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Abstract. A promising wireless telemetry infrastructure based on acoustic transmission of in-pile measurements (information) is being developed at the Idaho National Laboratory for use in nuclear reactors. A nuclear reactor core used either for research or commercial power production, presents a particularly harsh environment for sensors, while simultaneously imposing challenging constraints on the transmission of their signals outside the reactor. The traditional approach to these problems is to "harden" conventional sensors and their associated signal-conditioning electronics against the degradation introduced by intense fluxes of energetic particles and waves. In this paper, we will demonstrate a completely different approach to telemetry and sensing that exploits a reactor core's energy-rich environment to generate acoustic telemetry signals from self-powered telemeters that produce sounds. These sounds propagate through the reactor's coolant, whether it is gas, water, or liquid metal, through its mechanical structures (*e.g.*, lattice work, pressure vessel, and piping), and can be detected outside the reactor. This novel thermoacoustic (TAC) approach is being developed and tested by Idaho National Laboratory, Pennsylvania State University, and Westinghouse. The objectives for developing a vibroacoustic infrastructure are as follows:

- Design infrastructure to transmit data through physical boundaries normally found in nuclear facilities. The sensor data may be gathered simultaneously from multiple sensors and types (*e.g.*, temperature or energetic particle fluxes) by frequency-division multiplexing.
- Address the demand for measurement and control technology that can monitor in-core processes and materials through the intrinsic self-powering and acoustically telemetered nature of TAC.
- Establish that the acoustic-based infrastructure will operate effectively even under accident scenarios, because the transmitter is self-powered and acoustically telemetered, and because design of TAC telemeters takes advantage of thermal gradients, radiation, cooling fluid, and structures within and surrounding a reactor's core.
- Develop a fully-functional telemetry infrastructure to provide reliable and actionable process and material characterization data in research reactors and commercial reactors.

The technology required to acoustically telemeter temperature [1] and power information [2] from the core of a nuclear reactor to the exterior, while going through multiple physical boundaries without requiring external electrical power or wiring, is detailed in this paper. In doing so, a new vibro-acoustical paradigm for in-pile telemetry and sensing has been created. This acoustic infrastructure will provide useful information in a reactor accident, such as the one that destroyed the Fukushima complex in March 2011.

Keywords: Acoustic, sensor, telemetry, wireless, self-powered sensing, thermoacoustics

INTRODUCTION

The core of a nuclear reactor, used either for research or commercial power production, presents a particularly harsh environment for sensors while simultaneously imposing challenging constraints on the transmission of their signals outside the reactor. Although many sensors used in reactors, like thermocouples and charge collection flux sensors (*e.g.*, rhodium wires), are self-powered, each sensor requires at least two signal wires that must penetrate the reactor vessel. The situation for sensors or data transmitters that require even small amounts of electrical power to be provided within the reactor create further complications, as well as additional wiring requirements. Management of those wiring harnesses and pressure vessel feed-throughs makes fueling and other inspection and maintenance tasks more difficult and wire breakage or loss of external electrical power availability under accident conditions can lead to serious problems. [3] Testing with thermocouples has shown that the harsh reactor environment can also cause significant sensor drift and performance degradation with time. [4]

The conventional solution to these problems is to “harden” conventional sensors and their associated signal-conditioning electronics against the degradation introduced by intense fluxes of energetic particles and waves. In this presentation, we will demonstrate a completely different approach to telemetry and sensing that exploits a reactor core’s energy-rich environment to generate acoustic signals from self-powered sensors which produce sounds that can propagate through the reactor’s coolant, whether it be gas, water, or liquid metal, and be transmitted through its mechanical structures (*e.g.*, lattice work, pressure vessel, piping) and be detected outside the reactor.

A salient grand challenge for a number of Department of Energy Programs, such as Fuel Cycle Research and Development (FCRD) which includes accident tolerant fuel research and the resumption of transient testing of nuclear fuels and materials at Idaho National Laboratory (INL), Light Water Reactor Sustainability, National Science User Facility and Advanced Reactor Technologies, is to enhance our fundamental understanding of fuel and material behavior subjected to intense irradiation. Robust and accurate in-pile measurements will enable development and validation of a computationally predictive, multi-scale understanding of nuclear fuel and materials linking fundamental micro-structural evolution mechanisms to macroscopic degradation. One of the major obstacles to development of practical, robust, and cost effective in-pile sensor systems is instrument lead requirements. If a wireless telemetry infrastructure can be developed for in-pile use, in-core measurements would become more attractive and cost effective.

In the following, we provide a high-level overview of a promising wireless telemetry infrastructure based on acoustic transmission of in-pile measurements (information). This novel approach is being developed and tested by INL, the Pennsylvania State University (PSU), Westinghouse, and IST Mirion. This team of collaborators was assembled to accelerate the transfer of TAC technology from a University and a National Laboratory and to both the power and in-core sensor industries. We also present data from the first fission-powered TAC sensor that was tested in the core of PSU’s Breazeale Nuclear Reactor in September, 2015, as well as acoustically telemetered data from the Advanced Test Reactor (ATR).

Acoustically-Enabled Telemetry System

When contemplating technologies to transmit sensor information out of a reactor vessel, it is almost self-evident that acoustics would be synergistic with the nuclear reactor environment. Unlike radio-frequency telemetry, requiring an external electrical power source and propagation through the electromagnetic shielding effects of water, acoustic signals take full advantage of the structural components used in the construction of reactors when communicating the measured signals to the outside world. In our initial implementation, the telemetered signal is a resonant acoustic frequency; a pure tone. Most structural components that comprise a reactor, including the cooling fluid, will readily transmit such a continuous acoustic tone. The reactor’s volume can literally be filled with the sound produced by a multiplicity of such acoustically-telemetered sensors. Internal structural latticework and piping can act as acoustic wave guides that can function as “acoustic antennas” that transmit sound directly to receivers. The acoustic signal’s frequency is encoded in a similar manner as FM radio transmissions and its amplitude also contains useful information, as long as the amplitude is above the background noise levels within the relatively narrow frequency range of interest. Hydrophones can be placed within the reactor fluid or accelerometers or other vibration sensors can be placed on the exterior of the reactor vessel or piping to receive the signals. Multiple sensors can be frequency multiplexed, thus many sensors can be utilized and monitored simultaneously by a single acoustic receiver. The transmission and detection of signals by the acoustic receiver is completely cable free; a truly wireless technology.

Thermoacoustic Signal Production

The production of sound by heat has been observed as an "acoustical curiosity" since a Buddhist monk reported the loud tone generated by a ceremonial rice-cooker in his diary, in 1568. [5] In 1850, Karl Friedrich Julius Sondhauss investigated an observation made by glassblowers who noticed that when a hot glass bulb was attached to a cooler glass tubular stem, the stem tip sometimes emitted a pure tone. [6] The Sondhauss tube is the earliest thermoacoustic engine that is a direct antecedent of our fission-powered sensor. [7]

The first qualitative explanation of these acoustical curiosities was provided by Lord Rayleigh: "If heat be given to the air at the moment of greatest condensation or be taken from it at the moment of greatest rarefaction, the vibration is encouraged." [8]The standing sound wave created by a temperature gradient transfers heat from a solid substrate to a gas in a manner that is analogous to a four stroke car engine: compression, heat input, expansion, exhausting of heat. The thermoacoustic engine is an extremely simple heat engine when compared to an automobile engine that requires pistons, valves, cams, rocker-arms, flywheel, etc. to ensure that the compressions and expansions are synchronized with the heat input and exhaust at the proper phase in the cycle. The pressure changes induced by the sound wave synchronizes the strokes in a thermoacoustic engine. The standing-wave thermoacoustic process requires no moving parts other than the oscillation of the gas. The thermoacoustic engine can be constructed from materials found in reactors. The details of the thermoacoustic process for reactor use are found in our earlier publication. [9]

The thermoacoustic engine used in the experiment reported here is shown in Fig. 1, along with the supporting structure that had the same dimensions as the other fuel rods in the reactor. The resonator was supported within that structure by two springs that allowed the vibratory motion of the resonation that radiated the sound into the surrounding coolant. Fig. 2 shows the hot heat exchanger that was placed in the larger-diameter section of the resonator and contained to $^{235}UO_2$ fuel pellets. For the results we report here, we used a nuclear fuel as the heat source for our thermoacoustic engine and the exhaust heat was rejected to the reactor cooling fluid to sustain the necessary thermal gradient. In most circumstances, it would be preferable to provide the engine's heating by gamma-ray absorption, since gamma absorbing materials do not become depleted and are not regulated.

Signal Transduction and Telemetry

The beauty of the thermoacoustic engine is that the transduction mechanism for certain physical phenomena is intrinsic to the heat engine. Changes in temperature, resonator length, and gas composition are encoded in the frequency of the sound. [1] Neutron or gamma absorptions are encoded in the amplitude of the sound. [2] Although the intrinsic transduction capabilities of the TAC heat engine, developed by INL, have now been demonstrated in the core of a nuclear reactor, [10] other schemes can be developed to encode the acoustic signals for sensing different parameters. An acoustically transduced sensor, reported by Thompson and Holmes [11], was developed at Oak Ridge National Laboratory. They used acoustics to convert eddy current induced vibrations within a graphite reactor to telemeter RF signals that characterized microstructure.

The INL developed TAC sensor is shown in Fig. 1. It was designed to be geometrically indistinguishable from the other Training Research Isotopes General Atomics (TRIGA) fuel elements in the Breazeale reactor's core. Heat was produced by fission of two Pathfinder $^{235}UO_2$ fuel pellets contained within a finned heat exchanger produced by additive manufacturing technology shown in Fig. 2. [12]. The sensor's resonance frequency is dependent upon the resonator's length and the sound speed of the gas in the resonator. The gas is in good thermal contact with the coolant, and thus is a measure of coolant temperature, because of the acoustically-enhanced thermal contact due to streaming [13]. The radiated sound amplitude can be correlated with reactor power. The acoustic signals from the TAC sensor can be picked up by hydrophones and accelerometers anywhere in the reactor pool and from structures that penetrate the pool. The accelerometers were attached to structures in and out of the water that can couple sound-induced vibrations to the sensors. One such accelerometer is even mounted on an external structure. Most of the signals we acquired had sufficient signal-to-noise ratios even with both the ^{16}N diffusion pump and the pool coolant pump operating.

In-Core Test Results

The TAC sensor was tested during eight irradiation runs in the Breazeale Nuclear Reactor over the span of a week. Figure 3 is a time record made during the 5^{th} irradiation. It shows the temperature of the thermocouple that was brazed to the hot-end of the TAC resonator, contained within the insulation space, as well as the output of two hydrophones that were located far from the core in the reactor's coolant pool. Short Time Fast (essentially sliding-average) Fourier transforms of ten-second time records were produced every two seconds and the frequency of only the largest-amplitude spectral component is plotted in Fig. 3 for both the hydrophones. The TAC sensor achieved onset at about t = 810 s, which is the time the largest amplitude spectral components for both the hydrophones coalesced at the same frequency. Before onset of thermoacoustic oscillations (t < 810 s) and after their cessation (t > 1,100 s), the frequencies of the dominant spectral components from both hydrophones' signals are fairly random and were different due to the proximity of the hydrophones to the sources of pump noises in their respective locations. This is as would be expected when the pump noises were received within the displayed bandwidth, $\Delta f = \pm 40$ Hz.

Figure 4 shows one of several accelerometers that were attached to structures external to the reactor's coolant pool. The spectrogram displays the frequency of the detected vibration as a function of time with the amplitude of the signal coded as color from blue to yellow. Because the characteristic impedance of the water is close to the impedance of the solid structures that penetrate the reactor pool, the sound produced by the TAC sensor coupled well to those structures.

As demonstrated in Fig. 5, we were able to show that the frequency of the thermoacoustically generated sound provides an accurate determination of the reactor's coolant temperature. The speed of sound in an ideal gas or gas mixture, c, is pressure independent and related to the acoustically-averaged absolute (Kelvin) temperature, T, the mean molecular mass of the gas mixture, M, the mixture's polytropic coefficient, $\gamma = 5/3$, and the Universal Gas Constant, $\Re$: $c = (\gamma \Re\, T / M)^{1/2}$. Ignoring the small localized changes in the resonator's otherwise uniform cross-sectional area caused by the partial occlusion produced by the porous heat exchanger and stack, the fundamental resonance frequency of the thermoacoustic sensor occurs when the wavelength of the sound in the gas mixture, $\lambda = c/f$, is twice the resonator's length, $L \cong \lambda/2$: $f^2 = (c^2/4L^2) = (\gamma \Re T / 4\, M\, L^2) \propto T$. As is apparent from Fig. 5, just forming the ratio of the square of the measured resonance frequency, f^2, to the absolute (Kelvin) temperature of the reactor's coolant, T, produces values of f^2/T that vary by only ±0.12%, while the temperature changes by 3.4%.

ATR Vibroacoustic Infrastructure

As a salient part of the TAC technology transfer to reactor research and industry, an acoustic receiver infrastructure has been installed at the ATR to measure acoustic emissions from within the reactor. The ATR is the next logical venue for testing TAC telemetry and sensing. A TAC sensor has already been designed and is scheduled for insertion in the ATR as part of the 2017 Accident Tolerant Fuel Sensor Experiment.

In preparation for using a TAC sensor in the ATR, the acoustic background signatures in the ATR were characterized. The First Acoustic Baseline Signature of ATR from start-up to shut-down has been generated by the acoustic receiver infrastructure at the ATR, and is shown in Fig. 6. Data is being taken, analyzed, and archived so that the various operational states of the ATR can be identified and used for TAC sensor design as well as for diagnostic and prognostic applications. The following are the objectives of the current ATR acoustic monitoring effort:

- Develop an acoustic baseline for the ATR under a variety of operating conditions.
- Identify quiescent frequency regions for TAC sensing exploitation.
- Develop acoustic signal processing techniques to provided improved signal-to-noise ratios and subtract background signatures.
- Identify potential diagnostic and prognostic health monitoring opportunities.

The ability of the ATR acoustic receiver infrastructure to monitor active noise sources emanating from within the reactor has been successful. The periodic pressure pulses from the five-vane pump attached to the rotating shaft of the primary coolant pump makes an excellent "surrogate" TAC signal source. The frequency and harmonics generated by the pump vanes are nearly identical to signals that would be generated by TAC sensors inserted into the reactor core. Surrogate TAC signals allow us to understand and anticipate the changes in frequency, amplitude, and phase of an actual TAC sensor signal.

The surrogate TAC signals generated by the cooling pump provide insight to effectively detect signals from an actual TAC sensor. The data shows that the majority of the ATR reactor noise has frequencies above 2 kHz. TAC sensor signals will be designed to operate within the quiescent frequency range below 2 kHz and produce signal amplitudes well above the noise floor. The receivers have sufficient amplitude sensitivity to monitor three or more harmonics generated by the cooling pumps with a frequency resolution better than 0.02 Hz and a phase resolution below six degrees. Thus the acoustically-telemetered technique has the capability of making high-fidelity observations that will allow for sensitive in-core thermal, microstructural, and radiation measurements produced by acoustic sensors. In summary, the ATR reactor makes a surprisingly good signal transmission medium for acoustic signals below 2 kHz.

FIGURE 1. “Fuel rod” thermoacoustic sensor. (Above) The thermoacoustic resonator is shown at the center of the photograph. (Below) The resonator and suspension springs are contained within a “slotted tube” that has the same outer diameter as the reactor’s fuel rods. The thermoacoustic sensor can be designed to meet the same geometrical constraints as most fuel rods.

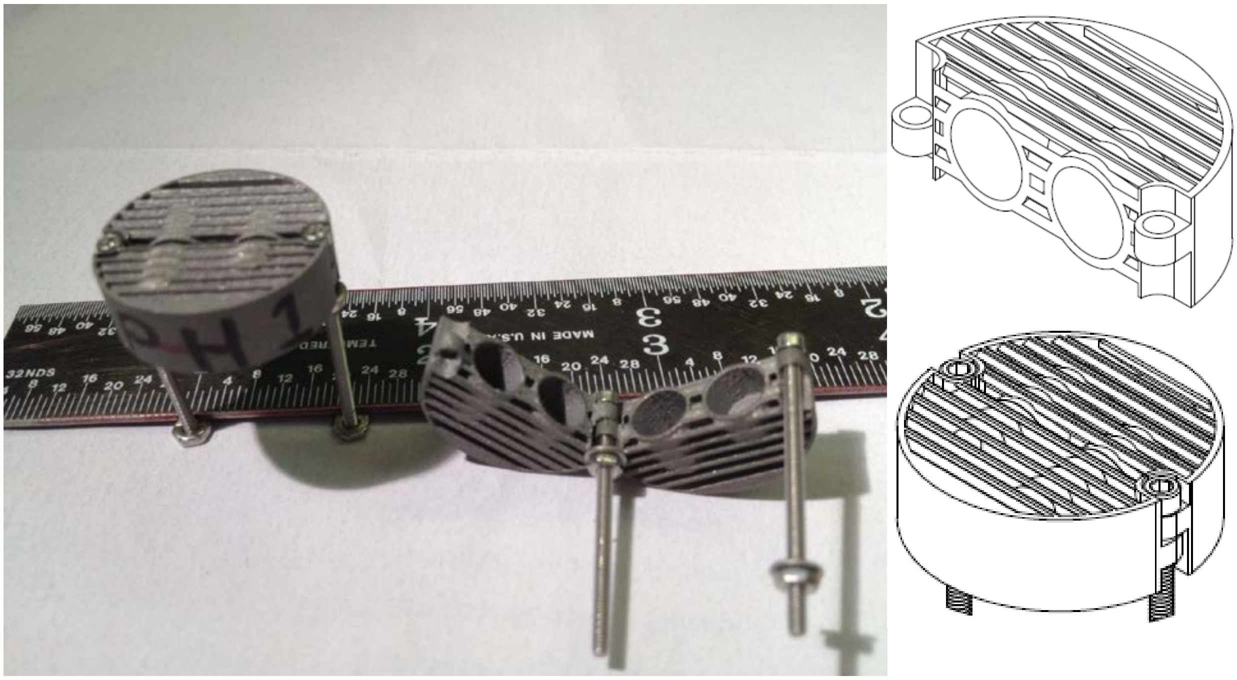

FIGURE 2. (Left) Photograph of the stainless-steel two-part heat exchanges that contained the two $^{235}UO_2$ fuel pellets. (Right) Three-dimensional renderings of one of two identical pieces (upper) that are shown joined together by two 0-80 machine screws.

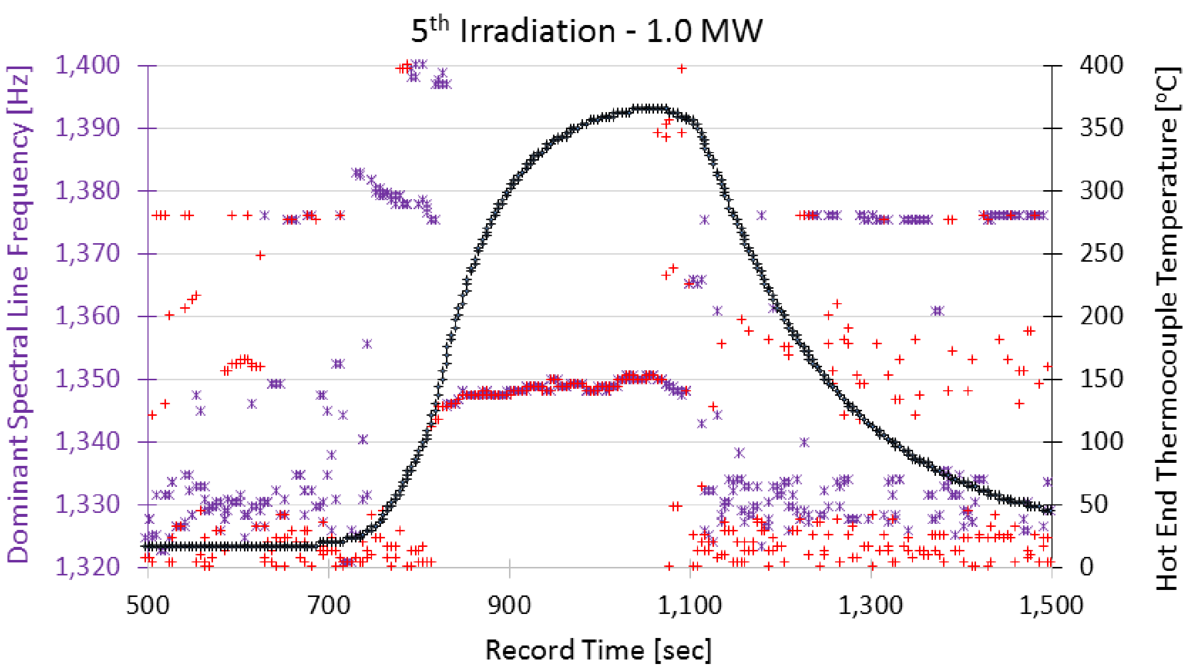

FIGURE 3. Time record of the resonator's hot-end temperature and the frequency of the largest spectral component received by two hydrophones at different locations. The temperature of a Type-K thermocouple is plotted as the black diamonds. The blue "x" and red "*" symbols are the frequencies of the largest spectral component within the frequency range between 1,320 Hz ≤ f ≤ 1,400 Hz. The reactor reached full power (1.0 MW) at $t \cong 800$ s. The reactor power was reduced to 800 kW at $t \cong 1{,}060$ s, then the reactor was shut down at $t \cong 1{,}100$ s. The frequency only gets locked in when there is enough reactor power to energize the TAC engine.

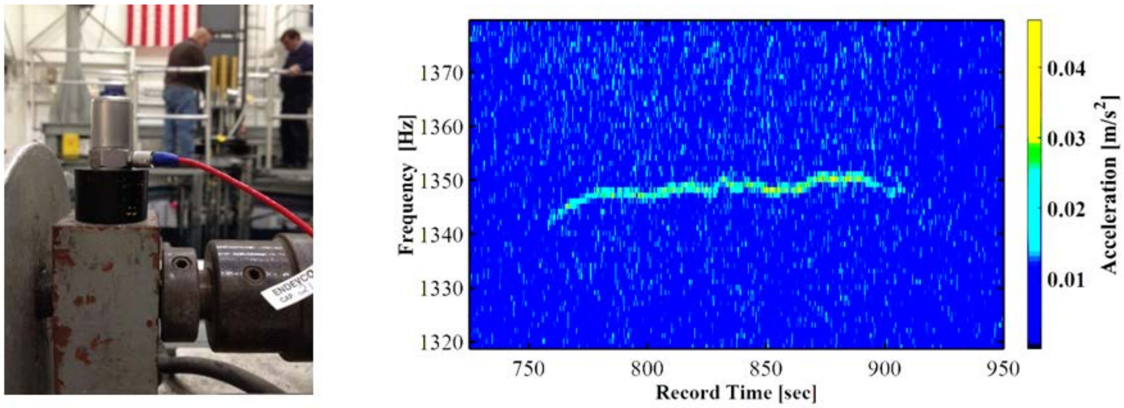

FIGURE 4. Time record (spectrogram) of the vibration signal received by an accelerometer mounted on a structure outside the reactor pool. (Left) An accelerometer with a magnetic base (black) is attached to the motor mount of an instrumentation tower that extends into the reactor pool. (Right) Spectrogram showing the accelerometer's output frequency on the vertical axis as a function of time represented by the horizontal axis. The thermoacoustic sensor's signal is clearly visible above background noise.

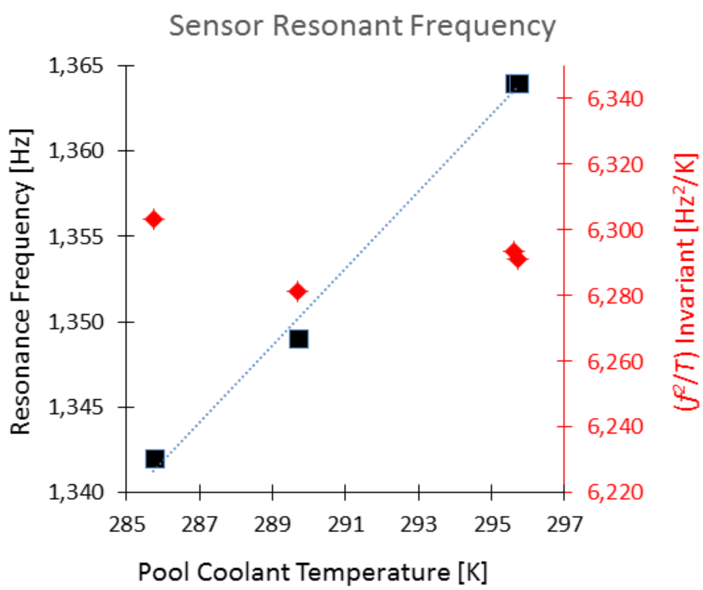

FIGURE 5. The resonance frequency of the thermoacoustic sensor's standing-wave is different for different coolant temperatures, demonstrating that frequency is a function of temperature. The resonance frequencies corresponding to temperatures are plotted as black squares that spans ±1.7%. The right-hand (red) axis has the same relative span, but the value of the f^2/T invariant [9], plotted as red diamonds, has a standard deviation of only ±0.12%.

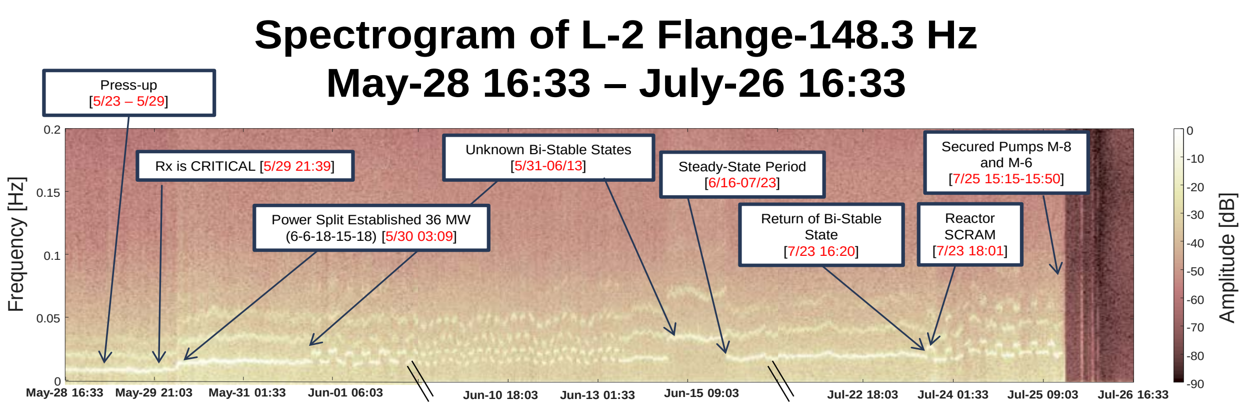

FIGURE 6. ATR vibroacoustic environment. Panoramic spectrogram view of a surrogate TAC signal produced by a five-vane pump, at 148.3 Hz, showing different ATR process states during the testing period from May 28 through July 26, 2015.

CONCLUSION

We have demonstrated the ability to acoustically telemeter temperature and power information from the core of a nuclear reactor to the exterior without requiring external electrical power or wiring. In doing so, we have created a new vibroacoustical paradigm for in-pile telemetry and sensing. Such a sensor strategy might have provided useful information in a reactor accident like that which destroyed the Fukushima complex in March 2011. In a commercial reactor, the flux of gamma radiation could provide sufficient heating that tungsten or stainless steel could be used as a heat source instead of nuclear fuel. This would avoid degradation in the sensor's sensitivity with time (due to fuel depletion) and alleviate the controls imposed for handling of enriched uranium. Multiple sensors in various core locations could also be used to optimize power distribution and improve the reactor's operational efficiency.

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