# SMART MULTI-SENSOR RADIO FREQUENCY TAGS FOR PROPULSION SYSTEMS

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## ABSTRACT

Pacific Northwest National Laboratory (PNNL) has developed substantial expertise and continues to further gain experience in both Radio Frequency (RF) tagging and a wide variety of sensor technologies. Over the past year these combined technologies have been merged to support research in the field of Predictive Technology. This paper presents applications of solid-state Radio Frequency (RF) Tags with multiple, embedded sensors to monitor the health of propulsion systems. The devices need to be small and fit on the inside and/or outside of a solid rocket motor (SRM) or aircraft and operate over a fairly long lifetime. This paper will illustrate this technology through the concept for the development of an advanced RF Tag-type device, which is not currently commercially available.

The various parameters to be sensed which could include strain, acoustic information, shock history, or selected chemicals, will be continuously or periodically logged into the RF tag. A hand-held device or a stationary interrogator unit with a longer range would then periodically interrogate the RF Tag. A microcontroller is used in the RF Tag to measure data and to set desired threshold levels, including those that would indicate an “alarm” or adverse condition. The threshold level will be programmable via the RF link from a handheld interrogator/reader. This will allow the same tag to be used with various types of SRM or aircraft.

Preliminary work in Predictive Technologies involved developing a proof-of-concept prototype utilizing an Intel 196 micro-controller to acquire acoustical and temperature data from simulated rocket motor propellant. (See Figure 1)

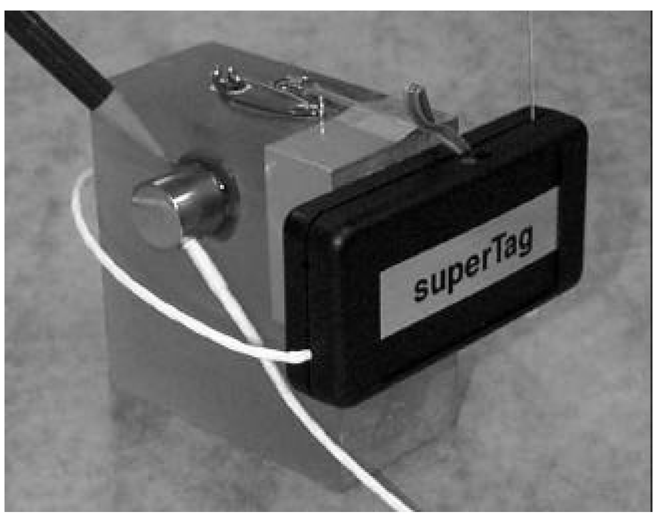


**Figure 1: Prototype rocket motor propellant monitoring tag.**

The acquired data were then sent via RF telemetry link to a remote computer for operator display. This demonstration prototype has already been shown to a variety of potential end users both in the government and the private sector. Future versions of this sensor/tag will probably be developed which are very small (perhaps even a single chip), integrate to a variety of sensor inputs, and incorporate advanced processing on-board through the use of embedded intelligence.

As a result of the proof-of-concept prototype it is believed that a completely passive Predictive Technology RF tag can be developed which may be embedded in rocket motor propellant. Power and sensor data will be transferred to the outside of the motor without the need for drilling holes or running wires. Additional telemetry links can then be used to transfer the rocket motor "health" to a hand held interrogator or base station a great distance away.

It is believed that there is a strong need for a predictive technology device such as this. The United States legacy munitions stockpile is very large and would benefit from a RF tag such as the one being developed. The integration of RF Tag and sensor technologies provides a family of technologies for which the range of applications and opportunities are mostly limited by the imagination of the researchers and engineers.

## INTRODUCTION

PNNL has been designing, developing, demonstrating, and deploying small Radio Frequency (RF) tags for tracking and status evaluation of multiple objects for over six years. Development efforts have been focused on read/write tags that allow the interrogation and updating of item specific data at longer distances than tags that are commercially available.

Tags have also been developed that have input monitoring and output control capability. This allows for tags to monitor external parameters such as temperatures, pressure, tamper detection, etc. Output control allows for the enabling and disabling of external circuitry.

Tags being developed fall into three categories; passive, semi-passive, and fully active.

Passive tags operate on a method known as continuous wave backscatter modulation. These tags receive enough power from the reader or interrogators RF beam to power up the internal circuitry within the tag. The tag then modulates information back to the interrogator. The tags are not transmitters. They are merely good reflectors or poor reflectors of the RF energy being beamed to them. Since they are powered by the RF beam, these tags require no battery, can be made extremely small, are low in cost, and have a very long lifetime. An example of a passive tag that has been developed at PNNL is shown in Figure 2. This tag is used for small arms inventory specifically M-16 rifles for the U.S. ARMY. It operates at 915MHz, contains 1024 bits of read/write memory, and has a maximum interrogation range of approximately 30 feet.

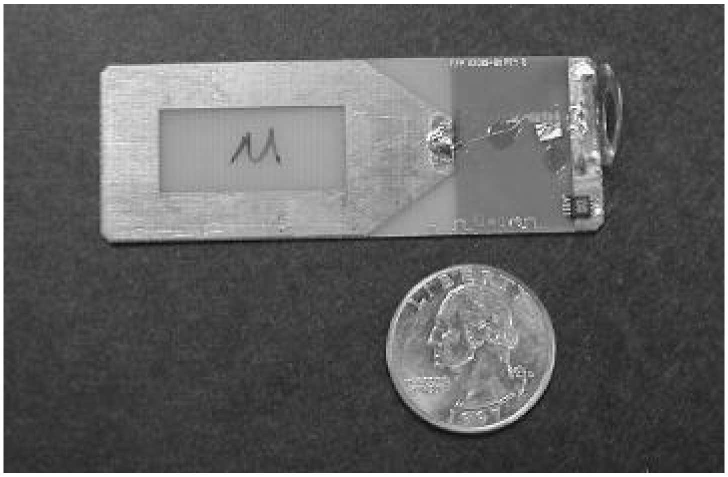

**Figure 2: Passive 915MHz RF tag.**

Semi-Passive tags utilize a battery but still operate using backscatter techniques. Tags of this type have greater range than totally passive tags and have the ability to monitor sensor inputs even when they are not in the presence of an RF field. Since they are not transmitters they require very little power to operate.  A typical semi-passive tag using a small watch battery can operate on the order of five to ten years.

A semi-passive tag developed at PNNL is shown in Figure 3.  It operates at 2450 MHz and has a range in excess of 500 feet.   As with the passive tags, this tag has read/write capability and multiple tags can be interrogated in a RF field.  The addition of a micro-controller, and a battery allow this tag to monitor external inputs both analog and digital, and control outputs such as enabling or disabling the item it is attached to.

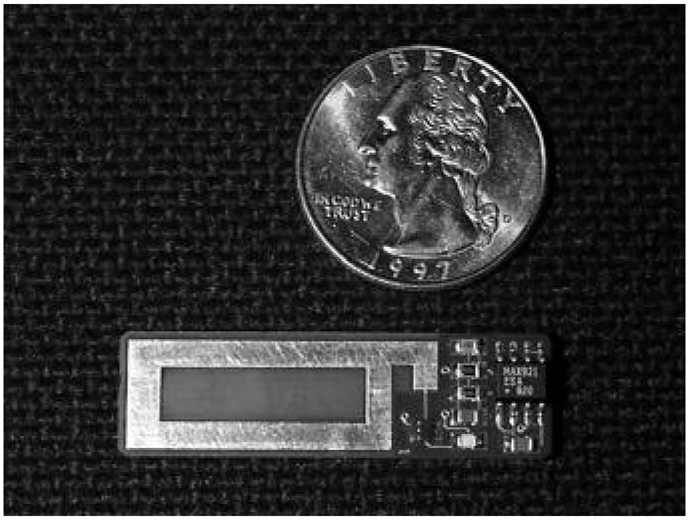

**Figure 3: Semi-passive 2450MHz RF tag.**

The battery and digital portion of the semi-passive tag discussed above is shown in Figure 4.  The battery will operate the tag in excess of five years if the tag is interrogated on a daily basis.

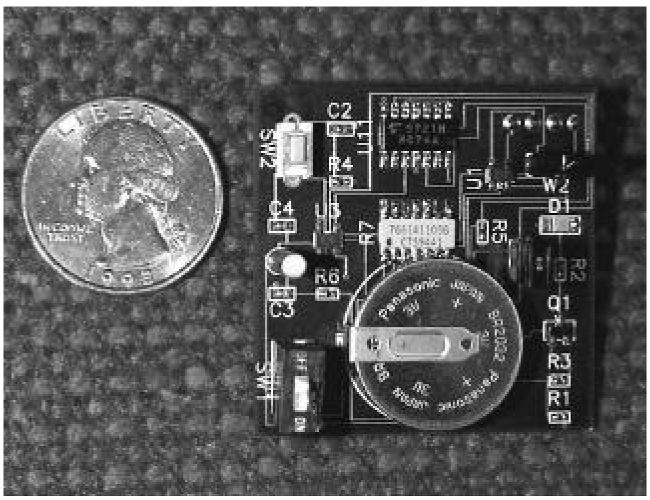

**Figure 4: Semi-passive tag's digital electronics board with battery.**

Active tags developed at PNNL are true transmitters of RF information.  They have shorter battery lives than the semi-passive designs but can communicate over greater distances and at higher bit rates.  If the tags are required to transmit infrequently (on the order of once a month) battery lives in excess of five years can be expected.  The "Super Tag" shown in Figure 1 is an active tag which uses low cost, commercially available, cordless telephone surface mount integrated circuits.

PNNL has developed advanced tag designs above and beyond what is commercially available. Advanced features include tag specific identification codes allowing for multiple tag interrogation in a single RF field. Improved RF designs allow for operation at extended ranges, the development of read/write & input/output control mechanisms, and the development of optimized system configurations which allow deployment and evaluation of practical RF tagging systems.

## DISCUSSION

Engineers at the PNNL have proposed an advanced propellant-monitoring concept with a RF link in addition to demonstrating a preliminary prototype of the concept. This proprietary system concept dubbed "SuperTag" is shown previously in Figure 1. A requirement for a specific rocket motor monitoring application has been defined. This paper details the proposed study to address feasibility for adapting and enhancing PNNL's present concept to that specific design.

The scope of the development effort is to develop and verify the feasibility of an advanced monitoring concept illustrated in Figure 5. The focus is for a passive system, which resides in the outer layers of the rocket motor propellant, monitoring material characteristics without the requirement for external wires or an internal battery. The final outcome will be a custom, system that can sense the material parameters of temperature, velocity and attenuation (other parameters such as shock, vibration, acceleration, and humidity may be incorporated also). Although the concept can accommodate a wide breadth of sensors, these three listed above would demonstrate the heart and versatility of the monitoring concept. PNNL has recently been developing custom measurement techniques for velocity and attenuation that would be used as a starting point.1 These two parameters have been previously demonstrated by multiple studies to track changing bulk material properties, which have been altered due to external factors such as temperature and humidity. The two parameters (velocity and attenuation) are measured using acoustic ultrasonic principles involving two transducers; one to transmit and the other to receive. PNNL has recently made a key significant advancement in the ultrasonic electronics by developing a system that is miniature, low power and acoustically efficient in the highly attenuative propellant. Without this advancement, embedding of an entire ultrasonic measurement system into the propellant would not have been even remotely feasible.

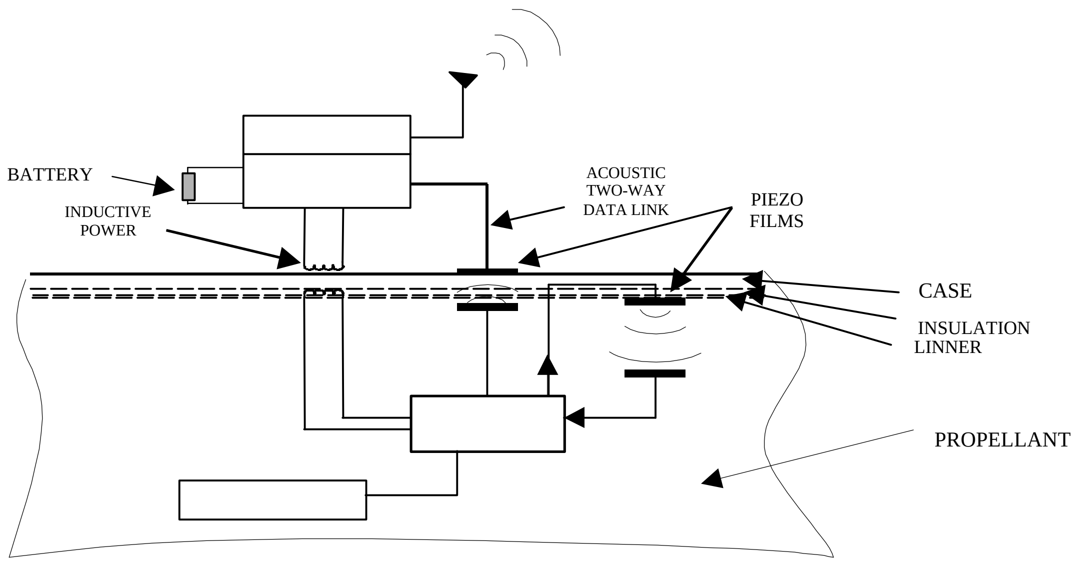


**Figure 5: Rocket motor propellant embedded tag – block diagram.**

In addition to obtaining the sensor measurements two supporting requirements are to remotely power all electronics (no internal battery) plus extract the data. Thus, this technique would not use wires that would penetrate the motor lining. PNNL has two ongoing projects that address these same issues and has demonstrated a solution path for both requirements. This particular application would expand upon these principles aimed at the hard specifics of the embedded motor monitoring application. The initial plan is to inductively couple electrical power through the lining and to extract the data via an acoustic modem.

<u>POWER COUPLING CONCEPT</u>

The present PNNL "SuperTag" concept utilizes 3 Volts at approximately 60 micro-amps. This would be a ballpark value for the power-coupling requirement. The method used in our past effort was to inductively couple energy from a source coil to a pickup coil. The two coils in essence form a transformer that is affected by both alignment and distance between the coils. Figure 6 is a data set taken with fairly large diameter coils that demonstrates the concept validity and will serve as a starting point for refinement of this technique. The data illustrates the ability to couple voltage over three dielectrics (air, inert propellant and copper foil) at thickness' more than 0.25 inches. At a thickness of 0.3 inches of propellant, 7-10 volts was available at 10,000 microamperes current. This is more than twice the required voltage and over 100 times the needed current. The inert solid propellant performed essentially the same as air due to the penetration ability of the low inductive coupling frequency (9.6 kHz). Two mils of copper foil were tested to determine the effects a metal motor case would have on the ability to couple power. The tests revealed it did degrade the coupling power by a concerning 30%. Since the actual steel cases are much thicker more tests will need to be performed.

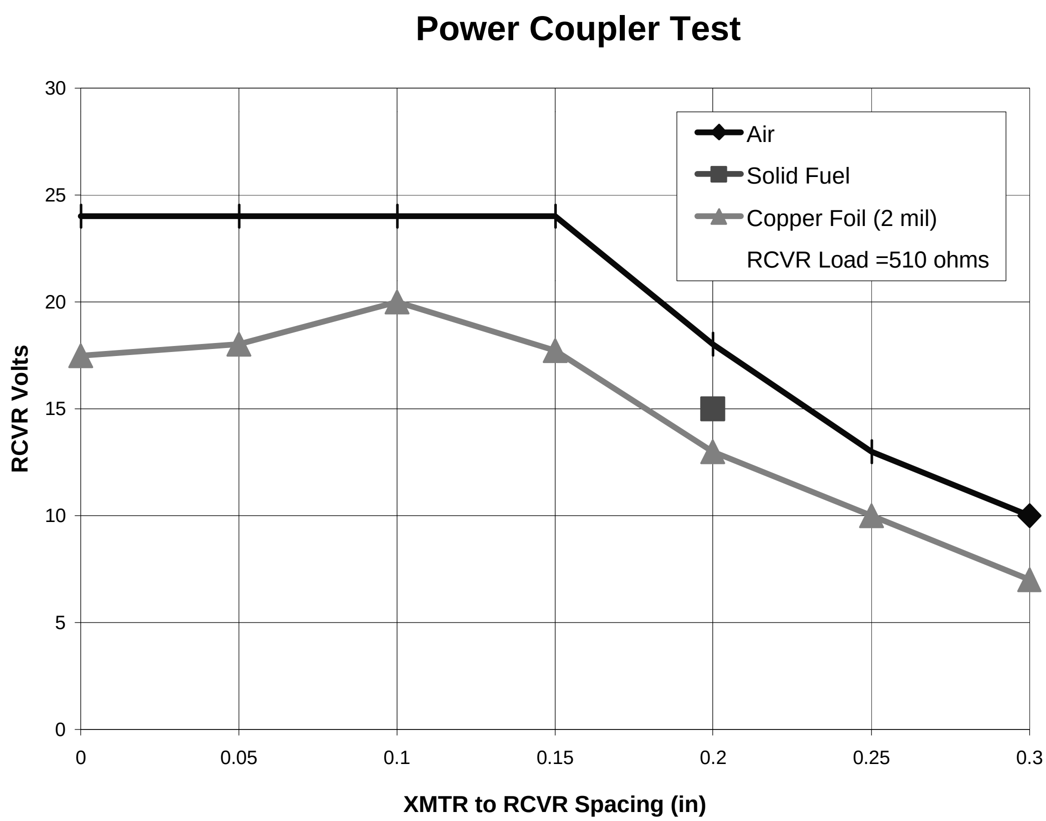


**Figure 6: Power coupler test data.**

The effort for this research would be to improve upon the inductive technique evolving to a design that is small, efficient and that could penetrate all composite case motors and even most tactical motors with thin metal cases (~100 mils). A key effort will be to eliminate or minimize the magnetic cores used in both coil pairs.

DATA COUPLING TECHNIQUE

The assumed data transmission method would be acoustic using an internal transducer in conjunction with a companion transducer on the outside of the motor lining. This would be an expansion of an existing PNNL design that is being used to exchange data between the inside of one metallic container to the outside of a second enclosing metal container. An acoustic “waveguide” has been built which resides between the two containers completing the data path. Preliminary tests using inert propellant (a much poorer acoustic conductor than metal) have shown that this same acoustic modem technique is feasible. Data coding is accomplished using pulse width modulation (PWM) techniques and can be completely bi-directional allowing communication from inside-to-out and from outside-to-in. A key implementation element for the rocket motor application is to be able to use a piezo film transducer, as it would be easier to embedded into the motor. All existing applications at PNNL to date have been with the highly sensitive piezoelectric crystals (~400 kHz range). Usage of the less sensitive piezo films with their unique propagation and reception modes would be investigated as this project progressed.

SENSOR MEASUREMENTS

The three initial internal parameters that would be integrated into the first generation design would be (1) temperature, (2) material velocity and (3) material attenuation. The temperature measurement is straightforward, as there is a host of miniature solid-state devices that are low power and have simple interfaces. The other two parameters would be measured using ultrasonics (UT) which has been illustrated by earlier propellant studies to be a useable tool.2 Two transducers would be used in a pitch-catch mode to transmit an acoustic wave between them. The measured time over this known distance is the acoustic velocity and the received signal has an amplitude which can be measured. Studies have shown that humidity and temperature over time influence the materials attenuation (amplitude changes) and its velocity (time-of-flight changes). Researchers at PNNL have been able to initially demonstrate on samples of inert propellant with its "SuperTag" concept a miniature, low power UT measurement technique. A key unique aspect is the usage of specific sensitive piezo crystal transducers that allow for a low power adaptation. The "SuperTag" concept has to date only demonstrated velocity and not attenuation, which is a feature that would be adapted in future designs. Also, the usage of piezo films would be investigated.

## FINAL SYSTEM INTEGRATION

The near term demonstration system will consist of switching to a lower power micro-controller (the Texas Instruments MSP430 has been selected). This micro-controller will be interfaced to additional sensors as well as the existing temperature and acoustic sensors used on the existing prototype. A block diagram of an existing system similar to the one proposed (without power coupling and acoustic modem capability) is shown in Figure 7.

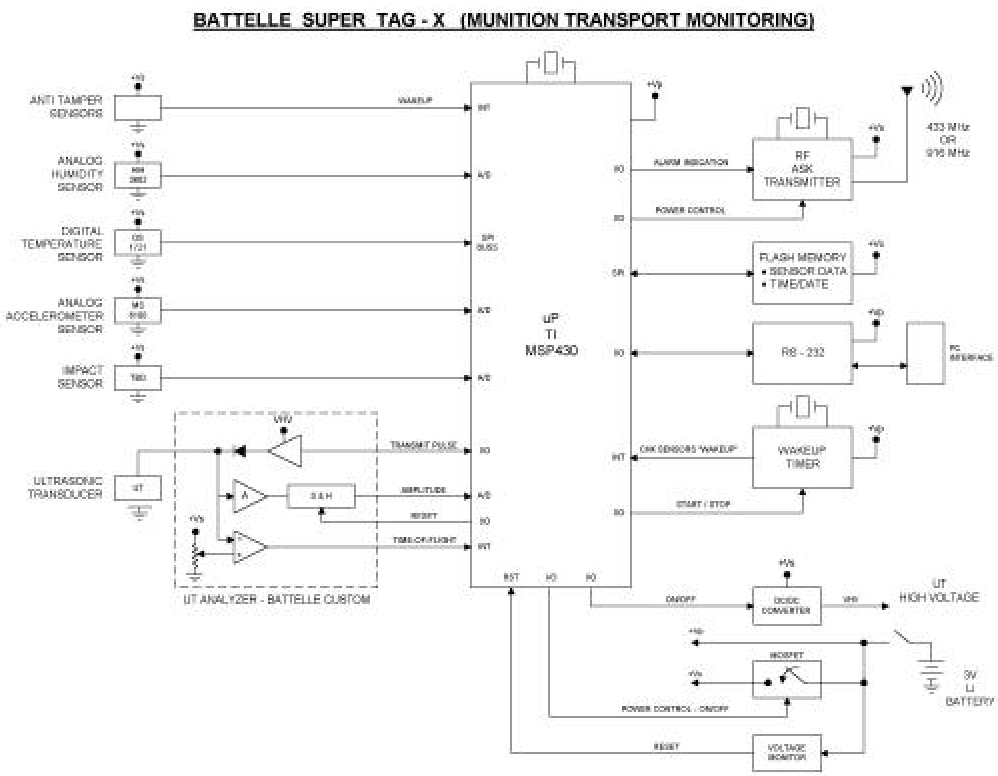


**Figure 7: Micro-controller based tag system.**

## SUMMARY AND CONCLUSIONS

Follow on work would consist of taking the new, working prototype and making it even smaller, perhaps even fabricating a custom Application Specific Integrated Circuit (ASIC) or Application Specific Intelligent Microsensor (ASIM) by integrating the sensor technology with the electronics. This would allow for low cost, mass production of the device. Such devices provide the potential for design and deployment of smart, light-weight, SRM/vehicle health monitoring concepts where data measurement and recording could be embedded in ground based readers, such as in an arch integrated set at hanger or magazine doorway.  This concept would enable regular pre-use checks and monitoring for aging trends for key parameters to be continuously performed and prognostics strategies developed to give improve procedures and practice for maintenance and repair.

## REFERENCES


1. Bond, L.J.,  "Inspection of Solid Rocket Motors and Munitions using Ultrasonics," presented at the 1999 Unclassified joint meeting of the Nondestructive Evaluation Subcommittee, Rocket Nozzle Technology Subcommittee, and Structures & Mechanical Behavior Subcommittee Meeting, November 15 – 19, 1999, JANNAF Interagency Propulsion Committee, Salt Lake City, Utah.

2. Pearson, L.H., Doyle, T.E., Hamilton, R.S., and Davis, I.L., "The Role of NDE in Service Life Prediction of Solid Rocket Propellant," AGARD Conference Proceeding 58, 1996.