeyan, "We look for hot spots and cold spots on the part, and then adjust the amounts and locations of our twelve heat inputs into the oven accordingly. We know that the TCs suspended over the part and under the tool next to the tooling surface will always come up to temp fastest. By basing our process timing on the slowest TCs to come up to temperature, doubling the minimum cure time, and then adding an hour, we're confident of complete cures." Once the cure starts, six horizontal lines start to appear in the top window of the display. The air-sensing TCs rise fastest. "When the process has stabilized," says Telfeyan, "all the lines become parallel." The digits in the center columns are also color coded: green for under temp, red for over, and white for on target. On the far right, the vertical window shows automotive-style gauges for the process paramaters. Shown here is a screen capture of the "cook" of the 52-footer on page xx. Says Telfeyan, "I had a problem with the thermocouple at the lower left. That's why the purple graph line is erratic. When one TC drops out, it goes to –214° and throws off the_

fans, and baffles around inside the oven to produce uniform heating. We also have one display, showing global temperature information about the whole part, not just the local information from individual thermocouples, and that makes the heating process easier to visualize. Our goal is uniform heating rates and soak temperatures."

Distributed Data-Collection Systems

In a distributed system, as opposed to a central system, data is recorded in a small data-logger box located on or near each individual thermocouple. Not that long ago, single-channel data loggers with the storage capacity of a 3.5″ floppy disc cost close to $200. Now the cost is below $50 for multichannel models with much higher capacity. Sixty TCs could be monitored by six 10-channel data loggers, each connected to an array of 10 TCs.

Data loggers can be self-powered by internal batteries or supplied with AC or low-voltage direct current, so you can't always escape running some sort of wiring. The advantage of an independent, battery-powered data logger is that, unlike a network, it is always at work collecting data. For temperature-monitoring of laminates on board and at sea, round the clock for a week, an environmentally sealed, self-powered data logger is ideal.

For analysis and long-term recording, the data-logger memory is downloaded to a desktop or laptop computer, or sent to a central computer through a network connection. Old models used the RS232 plugs and software protocols for data transfer, typically a software package written in Basic programming language. The logger had to be brought relatively close to the input device due to RS232 cable-length restrictions. Modern data loggers have USB or Firewire plugs and protocols for fast, longer-distance data transfer by cable. There is an abundance of inexpensive process-monitoring-and-control software available to record, crunch, and display the information. Data loggers with either wireless 80211 B, G, or T Base 10 network connections are also common.

Getting Started

This article provides just enough information to get you started on using electronic temperature measurement in your shop. Want to learn more? There is no larger single source in the United States for good information as well as temperature-measurement products than OMEGA Engineering (Stamford, Connecticut). It shows up on the top of any Internet search-engine's listings when you type in "thermocouples" or "electronic temperature measurement." OMEGA's catalogs are packed with excellent technical information, and their product listings will give you a full perspective of what's available. The company's Web site (www.omega.com) matches the physical catalog in quality of information. Interestingly, OMEGA declined my request to interview one of their application engineers for this article. The manager I spoke to said, "Our engineers are too busy helping customers to talk to you for a magazine article." When I have been an OMEGA customer, that level of technical support has proved helpful.

Aside from OMEGA, there are hundreds of other vendors and manufacturers of electronic temperature measurement products. Search on "process monitoring software," and you will find dozens of packages for Mac and Windows operating systems that will record and display your data. Next in sophistication is software that offers process-control functions—perhaps operating relays that could control a bank of heaters and fans that are cycled on and off during a postcure cycle. The sky's the limit when temperature control is added to measurement.

I suggest starting out with a small budget for an electronic thermometer, some thermocouple cables and plugs, and an interest in temperature measurement. According to Goetz's Telfeyan, "If you need to monitor more than two or three channels, I'd strongly suggest that you dive right in and buy a computerized system. You don't need a fancy computer—I think ours is still running Windows 95—and the input boards and software are cheap." PBB

About the Author: *As "Bruce Pfund/Special Projects LLC," Bruce consults on composite processes and inspects marine composite structures. He is the technical editor of* Professional BoatBuilder.