

# Tradeoffs in Parameter Values for Optimal Performance

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*Transmission of Information by Acoustic Communication along Metal Pathways in Nuclear Facilities*

**Nuclear Science and Engineering Division**

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prepared by

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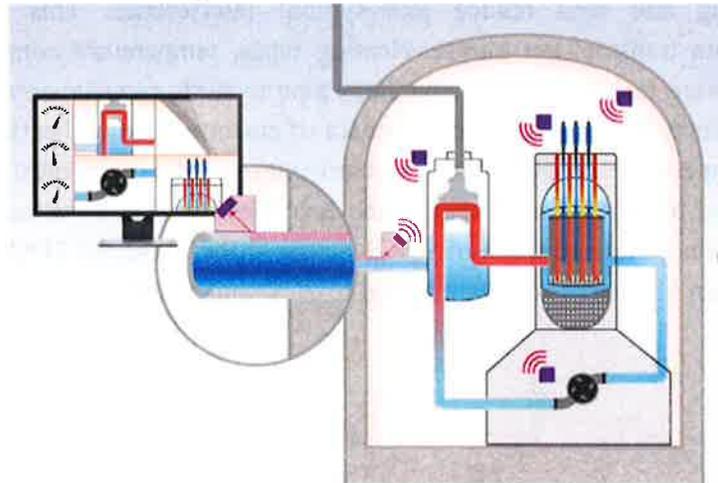
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## Abstract

Transmission of information using elastic waves on existing metallic pipes provides an alternative communication option for a nuclear facility. The advantages of this approach consist of transmitting information through barriers, such as the containment building wall. A viable candidate for acoustic communication channel is a chemical volume control system (CVCS) stainless steel pipe, which penetrates through the containment building wall. A laboratory bench-scale system consisting of a nuclear grade CVCS-like pipe and ultrasonic transducers was assembled for a preliminary communication system analysis. Because of low bandwidth and spectral dispersion of ultrasonic transducers, on off keying (OOK) protocol was chosen for data communication. Operation of the acoustic communication during normal and post-accident conditions involves data transmission on the CVCS pipe, which according to literature guidelines, will be at 50°C and 150°C, respectively. In general, continuous operation of most commercial ultrasonic transducers above 50°C is challenging because of transducer material incompatibility with high temperature. High-temperature LiNbO<sub>3</sub> acoustic transducers, originally developed for flow metering applications of EBRII reactor at Argonne, were utilized to develop a high-temperature acoustic communication system. A Gaussian pulse shape filter was introduced to suppress ringing and thus reduce inter-symbol interference. This resulted in enhancement of data transmission bitrate. Heating tapes, temperature controllers, and thermal insulation were installed on the laboratory pipe to study acoustic communication at elevated temperature. This included development of custom insertion heating elements for controlling temperature at pipe ends. Demonstrations of communication at high temperature included transmission of images and text files. Main achievements thus far include demonstration of transmission of 90KB image at the bitrate of 10Kbps with bit error rate smaller than 10<sup>-3</sup> across the pipe heated to 50°C and 150°C.

## 1. Introduction

Integration of advanced communication technologies into nuclear facility operation has the potential for enhancing safety and efficiency of the existing fleet of aging light water reactors, as well those of future advanced reactors [Korsah 2017]. Conventional wired and wireless communication systems face implementation challenges at nuclear facilities due to the presence of thick reinforced concrete walls with steel liners, such as those of the containment building. In addition, concerns related to security vulnerabilities in conventional communication networks have to be addressed when developing communication systems for nuclear facilities. In this report, we describe recent progress on developing a wireless communication system for a nuclear facility, in which information is carried with elastic waves propagating on metallic pipes. Traditionally, elastic wave propagation has been a frequent technique for non-destructive testing (NDT) of steel pipes (Bakhtiari 2018). In our approach, ultrasonic NDT techniques are combined with methods of communication theory to develop an acoustic communication system for a nuclear facility. Such communication system would take advantage of the existing piping infrastructure to transmit information in and out of containment building, as shown in Figure 1 [Argonne 2018]. Furthermore, information sent over this system would only be accessible through direct physical contact with the pipes, thus establishing a protection layer against unauthorized eavesdroppers.



**Figure 1 – Proposed acoustic communication system at a nuclear facility would transmit information on steel pipes already in place for nuclear reactor operation.**

The charging line of CVCS (chemical and volume control system) was previously identified as a promising channel for acoustic information transmission in and out of the containment building [Heifetz 2017, Heifetz 2018]. The CVCS pipe passes through a specially designed tunnel through concrete wall, in which the pipe is not in direct contact with concrete. The CVCS pipe is welded to two metallic baffle plates, which are bolted to both sides of the concrete wall at the openings of the tunnel. The baffle plates seal the tunnel, which prevents insertion of any communication link through the tunnel, such as an electrical or fiber optic cable. As described in prior reports, CVCS

pipes contain water during normal and post-accident operating conditions. Therefore, acoustic shear waves, which do not couple into water, were selected as the information carries on the pipe to minimize losses due to propagation in the channel. A laboratory bench-scale prototype of a CVCS pipe, consisting a six-foot long stainless steel schedule 160 pipe with 2.375in outer diameter and stainless steel baffle plates was developed for proof-of-principle demonstrations [Heifetz 2018]. Because of limited bandwidth of ultrasonic transducers, on-off-keying (OOK) digital communication protocol was chosen for information transmission over an acoustic channel [Chakraborty 2015, Heifetz 2017]. Amplitude shift keying (ASK) communication protocol was developed and implemented using GNUradio software defined radio (SDR) environment. Prior results included demonstration of information transmission, such as images, text files, and sound, using 2MHz paintbrush piezo electric transducers (PZT) on the room-temperature pipe. The PZT's were mounted on angled wedges to generate refracted shear waves in the metallic sheath of the pipe. A proof-of-principle demonstration consisted of transmitting a 32KB image at 2Kbps bitrate with bit error rate (BER) smaller than  $10^{-3}$ .

The acoustic communication system under development is expected to function under normal and post-accident environment at the nuclear facility. This implies that transducers installed on the CVCS pipe inside the containment should be resilient to the worst-case scenario temperature, humidity, and radiation environments. Typical value of environmental stresses of containment isolation function components inside the PWR containment [Lee 2018, Heifetz 2019, Heifetz 2018] are listed in Table 1. Note that in post-accident conditions, the acoustic communication system is expected to operate continuously at least for the first 72 hours. Therefore, ability to function at 300°F or 150°C is a critical requirement for acoustic communication system.

**Table 1 – Typical environmental stresses of containment isolation function components**

Parameter	Normal	Accident
Temperature	50-120 °F	300 °F
Pressure	Atmospheric	70 psig, max
Relative Humidity	30-100 %	100 %
Radiation	50 rads/hr	150 Mrads/hr

This report describes development of bench-scale setup for transmission of information on a pipe at elevated temperature. Developing of OOK communication system involves tradeoffs of several design parameters. After installing heaters and controllers on the laboratory pipe, acoustic data transmission was performed on a pipe heated to 50°C and 150°C to simulate communication on a pipe during normal and post-accident nuclear facility operation. Conventional PZT transducers and edges used in prior work on this project for development of ASK communication protocol are not compatible with high-temperature environment (above 50°C). Specialized high-temperature  $\text{LiNbO}_3$  shear wave transducers, previously developed at Argonne for liquid sodium flow metering

in EBRII pipes, were utilized for data transmission at elevated temperature. Details of LiNbO<sub>3</sub> transducers performance characterization in data transmission applications are provided in Section 2. Spectral response of LiNbO<sub>3</sub> was characterized to determine optimal center frequency of the carrier acoustic waves. Transducer ringing following short temporal duration pulse generation, which led to inter-symbol interference, was determined to be one of the key factors limiting data transmission bit rate. A pulse shaping Gaussian filter was implemented in software to suppress transducer ringing, which allowed increasing communication data transfer rate upward from previously achieved 2Kbps bitrate with commercial PZT transducer at room temperature. Section 3 provides the details of developing high-temperature communication channel. Heating tapes and temperature controllers were installed on the pipe to achieve controlled temperature elevation to 150°C. This included development of heating elements for insertion into pipe ends to raise the temperature at transducer mounting points to 150°C. High-temperature LiNbO<sub>3</sub> transducers were installed on the pipe and enclosed by insulation material. Data transmission experiments on elevated temperature pipe are discussed in Section 4. High-temperature LiNbO<sub>3</sub> transducers were integrated into previously developed ASK acoustic communication system implemented with RedPitaya electronic boards and GNURadio software [Heifetz 2018, Shribak 2018]. Main achievements thus far include demonstration of transmission of 90KB images at 10Kbps bitrate on 150°C pipe with BER smaller than 10<sup>-3</sup>. Section 5 provides a summary of the report.

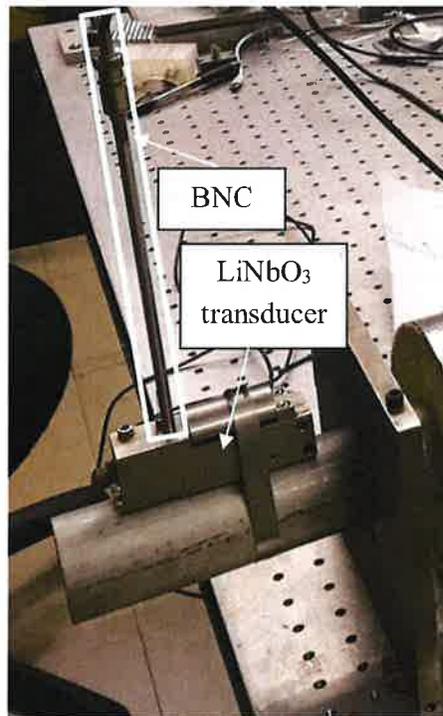
## **2. Design and characterization of high-temperature communication system**

As described in Section 1 of this report, one of the requirements of the acoustic communication system is ability to perform continuous operation for 72 hours on a pipe at 150°C. Majority of acoustic transducers are not suitable for operation at elevated temperature. For example, paintbrush PZT transducers utilized for proof-of-principle acoustic communication system development have a limiting operating temperature of 50°C. Beyond this threshold, the transducer material degrades rapidly. To perform measurements on high-temperature pipe, the transducer is coupled to the pipe with a high-temperature wedge. However, most commercial wedges are designed for touch mode operation, where a measurement is made in a brief period of time (e.g., 10s), followed by a longer cool-off period (e.g., 60s). In other designs, a long metallic waveguide could be in contact with the high-temperature pipe surface, while transducer would be placed at the opposite end of the waveguide, which is at lower temperature. However, this would require insertion a relatively large wide diameter waveguide through the insulating material to couple to the pipe. This approach could lead to considerable heat losses. A preferred method would be to embed a high-temperature compatible transducer under the insulation, with a narrow communication channel piercing the insulation material.

### **2.1. High-temperature compatible LiNbO<sub>3</sub> ultrasonic transducers**

Specialized high-temperature compatible LiNbO<sub>3</sub> shear wave ultrasonic transducers were developed at Argonne for EBRII liquid sodium flow metering applications. The LiNbO<sub>3</sub> crystal

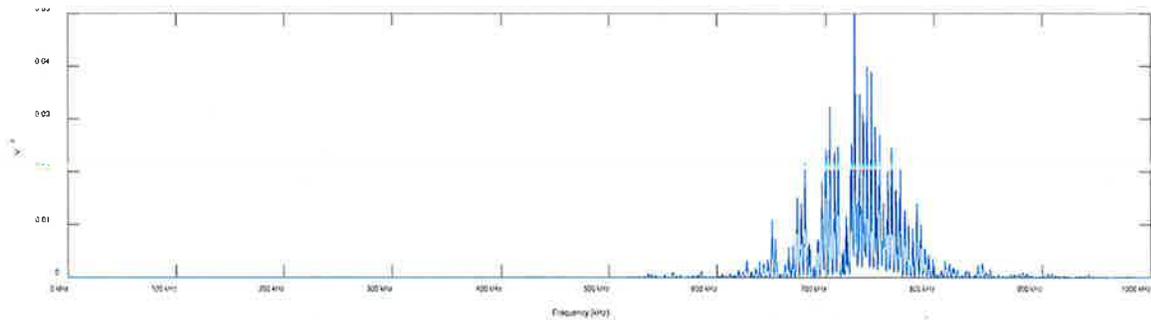
Curie temperature of 1145°C, which allows for long-term deployment of these transducers on pipes carrying liquid sodium, for which the operating temperature is typically under 650°C [Brice 1989]. In this project, these LiNbO<sub>3</sub> transducers were utilized for the first time for information transmission applications. The transducer consists of a single LiNbO<sub>3</sub> crystal in stainless steel case, and couples to metallic pipe with metallic foil. The transducer attached to the stainless steel pipe with metallic hose clamp is shown in Figure 2. The transducer is dry-coupled to the pipe with copper foil. Communication with the transducer takes place through the long rigid metallic BNC cable. This allows embedding the LiNbO<sub>3</sub> into thermal insulation material enclosing the pipe. The narrow rigid BNC cable would penetrate thermal insulation, which would cause relatively small thermal losses. The end of the long BNC rod cools off to room temperature, which allows for coupling to regular commercial BNC cables, as shown in Figure 2.



**Figure 2 – High temperature LiNbO<sub>3</sub> transducer mounted on a stainless steel pipe.**

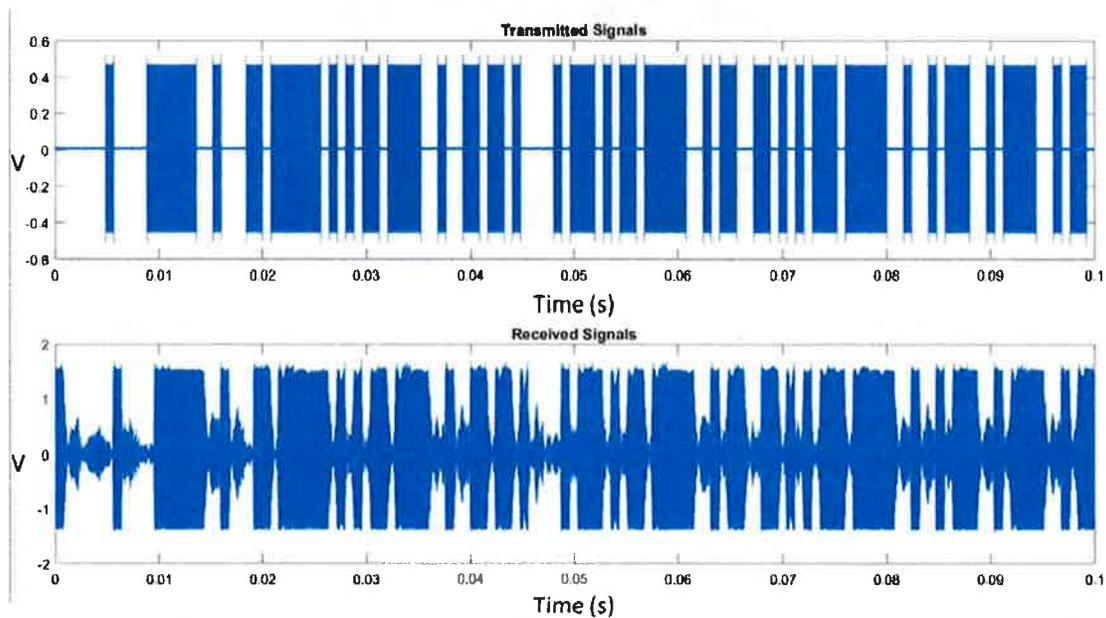
## **2.2. Characterization of LiNbO<sub>3</sub> ultrasonic transducers performance**

Preliminary evaluation of high-temperature LiNbO<sub>3</sub> transducers for data transmission application consisted of characterization of their frequency response. The spectrum of received signal for two LiNbO<sub>3</sub> transducers separated by 170cm (~5.5 feet) on a stainless steel pipe is shown in Figure 3. The transmitted signal was amplified with 50dB power amplifier, and the received signal was amplified with 20dB low noise amplifier. Frequency response characterization was performed at room temperature. The spectrum was acquired using LabView software. The spectral response of LiNbO<sub>3</sub> transducer has a maximum at approximately 730KHz, with approximately 10% full width half maxima (FWHM) bandwidth.



**Figure 3 – Frequency response of high-temperature LiNbO<sub>3</sub> transducer mounted on a stainless steel pipe.**

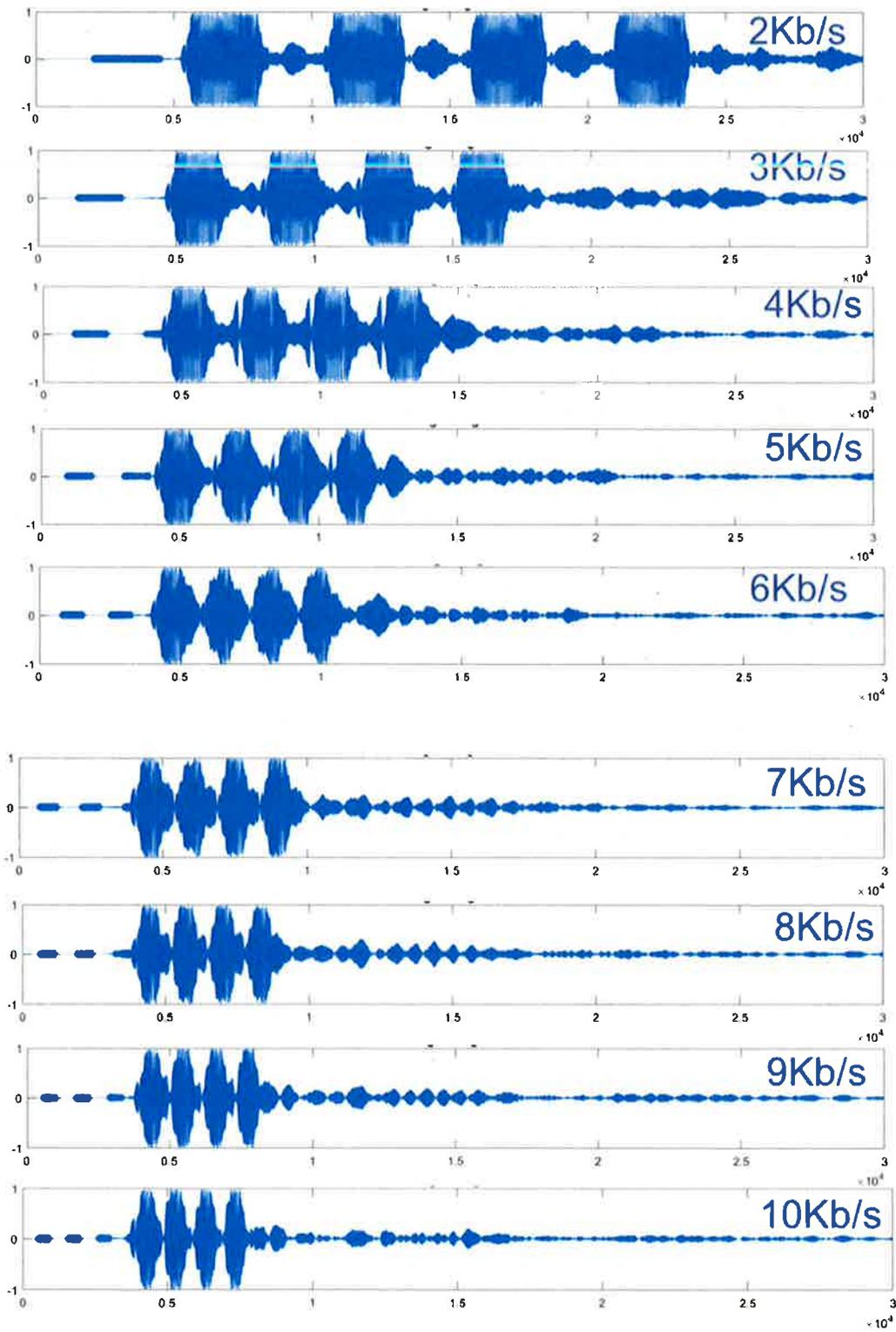
Performance of LiNbO<sub>3</sub> transducers in data transmission applications was characterized by generating a train of binary signals and detecting the received signals using LabView software. The center frequency of the carrier was chosen to be 728 KHz, which corresponds to maximum of transducer spectral response as shown in Figure 3. Transmitted and received amplitude shift keying (ASK) signals are shown in Figure 4. The strip chart shows a string of pulses transmitted over 100ms. Bit pulse duration shown in the figure is 200  $\mu$ s, which corresponds to 5Kbps bitrate. The transducers are separated by 170cm distance on a pipe. Transmitted signal is amplified with 50dB power amplifier, and received signal is amplified with 20dB low noise amplifier. The experiment was performed at room temperature. The data in Figure 4 demonstrates qualitatively that LiNbO<sub>3</sub> high-temperature can be used for ASK transmission and reception of pulses representing logical “1” and “0.”



**Figure 4 – Transmitted and received ASK pulses with 5Kbps bitrate**

### 2.3. Limitations on data transfer rate due to transducer ringing

Following preliminary evaluation, which confirmed that high-temperature LiNbO<sub>3</sub> can be used for OOK communication, we have investigated factors which limiting data transfer rate. Using the setup with LiNbO<sub>3</sub> transducers described in section 2.2, we recorded transmission of a byte of information consisting of a sequence of 10101010 bits. All measurements were performed at room temperature. Received signals for different data transmission rates, encoded via amplitude shift keying (ASK) communication protocol, are shown in Figure 5. The data was recorded with LabView software. The panels in Figure 5 show received signal with a sequence of logical “1” and “0” bits were represented by acoustic pulses with 500 $\mu$ s, 333 $\mu$ s, 250 $\mu$ s, 200 $\mu$ s, 167 $\mu$ s, 143 $\mu$ s, 125 $\mu$ s, 111 $\mu$ s, and 100 $\mu$ s temporal duration. These correspond to bitrates of 2Kbps, 3Kbps, 4Kbps, 5Kbps, 6Kbps, 7Kbps, 8Kbps, 9Kbps, and 10Kbps. One can observe from the panels in Figure 5 that as the data rate increases, transducer ringing caused by short temporal pulse duration makes it difficult to resolve logical “0” from logical “1.” Therefore, the factor limiting data transmission rate in the inter-symbol interference (ISI). For lower data rate values, such as the top panel showing data transmission at 2Kb/s, thresholding can remove the weak ringing signal appearing in the time interval allocated for logical “0.” However, for higher data rate values, such as for panels displaying received signals at 6Kb/s data rate and above, residual ringing from logical “1” pulse injects sufficiently large signal into the time slot allocated for logical “0” which cannot be removed by thresholding or averaging. Thus, the probability that the decimation procedure will mis-identify “0” as “1” is relatively high. It was observed in several experiments that transmission of images, such the image of ANL logo used in previous reports [xx], resulted in relatively low bit error rate (BER <10<sup>-3</sup>) for data transfer rate of 2KB/s. However, at higher data transfer rates, BER increased substantially to the point that transmitted images became unrecognizable. Several strategies for suppressing ringing were investigated, including matched filtering and Gaussian pulse shaping filter.

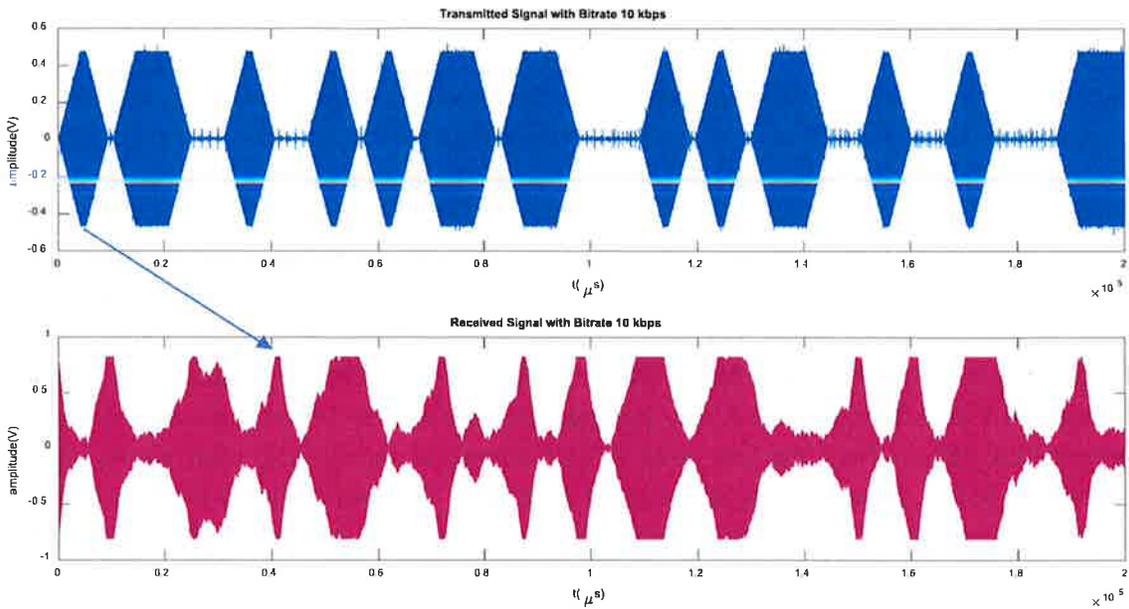


**Figure 5 – Received ASK pulses with bitrate ranging from 2Kbps to 10Kbps**

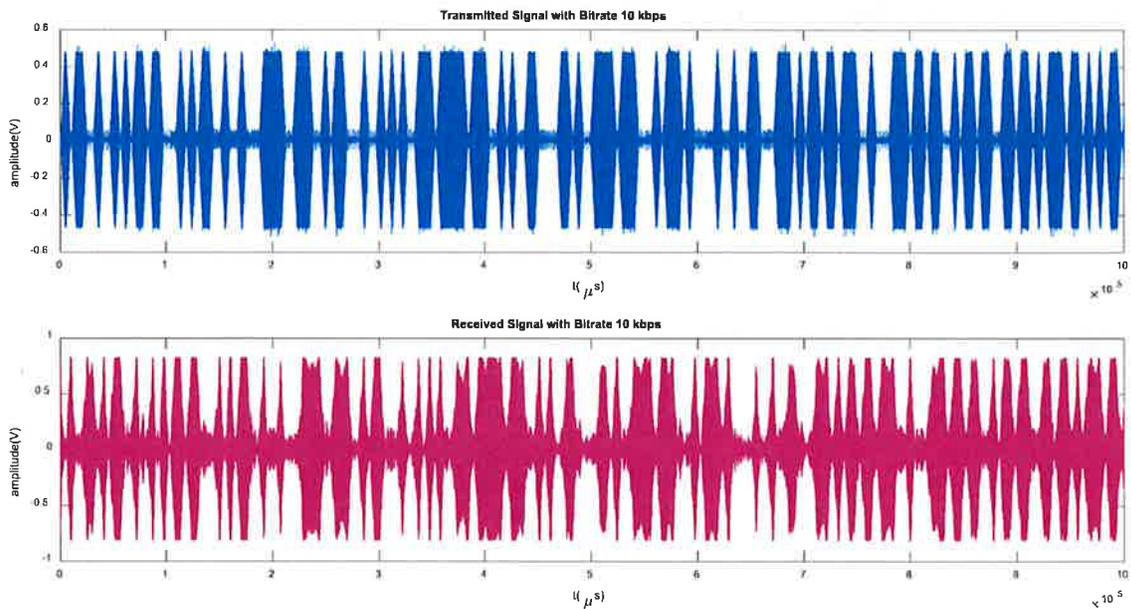
### 2.3. Enhancement of data transfer rate with Gaussian pulse shape filter

In our study of transducer ringing suppression to increase data transfer rate, application of Gaussian pulse shape filter proved to be the most efficient solution. In this approach, instead of a square pulse representing logical "1", a Gaussian pulse of the same amplitude is used for encoding an ASK signal. Because of the gradual rise and decay of Gaussian pulse amplitude, the result of using a Gaussian filter is a significant suppression of transducer ringing. This effect can be observed in Figure 6, which shows a string of transmitted and received bits represented by 100 $\mu$ s (10Kbs bitrate) temporal duration Gaussian shape pulses. The segment shown in Figure 6 corresponds to "10110010010101101100010101100100100100011" Time delay between received and transmitted signals due to propagation time across 170cm distance on a pipe is approximately 350 $\mu$ s. Thus, the first pulse in the transmitted signals strip chart shows up at the time mark of 350 $\mu$ s, as indicate by the arrow in the Figure. The data in Figure 6 can be compared with the last panel in Figure 5, which shows received square wave pulses with 100 $\mu$ s temporal duration, or equivalent 10Kbps bitrate.

The train of transmitted and received pulses in Figure 6 is a subset of data showing the first 200ms of transmission. The entire data set consisting of 1s-long strip chart of transmitted and received pulses is shown in Figure 7. One can observe that implementation of Gaussian pulse shape filter results in considerable improvement in received signal quality. After the received signal is thresholded, weak residual signal appearing in time slots corresponding to logical "0" can be suppressed. When the decimating procedure converts the analog signal to digital, the probability that a logical "0" is misidentified as logical "1" is significantly reduced compared to the case when communication is performed with analog square pulses. Thus, Gaussian pulse shape filter enables higher bitrate communications with relatively low BER. Demonstration of this approach in transmission of images on a pipe is discussed in Section 4.



**Figure 6 – Subset of transmitted and received Gaussian pulses with bitrate 10Kbps**



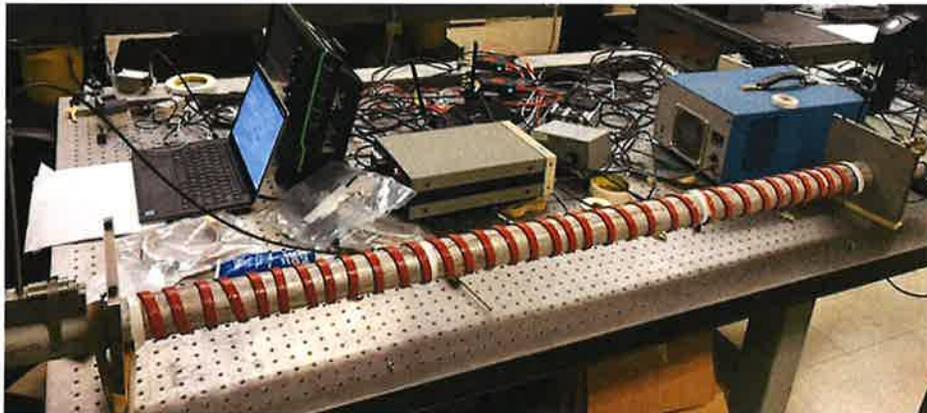
**Figure 7 – Longer train of transmitted and received Gaussian pulses with bitrate 10Kbps**

### 3. Development of High-Temperature Communication Channel

As described in Section 1, the requirements of acoustic communication system include the ability to transmit information on a pipe at 50°C prior work on the project consisted of development of acoustic communication protocols and performing proof-of-principle demonstrations of acoustic communication at room temperature. Prior work on the project consisted of developing and demonstrating acoustic communication on a stainless steel schedule 160 pipe with 2.375in outer diameter at room temperature [Heifetz 2018]. This section describes development of a laboratory setup for demonstration of acoustic communication on a stainless steel pipe at elevated temperature.

#### 3.1. Installation of heating tape and insulation on pipe

Temperature controllers, heating tapes and thermocouples were purchased from commercial Amptek vendor. This hardware was used to convert existing bench scale acoustic communication on setup into a high-temperature one. Figure 8 shows modifications to the existing setup with the heating tape wound on the stainless steel pipe. Heating tape cannot be wound over sections of the pipe where  $\text{LiNbO}_3$  transducers are mounted because the transducer coupling requires a several inches long clear section of the pipe.



**Figure 8 – Heating tape installed on stainless steel pipe**

Mineral wool thermal insulation was wrapped around the pipe and fastened with wires to prevent heat losses. Mineral wool sections cut out to contour around the transducers were installed as well. Thermocouples were installed at the center of the pipe to monitor temperature. Figure 9 shows the setup with thermal insulation on the pipe. Thermal insulation was enclosed with thin stainless steel cover, as shown in Figure 10. Thermal insulation enclosing transducers was wrapped in Aluminum foil. Preliminary tests have shown that with the new setup the temperature of the pipe could be raised to 150°C in approximately three hours. Once raised to this value, pipe temperature could be maintained steadily at 150°C.



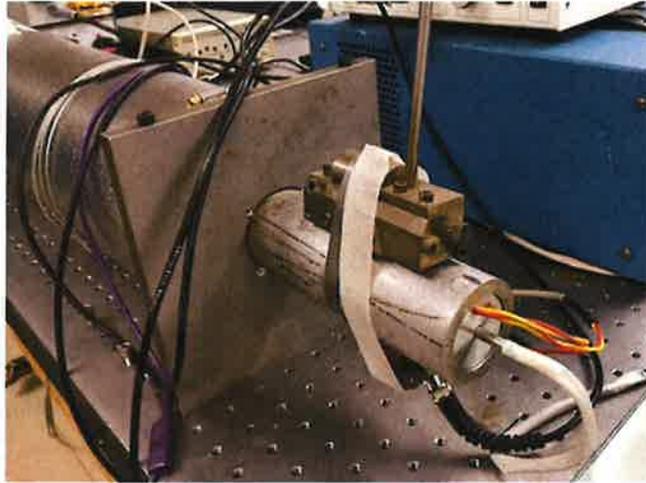
**Figure 9 – Mineral wool thermal insulation installed on the pipe**



**Figure 10 – Metal sheet cover and foil placed over mineral wool thermal insulation**

### **3.2. Installation of insertion heating elements at pipe ends**

Because of heat losses at the ends of the pipe, it was observed that the temperature at the transducer mounting points saturated at 50°C while the temperature at the center of the pipe was reaching 150°C. A solution to heating pipe ends was found by designing and fabricating cylindrical insertion elements matched to the pipe inner diameter. Figure 11 shows the Aluminum insertion element containing the cable from a 20W heater and thermocouple wires. Separate set of heaters and temperature controllers was installed for each end of the pipe. The final assembly for laboratory testing of high-temperature acoustic communication is shown in Figure 12. Preliminary tests have shown that the temperature at the center and at the ends of the pipe can be raised to 150°C in approximately three hours, and maintained steadily at the set-point value. During the laboratory tests, it was determined that the ends of transducers BNC metallic rods have cooled off to room temperature to allow coupling to standard laboratory BNC cables with plastic jackets.



**Figure 11 – Specially designed insertion heating elements for controlling temperature at pipe ends**



**Figure 12 – Final laboratory setup for acoustic communication at elevated temperature**

## 4. Demonstration of Data Transmission on Pipe at High Temperature

Prior work on the project consisted of developing of ASK communication system using GNURadio software defined radio (SDR) programming environment [Heifetz 2018, Shribak 2018]. User uploads a digital file into GNURadio program, where the file is converted into a string of bits. A digital wave is generated by the GNURadio program, which is next converted into an analog wave by transmitter Red Pitaya electronic board. The analog wave is sent to the ultrasonic transducer through a power amplifier. Ultrasonic shear waves generated with the transducer propagate along the pipe, where they are picked up by the receiving transducer. Electrical signal from the transducer is amplified with low noise amplifier, and converted back into a digital wave by the receiver Red Pitaya board. Digital information is further processed within GNURadio software and displayed to the user. This section describes data transmission on a high-temperature pipe with  $\text{LiNbO}_3$  transducers integrated into the communication system setup.

### 4.1. Examples of transmitted data

Data types considered in transmission experiments included text files and images. Similar data types were utilized in data transmission demonstrations on a pipe at room temperature. Transmission of images is most challenging because a few errors might render the reconstructed image unreadable. GNURadio screen capture of 90KB image of ANL logo used in data transmission demonstrations is shown in Figure 14. Another example of transmitted data type is a text file. GNURadio screen capture of a text file containing repeating string of characters “Hello World!” is shown in Figure 14.



Figure 13 – GNURadio screen capture of an image file used in data transmission demonstration



**Figure 14 – GNURadio screen capture of text file used in acoustic data transmission demonstration**

## 4.2. Summary of transmission results

Transmission of data files was performed using ASK communication protocol with Gaussian pulse shape filter described in Section 2, and LiNbO<sub>3</sub> transducers installed on thermally insulated and heated pipe described in Section 3. A summary of data transmission results is presented in Table 2. The 1<sup>st</sup> row in the table lists the results obtained using room-temperature 2MHz paintbrush PZT transducer mounted on 45° angled wedge [Heifetz 2018, Young 2018]. This result was obtained in the previous year of the project, and is listed in Table 2 for reference. The 2<sup>nd</sup> through 4<sup>th</sup> rows of the table list the results of data transmission with LiNbO<sub>3</sub> transducer. The 2<sup>nd</sup> row shows the results obtained at room temperature. The 3<sup>rd</sup> and 4<sup>th</sup> rows show the results of data transmission on a pipe heated to 50°C and 150°C, which represent normal and post-accident conditions according to Table 1. In all cases, data was transferred at 10KBps bitrate with BER<10<sup>-3</sup>. Note that the spectrum of LiNbO<sub>3</sub> changed slightly with temperature, and the exact center frequency used for different temperature transmission varied by a few KHz.

**Table 2 – Summary of achieved data transmission rates**

<b>Transducer Type</b>	<b>Temperature (C)</b>	<b>Bitrate (Kbps)</b>
Paintbrush 2MHz PZT with 45° flat wedge	20	2
High-temperature 700KHz LiNbO <sub>3</sub>	20	10
High-temperature 700KHz LiNbO <sub>3</sub>	50	10
High-temperature 700KHz LiNbO <sub>3</sub>	150	10

## 5. Conclusions

The objective of this project is to develop and demonstrate methods for transmission of information in nuclear facilities across physical barriers as acoustic/elastic guided waves along existing in-place metal piping infrastructure. A viable candidate for acoustic communication channel is a chemical volume control system (CVCS) stainless steel pipe, which penetrates through the containment building wall. A laboratory bench-scale system consisting of a nuclear grade CVCS-like pipe and ultrasonic transducers was assembled for a preliminary communication system analysis. Because of limited bandwidth of ultrasonic transducers, on-off-keying OOK digital communication protocol was chosen for information transmission over an acoustic channel. Design considerations of the OOK communication protocol are connected to physical characteristics of the communication channel, and involve tradeoffs of design parameters. In this report, we discuss acoustic communication system design considerations for transmission of information on a stainless steel pipe at elevated temperature, corresponding to normal and post-accident environmental conditions at the facility. The temperature values of the pipe used this project are taken from NUREG report guidelines [Lee 1996].

Ultrasonic PZT's used in prior phases of the project for proof-of-principle communication system development in prior work on the project are not suitable for operation at high temperature. To perform ultrasonic data transmission at temperatures up to 150°C, we have utilized custom-made high-temperature compatible LiNbO<sub>3</sub> ultrasonic transducers, originally developed at Argonne for liquid sodium flow metering application at EBR-II. Preliminary evaluation at room temperature showed that LiNbO<sub>3</sub> transducers can be used for OOK communications on a pipe. The bitrate of data transmission was further enhanced by developing a Gaussian pulse shape filter to suppress transducer ringing. A high-temperature laboratory setup was developed by installing heaters, temperature controllers and thermal insulation on the pipe. This included development of custom insertion heating elements for controlling temperature at pipe ends. Data transmission on heated pipes was demonstrated using a text file and a 90KB image of Argonne logo. In particular, transmission with 10Kbps bitrate of data was achieved on the pipe heated to 50°C and 150°C, which represented communication during normal and post-accident environment at the facility.

Next steps on the project will involve developing solutions for data transmission at high temperature with electromagnetic acoustic transducers (EMAT). In addition, transmission of information on bent pipes will be investigated.

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