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# Thermateq™-nology

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June 2004

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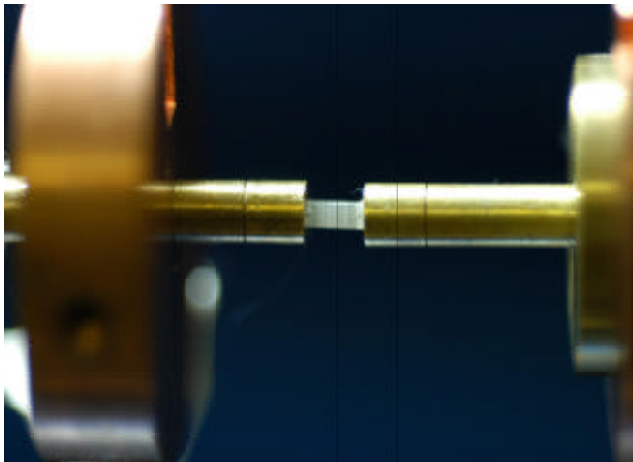
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## New Schmidt-Boelter Gage

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Vatell Corporation is proud to announce the newest addition to its product line, the Schmidt-Boelter gage. Heat flux gages of this type have been in use for many years. However, Vatell has developed an improved version of this sensing instrument.

Schmidt-Boelter gages are made by winding a spiral of Constantan wire around an electrically insulating wafer, then plating the turns on half of the wafer with copper. This process creates thermocouple junctions at the points on both sides of the wafer where the plating ends.



Schmidt-Boelter Winding Process

In a conventional Schmidt-Boelter gage, the thermocouples on one side of the wafer produce a first signal when a wave of heat energy reaches them, and the thermocouples on the other side of the wafer produce a second signal when the wave of heat energy reaches them. The two signals combine to produce a second-order response. With conventional construction the only way to achieve fast response is to use an extremely thin wafer. However, this does not eliminate

the second signal.

The patented (US 6,186,661) Vatell design isolates thermocouples on the back of the wafer and directs heat around them directly into the housing. Time response is inherently fast, and there is no second signal. Furthermore, the wafer does not have to be extremely thin. In fact, it is made thicker to reduce thermal resistance at the points of contact with the housing. Vatell uses wafers of aluminum nitride instead of anodized aluminum. Forty turns around a 3.5 mm substrate produce a sensitivity of 250 microvolts per watt/cm<sup>2</sup> and a first order response time of less than 10 milliseconds.

Schmidt-Boelter gages of the new design will be offered in a variety of housings, conduction or water-cooled, for measurement of total or radiant heat flux.

## BF Sensor to 170 °C

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We have improved the temperature rating of our BF sensor line. Until now these sensors have been rated at 150 °C. The new temperature rating is 170 °C, mainly the result of a change in soldering materials. The sensitivity, thermal resistance and geometry of these sensors is unchanged.

We have received many customer requests for sensors with the thin, flat geometry of the BF type, with even higher temperature ratings. We are planning other material changes which will further increase their temperature range. Our goal is to achieve ratings of 230 °C.

## HFM Space Qualified

Our HFM sensors have recently undergone space qualification testing. They will be used in a variety of applications that include measurements of the heat transfer during rocket launch. In these applications they will measure both total heat flux and radiative heat flux. Window adapters are used with the HFM's to create radiometers, for radiative heat flux measurements.

Most qualification tests were performed at a nearby test facility, Aerospace Testing. This company has a long history of performing tests for military and aerospace applications.

The first group of tests was for resistance to temperature change. The testing included 3 days of cycling between dry heat, moist heat and cold. Separate tests for dry and humid heat were then performed. A thermal shock test was performed in which the sensor was taken rapidly from room temperature to 200°C. It remained at 200°C for 10 minutes and was then rapidly cooled back to room temperature. The unit was also exposed to rain shower conditions.

The next set of tests was for tolerance to pressure changes. The unit was exposed to

high pressures and pressure cycles. A vacuum thermal transient test was also performed. In this test the unit was placed in vacuum and then the vacuum was rapidly released.

After this the units went through vibration, acceleration and shock testing. They underwent a logarithmic scan to find critical vibration frequencies. They were then exposed to two different random vibration tests and two sinusoidal vibration tests, at levels up to 30 g rms. After vibration testing the units were subjected to three axes of acceleration and six successive free falls. These were followed by a shock test and then a pyrotechnic shock test. After all of these tests, the units were subjected to electrical discharge testing in accordance with ESD S5.1-2001.

Our customer also performed some extreme performance tests in their specialized facilities. The results are confidential, but the HFM's passed.

We are happy to report that the HFM's passed this entire qualification testing program. Our customer approved the product for use in space and rocket applications. We are proud of this product and its performance during these tests.

### Customer Application: Thermal Window of Bottlenose Dolphins



At the University of North Carolina at Wilmington, research is being carried out on bottlenose dolphins using Vatell sensors. UNC Wilmington researchers, E. Meagher, W. McLellan, A. Westgate, D. Frierson and D. Pabst, and Mote Marine Laboratory researcher R. Wells are using heat flux measurements to learn more about how dolphins dissipate body heat. Aquatic environments remove heat at rates 25 times faster than air environments at the same temperature. Warm-blooded animals living in aquatic environments have adaptations that help them

minimize heat loss. These include reduced surface area to volume ratios and an insulating layer of blubber. They also have specialized vascular systems in their uninsulated appendages such as dorsal fins, pectoral flippers and flukes. Veins and arteries in these appendages are arranged like counterflow heat exchangers. The artery carrying warm blood is surrounded by smaller veins. Heat is readily transferred from the arterial blood supply to the returning blood in the veins, conserving body heat.

Earlier studies at UNC Wilmington examined heat flux at a single location on the dorsal fin.

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## Calibration News

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Calibrations are the heart of our business, and our sensors are only as good as their calibrations. We pursue continuous improvement in our calibration systems and procedures. Some adjustments to our calibration systems have been made recently, to make our calibrations as accurate, reliable and repeatable as possible.

We have set up a more robust ground plane around our black body furnace heat flux calibration system, to reduce electrical noise to a minimum. To measure the reference temperature more accurately, we have installed a NIST-traceable calibrated thermocouple in the Heat Flux Microsensor RTS calibration system.

We will continue to explore ways of improving our calibra-

tion systems and methods to ensure that our customers receive the most accurate heat flux measuring instruments available.

## Welcome Joe Reese

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Joe Reese has recently joined our staff to oversee ISO certification efforts and improve our manufacturing and quality systems. Joe has over 20 years of experience in a wide range of manufacturing and engineering fields. His education is in mechanical engineering.

When he is not working at Vatell, Joe is an accomplished ballroom dancer. He and his wife are also in the process of building an addition to their home.

We are happy to have Joe with us and look forward to working with him.

## ISO Information

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Vatell is in the process of becoming ISO 9001-2000 certified. We are documenting all of our procedures and double checking to be sure all required controls are in place. Our previously documented processes and established control parameters are now being updated to a standard format conforming to the ISO specification. We expect to apply for registration within 1 year.

One interesting fact that we have learned is the origin of the "ISO" name. Like many others we used to believe this was an acronym for International Standards Organization. In fact, the administering group is the International Organization for Standardization. ISO is derived from the Greek word isos, meaning equal.

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## Dolphin Heat Flux: Continued From Page 2

Following this work the researchers decided to study the influence of vascular structures on heat flux across the dorsal fin. To do this three locations were chosen on the dorsal fin. The locations were selected for comparison to prior studies and to determine the influence of the underlying venous structure. Heat flux and skin temperature were measured simultaneously on the dorsal fin at the distal tip directly over a superficial vein, at the center of the dorsal fin directly over a superficial vein, and at the center of the fin remote from a superficial vein. Measurements were made for approximately 15 minutes, under two conditions. The first was with the animal held stationary with its dorsal fin held above the water. For the second half of the test, the animal was held stationary with the dorsal fin submerged. To determine if the heat flux was related to breathing events and/or heart rate, data were also collected relating to these criteria simultaneously. The researchers found that the dolphin's dorsal fin was a spatially heterogeneous thermal surface. The underlying vascular structure strongly influences the heat flux associated with the fin. Therefore, a heat flux measurement recorded from a single location does not accurately represent the amount of heat the animals are dissipating. The study also found that heat flux across the fin varies with time under static conditions.

To get a better understanding of the dynamic function of the dolphin's thermal window, the researchers believe it would be useful to have data collected under more natural conditions. A special "pack" has been designed that will hold sensors in place temporarily on animals as they swim in the wild. Heat flux measurement test results are also being gathered and studied to determine how the animals adapt to seasonal changes.

The Vateq sensors being used in these studies were attached to the animals without harm, and the sensors survived in a harsh saltwater environment.

## **Noise Reduction and Theoretical Noise Limits for Heat Flux Measurement**

In measuring any electrical signal, the goal is to reduce the effects of noise as much as possible. This is especially true for sensor signals because they represent raw data that does not lend itself to correction schemes, like communication signals do. Reduction of noise is important for heat flux measurements, too; for most heat flux sensors, noise is the factor limiting low level measurements. This discussion explores theoretical noise limits, some common noise reduction techniques, and estimates the minimum resolvable heat flux based on theoretical noise limits.

### Minimum Theoretical Noise

For most heat flux sensors, thermal noise (also called Johnson noise) provides the noise floor for a heat flux signal. The voltage created by this noise is given by:

$$V_n = (4kTBR)^{1/2} \quad (1)$$

where  $k$  is Boltzman's constant ( $1.38\text{e-}23 \text{ J/K}$ ),  $T$  is the temperature in Kelvins,  $B$  is the bandwidth of the receiver in Hertz, and  $R$  is the resistance of the circuit in ohms. Other noise sources can ostensibly be eliminated; this represents a fundamental physical limit. Even so, the noise floor can be managed to some extent within the limitations of a given application. Strategies for noise reduction can be deduced from equation (1). Boltzman's constant obviously can't be changed, and the resistance of the sensor is fixed during production. But both temperature and bandwidth can be exploited to minimize noise.

The noise depends on the square root of the absolute temperature, so providing a good heat sink for the sensor is not just necessary for a reliable measurement (no heat sink = no heat flow = no signal) but also for reduction of noise. The minimum noise level is 50% higher at  $400^\circ\text{C}$  than it is at room temperature.

The noise also depends on the square root of the bandwidth of the receiver. The smaller the bandwidth, the less noise that will be picked up. Because the bandwidth range is much greater than the temperature range, the bandwidth will typically have a much greater impact than the temperature on the total noise. In most cases a wide bandwidth is only needed for fast time response, so when possible, set the bandwidth of the receiver by the Nyquist criteria:

$$B = 2/t \quad (2)$$

where  $B$  is the desired bandwidth in Hertz and  $t$  is the desired minimum resolvable time increment in seconds. The noise level is 10 times higher for a signal with a time resolution of 1 ms compared to one with a resolution of 100 ms.

### Noise Reduction

Knowing the minimum noise level is beneficial, but only if other noise sources can be eliminated. If this is not possible, the signal wire layout should be designed to resist noise. Common sources of noise are computer monitors, cooling fan and other motors, fluorescent lighting, high-current transformers, and noise carried on the power line. If any device appears to be producing noise, the best solution is to turn it off. A constant voltage transformer can screen out the noise from the power line, although the best solution is to run on independent batteries. Frequently the source of the noise cannot be eliminated, so the signal itself must be made as robust as possible.

Whenever possible, sensor signals should be measured differentially instead of single-ended. Differential measurement cancels noise picked up by the positive and negative legs of the signal wire, leaving only the desired signal. The differential configuration works best with twisted pair wire, because the twisted pair picks up noise more equally on the two wires than side-by-side wires. Shielded cable can be used to screen out noise as well, although the shield may pick up noise and add it to the signal.

Another important noise reduction technique is the elimination of ground loops. This may be more easily said than done, but can result in significant noise reduction. A ground loop is present when there is resistance between a circuit element and its ground. That resistance can create a voltage if the noise produces current through it. When connecting different components in a system to a common ground, always connect them in parallel, never in series. Connections to the common ground should be through heavy gage, low resistance wire. There should be only one connection to ground for each element. This can be trickier than it sounds, because there may be connections that were not made on purpose (e.g. through the sensor mounting), so testing with a good resolution multimeter can be helpful.

If there is still too much noise in the system, there are also some data acquisition techniques that can help. The most basic is to average data over some interval, which will tend to make high and low noise peaks cancel each other out. This technique limits the bandwidth, and hence the time response, by requiring many samples to be taken for each data point. The advantage is that it can be done by post-processing, so that the time-response versus noise level can be optimized. For slower signals, the data can be passed through a low-pass filter to screen out high frequency noise. To capture rapidly changing signals, the higher order frequencies must be accurately represented, so filtering techniques are less applicable.

### Minimum Resolvable Heat Flux

The minimum resolvable heat flux will depend on two things, the type of sensor being used and the desired signal-to-noise ratio (SNR). The required SNR will depend somewhat on the application, although typically a SNR of 1000 is considered good. A SNR of 100 is reasonable, but the accuracy will not be as high. Some useful information can even be obtained from a SNR of 10, although only order of magnitude measurements are possible. Any SNR below 10 is probably junk data. The type of sensor will also of course depend on the application, but for noise purposes the only important parameter is the resistance of the sensor. Here are some examples of minimum resolvable heat flux for Vatell sensors. We see again that the fastest sensors have to deal with the most noise.

For an HFM with a resistance of 3.6 kohms operating at 127°C (400 K) and being interrogated at 100 kHz to take full advantage of its time response, the minimum noise is 2.8  $\mu$ V. Assuming the HFM has a sensitivity of 150  $\mu$ V/W/cm<sup>2</sup> and we want a SNR of 100, the minimum resolvable heat flux is 1.9 W/cm<sup>2</sup>. If we drop the needed time response to 1 kHz, our minimum resolvable heat flux is 0.19 W/cm<sup>2</sup>.

For a Thermogage sensor with a resistance of 1 ohm operating at 127°C and being interrogated at 100 Hz for the fastest sensor, the minimum noise is 1.5 nV. Assuming the Thermogage has a scale factor of 2000 W/cm<sup>2</sup>/mV (which is a sensitivity of 0.5  $\mu$ V/W/cm<sup>2</sup>), and we want a SNR of 100, the minimum resolvable heat flux is 0.3 mW/cm<sup>2</sup>, or 3.0 W/m<sup>2</sup>.

For a BF sensor with a resistance of 49 ohms operating at 127°C and being interrogated at the fastest reasonable rate of 10 Hz, the minimum noise is 3.3 nV. Assuming the BF has a sensitivity of 50 mV/W/cm<sup>2</sup>, and we want a SNR of 100, the minimum resolvable heat flux is 6.6  $\mu$ W/cm<sup>2</sup>, or 0.066 W/m<sup>2</sup>.

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