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Passive, Wireless Temperature Sensor System for Harsh Environments

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Passive, Wireless Sensor Systems for Harsh Environments
Technology Description

Environetix Technologies Corporation (Orono, ME) is developing wireless, passive sensors and systems for harsh environments based on microwave acoustic sensor technology. The lightweight and low-profile nature of the sensor technology is achieved by using microwave acoustic devices that are less than 0.5 mm thick, a few mm^2 in size, and fractions of a gram in weight. Accurate and reliable sensing at high temperature results from the stable langasite piezoelectric family of crystals used as the sensing element and the novel, proprietary nanocomposite metallization layers derived from patented intellectual property licensed to Environetix. The miniature microwave acoustic sensors can be attached to typical turbine materials such as Inconel (Figure 1) and survive g-forces in excess of 50,000 g on rotating parts of turbine engines and at temperatures up to 1000°C. Although Environetix has initially targeted the development of temperature sensors capable of operating in harsh environments, the technology is also being developed to include sensors that measure pressure, strain, vibration, and corrosion.

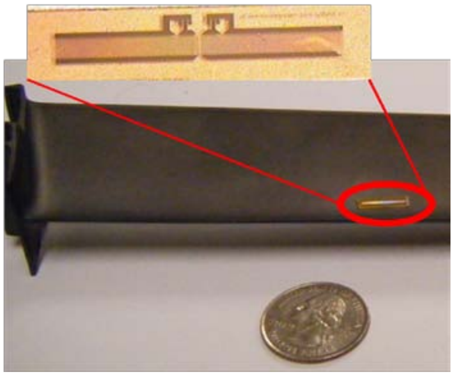

Figure 1: SAW sensor attached to a turbine blade

A key attribute of Environetix's sensor technology is the wireless interrogation capabilities of the sensor system. Wireless interrogation enables sensor operation in harsh environments on rotating parts. A single interrogation unit can be used for rapid sampling of multi-sensor arrays . Without wires, easier and more reliable sensor assignment to rotating parts is achieved, and there is improved flexibility in the sensor mounting locations. The wireless setup reduces overall weight and improves system reliability in harsh conditions, including high temperatures, high pressures, and corrosive gases. The sensors operate solely under the energy provided by the radio-frequency (RF) interrogating signal, eliminating the need for batteries or maintenance. Signal processing is performed outside the harsh environment; thus, the interrogation system can be constructed from reliable commercial components that do not need to survive in the same harsh environmental conditions.

Environetix Technologies Corporation is a technology-transfer start-up company spun out from high temperature microwave acoustic and thin film technology research in the Laboratory for Surface Science & Technology (LASST) at the University of Maine (UMaine). The interdisciplinary group at LASST involved in this work has extensive expertise in microwave acoustic wave materials and sensor devices, electrode thin-film processing and characterization at high temperatures, microwave propagation, wireless systems, and antenna design. These integrated components are well-developed and have benefited from a wide range of basic and applied research carried out at UMaine over the past ten years.

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Technology Background

Microwave acoustic sensors rely on acoustic wave technology. Among the acoustic wave modes that can be used for sensing — e.g. bulk acoustic wave (BAW), film bulk acoustic resonators (FBAR), acoustic plate modes (APL), and surface acoustic waves (SAW) — the SAW offers the greatest flexibility for direct implementation of distinct filtering and sensing applications by applying one layer of metallic electrodes on the surface of a piezoelectric crystal (Figure 2). SAW devices operate by transducing an electrical signal to electromechanical waves that propagate on the surface of a crystal, like waves propagating on a lake surface, when mechanically disturbed. Transduction for a SAW device relies on the use of piezoelectric crystals, which deform under the application of the electrical signal. Any change within the SAW environment, such as variation in temperature or pressure, affects the wave propagating in the structure. These changes in propagation are directly sensed by the device. Proper device design is needed to sense different measurands, and sensor performance is dictated by the specific piezoelectric crystal material, crystallographic orientation, and patterned electrode geometry.

As shown in Figure 2, both the input and output structures consist of a periodic interdigitated transducer (IDT) electrode structure with several wavelength periodicities, λ. The synchronous operation of the IDT at the surface launches an electromechanical wave which propagates at ~ $3x10^3$ m/s, five orders of magnitude slower than the propagation of the electromagnetic wave (EM) in vacuum ($3x10^8$ m/s). This allows for a significant delay from input to output, namely five orders of magnitude longer delay than for an EM wave propagating in air using a similar sized structure. For this reason, the device utilizing the IDT geometry shown in Figure 2 is called a delay line, and represents one of the many possible signal processing devices enabled by SAW technology. These devices are very small, ranging from a few millimeters to sub-millimeters in length depending on the frequency of operation (typically between a few MHz to several GHz).

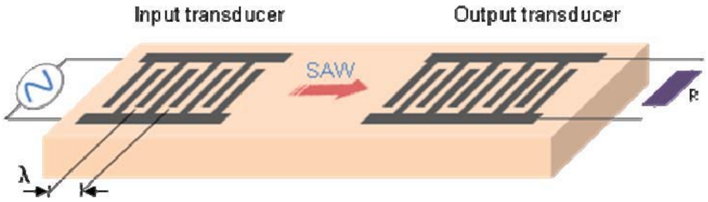

Figure 2: SAW delay line

In addition, the wireless surface acoustic wave tag (Figure 3) offers a SAW device configuration allowing wireless interrogation powered only by a radio frequency (RF) interrogating signal. Such passive operation eliminates the need for batteries or other external power source. Furthermore, SAW sensor technology supports coding, which permits multiple sensor wireless interrogation — an important feature that allows temperature, pressure, or other measurands to be extracted from multiple locations by a single interrogation unit.

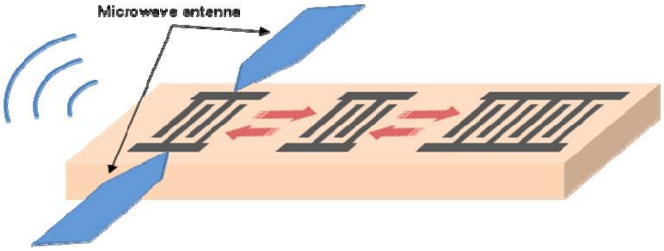

Figure 3: Wireless SAW tag and sensor

Environetix's reliable and accurate wireless harsh-environment sensor technology is based on SAW devices with three key features. First is the piezoelectric crystal substrate that can tolerate operation at high temperature (over 1000^{o}C) and withstand large temperature fluctuations. Conventional acoustic wave materials commonly used for commercial SAW communication applications (quartz, lithium niobate, lithium tantalate) cannot withstand rapid thermal shock or temperatures near 1000°C due to crystal phase transitions, thermal shock cracking, or accelerated crystal decomposition and degradation. A new family of piezoelectric crystals, named langasite (LGS), allows for operation at temperatures up to their melting point (~1470°C for LGS). The Environetix team has extensive experience with the LGS family of crystals exposed to temperatures up to 1300°C and corresponding SAW devices operated at temperatures as high as 1000°C.

The second key feature involves stable IDT electrodes that can withstand and operate at elevated temperatures. Environetix has licensed the patent rights for novel high temperature Pt/Rh/ZrO_2 electrodes developed at the University of Maine. The simplicity of the LGS device architecture, consisting of a polished crystal with microlithographically printed thin-film IDT electrodes on top, yields a sensor device with passive operation, design flexibility, ruggedness, and reliability.

The third key feature is wireless interrogation capability. The Environetix technology makes possible sensor operation on both static and rotating parts, including rapid sampling of multi-sensor arrays with a single interrogation unit. Removal of wiring:

- allows easier and more reliable sensor mounting to rotating parts
- yields improved flexibility in assigning sensors to different locations within a engine (inlet, compressor, exhaust) or other pieces of industrial equipment
- leads to reduced overall weight, and
- improves system reliability in harsh conditions including high temperatures, high pressures, and corrosive gases.

The sensors operate solely under the energy provided by the radio frequency (RF) interrogating signal, without the need for batteries and maintenance. The signal processing takes place outside the harsh environment area, thus allowing the interrogation system to be constructed from reliable, developed commercial components that do not need to survive in the same high temperature environments.

Passive, Wireless Sensor Systems for Harsh Environments

Technical Achievements

Environetix, in collaboration with the University of Maine (UMaine), has pioneered the introduction of harsh environment sensors and systems for operation up to 1000°C, with potential to 1300°C. Laboratory tests have demonstrated wireless temperature sensors with: (i) stable continuous operation for 5½ months without measurable degradation at 800°C; (ii) successful performance during multiple cycling between room temperature and 850°C; and (iii) thermal shock resistance as measured by propane torch shock treatments and exposure in the exhaust of small scale turbine engines up to 800°C.

Environetix has also conducted long-term tests to demonstrate the stability and minimal drift of SAW sensors at 650°C in a laboratory furnace. For this test, two SAW sensors were selected. One sensor was wire bonded to high-temperature cables and directly connected to the network analyzer (referred to as the “Wired sensor”) while the other was interrogated wirelessly (referred to as the “Wireless sensor”). The sensors were placed inside a temperature controlled furnace and subjected to the temperature profile shown in Figure 4. This temperature profile consisted of the following steps:

1. Four complete thermal cycles were performed between 200°C and 650°C with a thermal soak at 650°C for 30 minutes during each cycle. The ramp rate was approximately 25°C/min and the cooling rate was approximately 4°C/min.
2. After the final thermal cycle, the furnace was ramped to 650°C and the sensor was allowed to soak at 650°C for 137 hours.
3. The sensor was then exposed to a second set of four full thermal cycles between 200°C and 650°C.

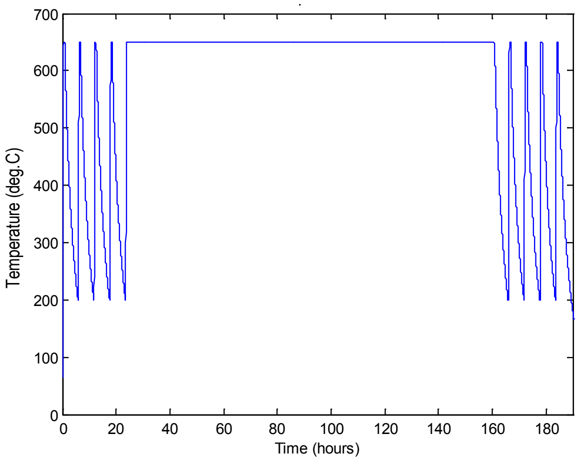

Figure 4: Temperature profile for long term test

For each sensor, a calibration curve was created to convert device response to the corresponding temperature. Using the calibration curves, Figure 5 and Figure 6 show that both the Wired and Wireless sensors accurately monitored changes in temperature over the entire test. Since the performance of each device at 650^{o}C before, during, and after the long hold is of primary interest (as these periods are where any sensor aging would be observed) these data were analyzed in detail.

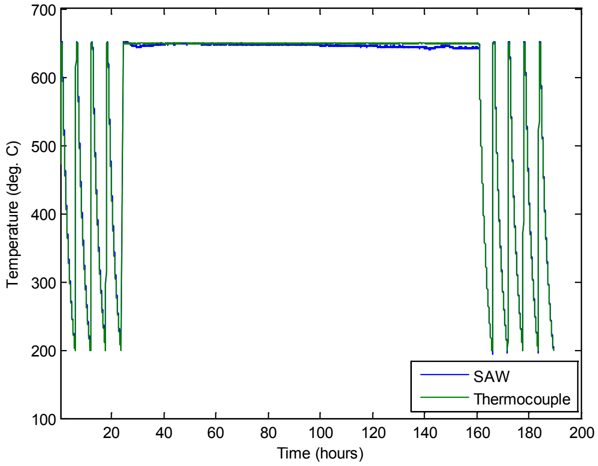

Figure 5: Temperature measured by thermocouple and Wired sensor

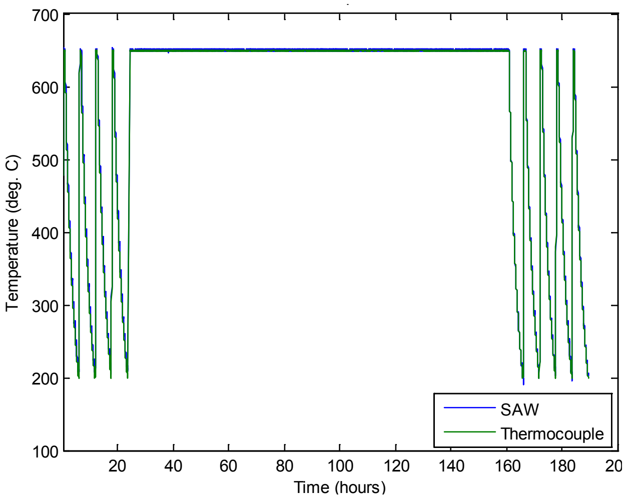

Figure 6: **Temperature measured by thermocouple and Wireless sensor**

Figure 7 and Figure 8 show the difference between the temperature measured by the furnace thermocouple and the temperature determined from the SAW resonant frequency during each of the 30 minute temperature holds at 650^{o}C. In both cases, the temperature measured by the SAW sensors was within +/- 3^{o}C of the temperature measured by the thermocouple, which is within the measurement error of the thermocouples. These results indicate that both the Wired and Wireless SAW sensors are highly accurate in this temperature range. Even more importantly, there is no sign of sensor aging or degradation after the 137 hour hold at 650^{o}C.

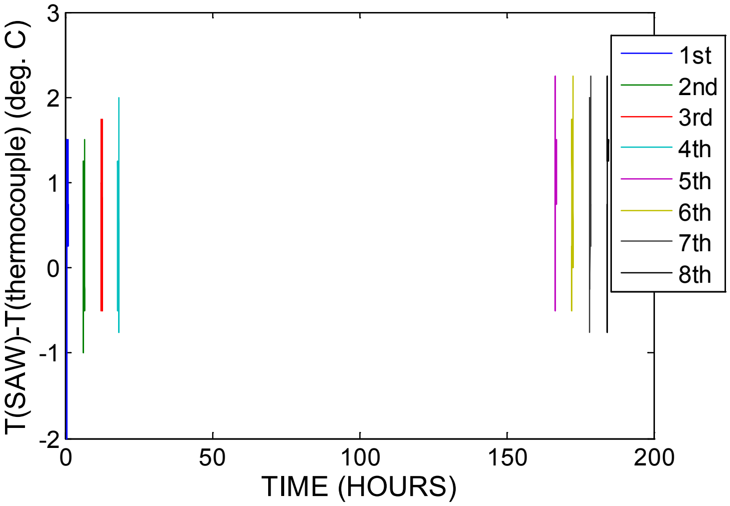

Figure 7: Measurement discrepancy (T_{SAW}-$T_{thermocouple}$) during the eight 650°C holds for Wired sensor

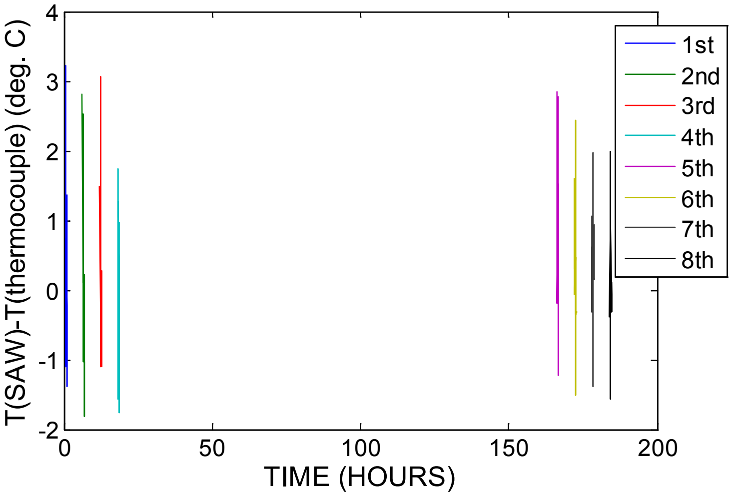

Figure 8: **Measurement discrepancy (T_{SAW}-$T_{thermocouple}$) during the eight 650°C holds for Wireless sensor**

Figure 9 and Figure 10 show the difference between the temperature measured by the furnace thermocouple and the temperature determined by both the Wired and Wireless SAW sensors during the 137 hour temperature hold at 650°C. The Wireless sensor is accurate to within +/- 2°C during the entire long temperature hold with no signs of sensor aging or degradation. The +/- 2°C error is within the accuracy of the thermocouple that was used as the figure of merit. The Wired sensor exhibits slightly more drift (variation between +2°C and -9 °C). This apparent error is actually due to the fact that the Wired sensor is attached to an Inconel coupon which is thermally connected to an Inconel coaxial cable that feeds outside the furnace acting as a heat sink. The actual temperature of the Wired SAW device may in fact be less than the temperature measured by the thermocouple and is affected by the temperature outside of the furnace. **This result highlights one of the primary strengths of Environetix's technology: The sensors measure the actual temperature of the object that the sensor is in contact with (turbine blade, etc.), unlike a thermocouple or similar technology which only measures the temperature of the surrounding environment.**

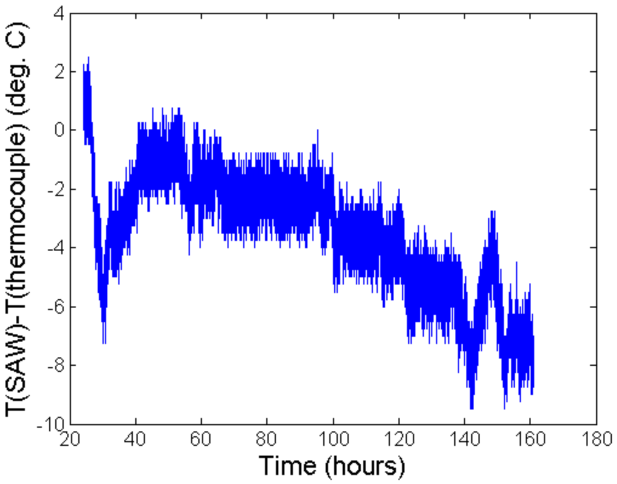

Figure 9: Measurement discrepancy (T_{SAW}-$T_{thermocouple}$) during long hold for Wired sensor

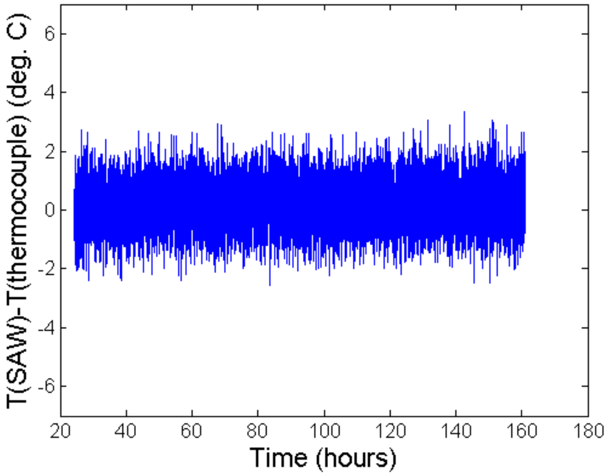

Figure 10: **Measurement discrepancy (T_{SAW}-$T_{thermocouple}$) during long hold for Wireless sensor**

Sensor packaging and attachment methodologies for integrating the sensors onto to high-speed rotating parts (>50,000g) have also been developed. Packaging was developed for both static long-term operation (testing in furnaces at 800°C for 5½ months); cycling between room temperature and 850°C; abrupt shock in temperature between room temperature and 800°C in seconds; and high rotational speed operation in turbine engines. Proprietary high-temperature epoxies, thermal spray techniques, and combinations of these two methods were developed.

This proprietary sensor attachment methodology has been successfully tested by an outside company, Vextec Corporation. For these tests, 10 wireless SAW sensors were attached to blades on an Inconel disk (see Figure 11). Initially the disk was rotated in the exhaust of a jet engine at 12k, 16.3k, 20.2k, and 24.3k rpm, which translates to g levels of 14k, 26k, 40k, and 58k on each sensor. The exhaust temperature was held constant at 1200^{o}F (650^{o}C). No attachment failures or sensor degradation occurred during these tests. In subsequent tests, the sensors were subjected to 10, 30, and 60 minute tests at 1200^{o}F (650^{o}C) and 24.3k rpm (58k g), with no failures. Finally, the sensors were subjected to temperature snap tests using the test profile seen in Figure 12. Again, no failure occurred.

Figure 11: SAW sensors attached to test disk

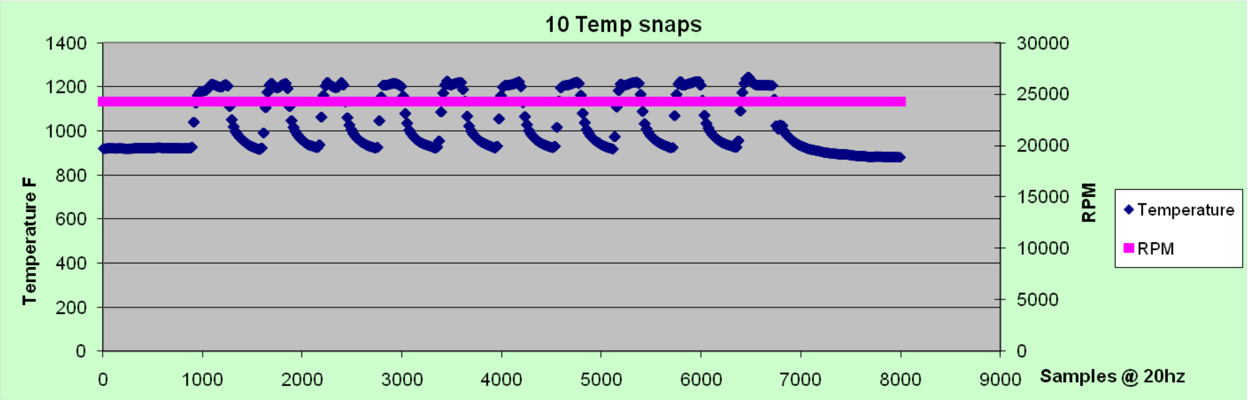

Figure 12: Temperature snap test profile

Multiple wireless interrogation systems were also investigated for operation in harsh environments using LGS SAW sensors: 15-bit coded transducers CDMA LGS SAW sensors, tested up to 750°C; frequency-modulated continuous-wave or frequency-stepped continuous-wave sensors (FMCW or FSCW), also tested up to 750°C; and LGS SAW resonator sensors interrogated both in the time and frequency domain, to above 910°C. For the resonator-based system, the high-Q of the resonator response provides the means for sensing based on variation of the resonant frequency. Improvements in the SAW resonator design and integrated sensor-antenna design provided multi-sensing interrogation of SAW devices at temperatures above 910°C using frequency multiplexing. An example of the simultaneous wireless interrogation response of 6 sensors operating at 850°C is shown in Figure 13.

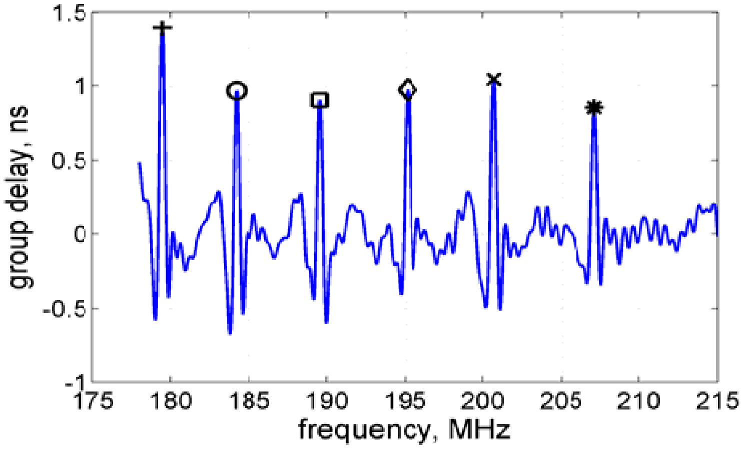

Figure 13: Wireless system response of 6 SAW sensors interrogated simultaneously at 850 °C, demonstrating the multi-sensing capability.

Finally, LGS SAW sensors were assembled to Inconel disks and attached to an integrally bladed rotor (IBR) in the 4-inch diameter exhaust section of a JetCat turbine engine (inset, Figure 14). During this test, the hybrid structure of a LGS SAW sensor with Pt/Rh/ZrO_2 thin-film electrodes and a Pt-wire antenna was attached to the IBR where it experienced turbine engine environments with temperatures over 525°C, and up to 65,000 RPM. Typical wireless temperature sensing data acquired during operation of the JetCat turbine is shown in Figure 14, indicating the direct temperature profile measured wirelessly at the rotating Inconel part.

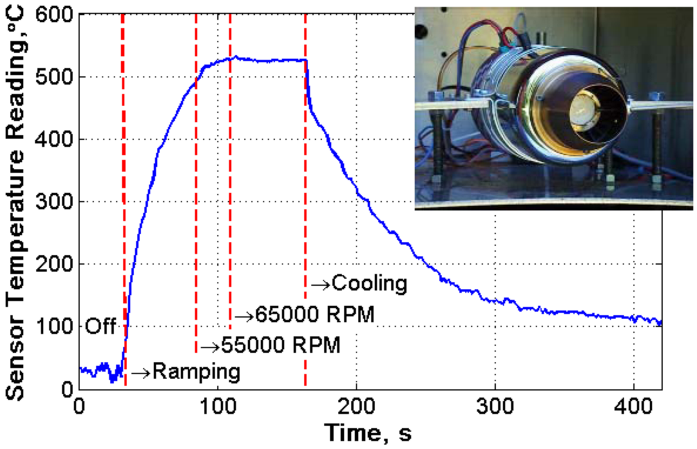

Figure 14: The temperature on the integrally bladed rotor (IBR) in the exhaust section of a JetCat turbine engine during operation, measured wirelessly with a passive SAW sensor