Ultrasonic *in-situ* determination of the regression rate of the melting interface in burning metal rods

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Results of tests in which metallic rods are burned in oxygen enriched atmospheres often include the determination of the regression rate of the melting interface for the burning test specimen. This regression rate is used as an indication of a metallic material's relative flammability and its general ability to sustain burning under the test conditions. This paper reports on the development and first application of an ultrasonic measurement system that enables *in situ* measurement of the regression rate of the melting interface in burning metal rods. All other methods currently used for determining this parameter are based on posttest, visual interrogation, which is costly and often inaccurate. The transducer and associated equipment used to drive and record the transducer's output signal are described and typical results for iron rods burning in pure oxygen at different gauge pressures are given along with a comparison of these results with regression rates obtained from visual interrogation. The excellent sensitivity, accuracy and reliability of the new ultrasonic transducer are demonstrated, thus indicating the transducer's great potential. © *1999 Acoustical Society of America.* [S0001-4966(99)00702-X]

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INTRODUCTION

The burning characteristics of metallic materials are important in the design, fabrication, and subsequent use of many industrial systems and processes when operations are in environments that support combustion. Initial work investigated the pyrophoric behavior of metallic materials under ambient conditions and was often focused on fire safety in relation to mining activities.[1,2] The use of metallic particulates as additives to enhance a propellant's performance also spurred interest in the burning properties of various metallic materials.[3–5] Another motivation for understanding the combustion characteristics of metallic materials has arisen as a result of costly component and system failures. Both aerospace (government and civilian) and industrial (air separation plants, turbine blade producers, medical component manufacturers, valve manufacturers, etc.) organizations are experiencing incidents involving burning metallic materials, typically in pressurized oxygen systems, that often resulted in serious system failures.[6–8]

These incidents motivated both NASA and The American Society for Testing and Materials (ASTM) to develop and incorporate standard tests to determine a metallic material's tendency to burn in oxygen-enriched atmosphere.[9,10] These test methods are very similar to one another and typically require five standardized samples (0.32-cm-diam rod) to be tested. The burning characteristics that are typically reported from these tests include the threshold pressure and the regression rate of the melting interface. The threshold pressure is the lowest pressure that will just support combustion of the test sample and the regression rate is the rate at which the melting interface (the surface between the unburned rod and the molten mass) moves up the test sample as it is burned. Both the threshold pressure and the regression rate are used as indicators of a metallic material's flammability in oxygen-enriched environments. The regression rate is used as an indication of a metallic material's relative flammability when different metallic materials burn at the same test pressure and as an indication of a metallic material's general ability to sustain burning under the test conditions.

With the exception of only two methods, all reported methods for determining the regression rate are based on posttest visual interrogation of either a video or film recording of the burning test sample. This method is expensive and time intensive, since the recording must be obtained on a reviewable medium and an individual must develop and implement the procedure to obtain the regression rate from this medium. In addition, quantification of the regression rate by visual techniques has other, more important, problems such as accuracy and reproducibility. The major sources of errors are related to inaccuracies in the determination of the correct scale factor used posttest when viewing the visual record, variations in the speed of the recording, and human errors associated with determining the melting interface due to contrast problems and obscuration of the melting surface by condensed-phase products.

The two methods, which have been reported to determine the regression rate without relying on posttest analysis of a visual recording, were both developed and used at NASA White Sands Test Facility (WSTF). The first technique relied upon the response of thermopiles (many thermocouples) put at the end of copper tubes, which were placed along the walls of the combustion chamber.[11] The second technique relied on a gravimetric transducer, which was recording the changing mass of a burning sample as a function of time.[12] Both techniques are no longer used, mainly due to their inefficiency, the associated reliability and accuracy problems, and extended maintenance requirements.

This paper reports on the development and application of an ultrasonic measurement system to directly determine realtime regression rate data of the melting interface for

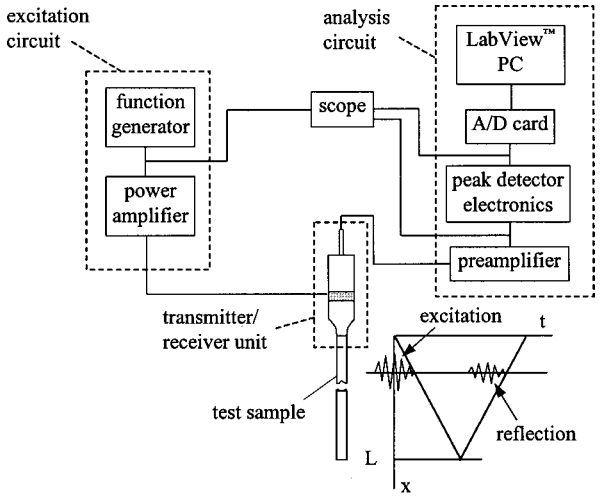
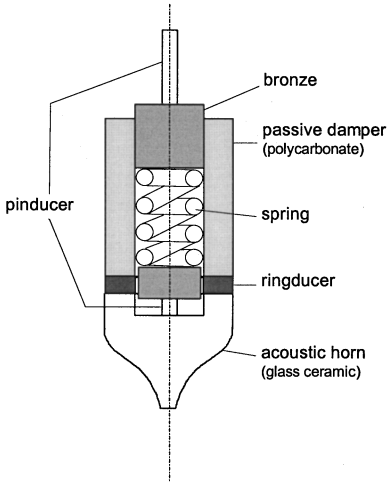


FIG. 1. Sketch of the ultrasonic measurement system and measurement concept.



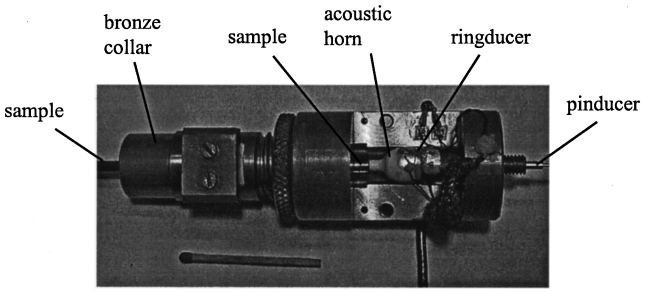


FIG. 2. Schematic and photograph of ultrasonic transmitter/receiver unit.

burning metal rods, thus eliminating all of the problems described above. It provides a description of the developed transducer and the associated equipment used to drive and record the transducer's output signal. Results from the first applications of the transducer for burning iron rods are given along with comparisons to regression rates calculated by standard visual techniques.

I. ULTRASONIC MEASUREMENT SYSTEM

In Fig. 1 the basic measurement concept is illustrated. The transmitting transducer, which is coupled to the test sample, emits an ultrasonic pulse of known center frequency that travels down the rod as a longitudinal stress wave (velocity $c_0 = \sqrt{E/\rho}$, where E is the Young's modulus and ρ is the density of the material). The receiver detects the pulse after it is reflected from the end of the rod. The peak detector electronics determines the time of flight for the pulse and this measurement, together with the known propagation velocity c_0, which is determined from a precombustion measurement, enables real-time automatic calculation of the changing rod length as a function of time (the regression rate). Thus, the major components of the measurement system shown in Fig. 1 and described in detail below are (a) the ultrasonic transmitter/receiver unit, (b) the excitation circuit and (c) the signal conditioning and analysis circuit.

Figure 2 shows a schematic and photograph of the ultrasonic transmitter/receiver unit, which consists of two piezoelectric parts: a ringducer (transmitter, Ferroperm, PZ 27, outer diameter 10 mm, inner diameter 6 mm, thickness 2 mm) and a pinducer (receiver, ValpeyFisher, VP 1093, aperture 1.3 mm). A transducer design using separate transmitter/receiver elements rather than a conventional, single-element pulse echo arrangement proved to be necessary to have sufficient signal strength on one side and good detector sensitivity on the other in the extremely harsh environmental conditions for burning metal rods. The bronze collar, shown in the photograph, isolates the transducer from the burning metal sample preventing ignition and providing temperature stability. It is also used to hold and align the sample in the axial and lateral directions. The ringducer is sandwiched between an acoustic horn manufactured from glass ceramic and a passive damper element from polycarbonate. The pinducer is held in good contact with the sonic funnel by spring loading using the polycarbonate damper element and the bronze collar as support structures.

The electronics to drive the ringducer and receive and analyze the signal from the pinducer are shown in Fig. 1. The excitation path of these electronics consist of an arbitrary function generator and a high-power amplifier. The arbitrary function generator creates a narrow-band excitation pulse of the required center frequency, which results in the propagation of longitudinal waves in the sample rod and allows for the unambiguous identification of the reflected pulse. For 0.32-cm-diam, 180-cm-long iron rods a three cycle, 300-kHz sinusoidal burst fulfills these requirements. It results in an interrogation length of approximately 6 cm, which is sufficient considering that a steady-state regression rate is usually reached within the first centimeter of burning. The major effects which restrict the unambiguous identification of the reflected pulse for shorter rod lengths are the ringing of the ringducer on one hand and the internal reflections within the transducer unit itself on the other. The high-power amplifier conditions the excitation signal to a peak-to-peak level of approximately 100 V, which results in sufficiently strong excitation signals that can be clearly delineated from the acoustic noise generated from the combustion process. In the detection path, an ultrasonic preamplifier is used to condition the signal, an in-house built electronic circuit, which is de-

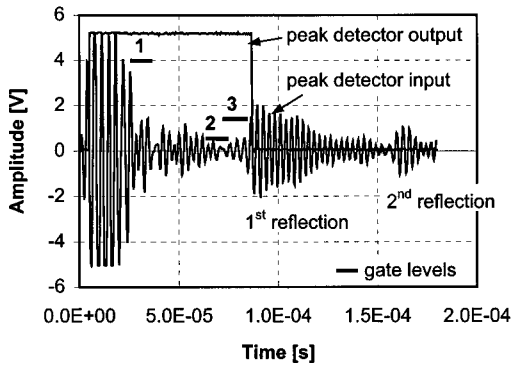


FIG. 3. Precombustion ultrasonic transducer output when attached to a 0.32-cm-diam, 18-cm-long iron rod and corresponding peak detector output signal.

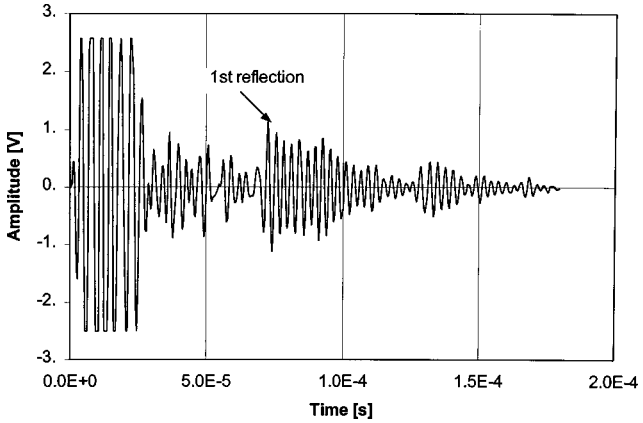


FIG. 4. Ultrasonic transducer output during combustion of a 0.32-cm-diam iron rod burning in pure oxygen at a gauge pressure of 0.69 MPa (100 psia).

scribed in detail below, allows for the real-time measurement of the time-of-flight, and a PC, running LabView™ data acquisition and analysis software, is used for data processing, storage and display. A digitizing oscilloscope is used to monitor the signals and is an important tool for pretest adjustments and fine tuning of the test system.

The new ultrasonic system has been commissioned for a combustion system with associated control software, connections, viewports, video equipment and test procedures that have been described previously.[13]

Figure 3 shows the precombustion signal received when the transducer is used on a 0.32-cm-diam, 18-cm-long iron rod. The second area of high amplitude in the peak detector input signal shown on the figure represents the arrival of the first reflection of the longitudinal wave from the end of the rod. Electronically, the time-of-flight of the induced stress wave that is directly related to the rod length is detected using three voltage level detectors with the gatings indicated. The first one is set up to detect a large signal level and to set the output voltage of the circuit to approximately +5 V as shown. The second one detects a certain period of low voltage level signal without changing the output voltage of the circuit. The third one detects the next large (relative) voltage peak and sets the output voltage back to zero. Since a high–low–high sequence is required, the correct sequential detection is ensured. As stated, the width of the rectangular peak detector output signal, shown in Fig. 3, represents a multiple-length of the rod (in this case two times). These ''signal widths,'' or multiples of the rod length, are electronically measured using a 20-MHz counter circuit and transferred to the PC at a rate of approximately 8 Hz for posttest calculation of the regression rate of the melting interface of the burning rod.

II. EXPERIMENTS, RESULTS AND DISCUSSION

As stated, Fig. 3 depicts the output from the transducer prior to a test. This data is used to calculate the velocity, c_0, of longitudinal waves in the rod, which then allows the calculation of the rod's changing length during a test. Since the regression rate of the melting interface is large compared to the heat transfer rate within the rod, any temperature increase is restricted to a small length at the end of the burning rod. Consequently, the temperature dependence of c_0 has not to be considered in a first-order calculation of the regression rate. During the burning of a sample, the transducer's output retains the same pattern except the reflections begin to move to the left as the rod becomes shorter. One such output from the transducer during burning of a 0.32-cm-diam commercially pure iron rod in 0.69 MPa (100 psia) oxygen is shown in Fig. 4, where it is noted that the first reflection has been shifted towards the left. Figure 4 would have an associated rectangular peak detector output signal of about +5 V similar to the one shown in Fig. 3, except it would be of smaller width. This decrease in width is a direct multiple of the change in rod length between the time the two signals were recorded. Figure 5 shows the changing rod length with time as determined real-time by the transducer and associated electronics as described above. The slope of a best-fit line to these data points represents the mean regression rate of the melting interface for the burning iron.

The slope of the line fitted to the points shown in Fig. 5 was calculated to be 4.07 mm/s and this is taken to be the mean regression rate of the melting interface of this 0.32-cm-diam commercially pure iron rod in 0.69 MPa (100 psia) oxygen. The video record obtained for this burning iron was

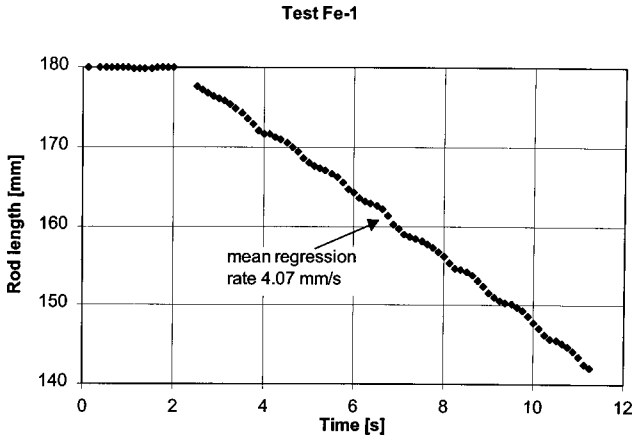


FIG. 5. Real-time changing rod length during combustion of a 0.32-cm-diam iron rod in 0.69 MPa (100 psia) oxygen pressure. The slope fitted to the data points represents the mean regression rate of the melting interface for the burning iron rod. The periodic variations of the instantaneous regression rates are related to the growth and detachment of individual drops of molten mass.

TABLE I. Regression rates of burning 0.32-cm-diam iron rods in pure oxygen at different gauge pressures.

Test	Oxygen pressure [MPa]	Measured regression rate pressure (mm/s) Ultrasonic system	Visual interrogation
Fe-0	~0.6	3.82±0.08[a]	–
Fe-1	0.69	4.07±0.08	4.0±0.3
Fe-2	0.69	4.06±0.08	4.1±0.3
Fe-3	0.69	4.07±0.08	4.0±0.3
Fe-4	0.5	3.77±0.08	3.8±0.2
Fe-5	0.5	3.64±0.07	4.1±1.1
Fe-6	0.5	3.60±0.07	4.0±1.1

[a]The various factors that contribute to the reported uncertainties of the ultrasonic measurement system are discussed and quantified in the Appendix.

interrogated visually and a regression rate of the burning rod by this method was determined to be 4.0 mm/s. Obviously there is excellent agreement between the regression rate obtained by the ultrasonic transducer and the visual interrogation method. Published values for the regression rate of the melting interface for a burning iron rod in 0.69 MPa (100 psia) oxygen were found in the literature.[14,15] The reported regression rate of about 4.2 mm/s is also in excellent agreement with the regression rate calculated by the new ultrasonic transducer.

In Table I the results of the measured regression rates for 0.32-cm-diam commercially pure iron rods burning in pure oxygen are summarized. The values of the calculated mean regression rates using the new ultrasonic measurement system are in excellent agreement with values determined using conventional visual interrogation. The system enables reliable identification of even small variations, which may result, for example, from slight changes in the applied oxygen pressure between individual tests. It is important to mention that the calculation of the regression rates using the new system requires almost no time compared to the conventional posttest visual interrogation technique. The various factors that contribute to the reported uncertainties of the ultrasonic measurement system are discussed and quantified in the Appendix.

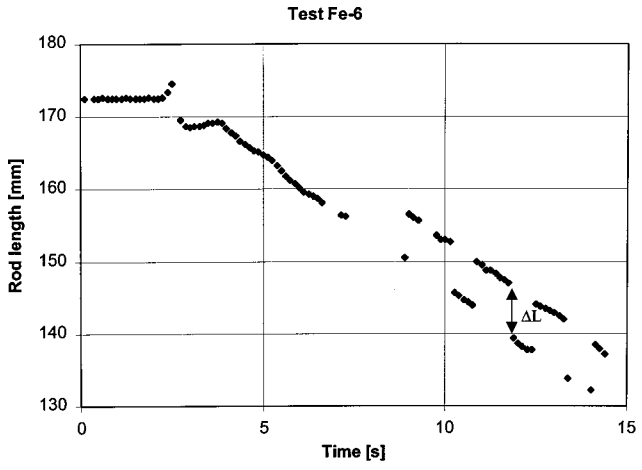


FIG. 6. Changing rod length raw data during combustion of a 0.32-cm-diam iron rod in 0.5 MPa (72.5 psia) oxygen pressure. The two parallel data sets result from the peak detector electronics locking on to different cycles of the reflected pulse.

A characteristic feature, which is present in Fig. 5, is the periodic variations in the measured instantaneous regression rates, which is the result of the growth and detachment of individual drops of molten mass. This effect has been reported in the literature,[14–16] but it has never been documented with such clarity, thus demonstrating the outstanding sensitivity of the new ultrasonic measurement system.

It is the authors' contention that regression rates calculated with this ultrasonic transducer will be more reliable and accurate than similar rates calculated visually. In general, most of the errors described above that are present during the visual interrogation process are completely eliminated when the ultrasonic transducer is used. No scale factors and no playback of recordings are necessary, thus no distance, parallax, or recording speed errors are present. In addition, there are no restrictions on access time to the burning rod, which is normally limited by the viewports of the recording system, and the combustion phenomena is not important in the calculation of the regression rate, i.e., ambiguities due to contrast problems and the obscuration of the melting surface by condensed-phase products are irrelevant.

In Fig. 6 the rod length versus time raw data for experiment Fe-6 are presented. It shows the effect when the amplitude of the reflected wave varies in time in such a way that the peak detector electronics locks on to different cycles of the reflected pulse. This results in unsteady rod length data as indicated by the two different data samples, which are vertically shifted by $\Delta L = c_0 T$, where $T = 3.3\mu s$ is the period of the 300-kHz excitation signal. The figure shows that the data can be used to calculate the regression rate, since although the absolute length of the burning rod varies, the slope of the curves, i.e., the regression rates are the same. In the Appendix further details are given on the accuracy of the new measurement technique.

III. CONCLUSIONS

A new ultrasonic measurement system has been developed which is capable of quantifying the regression rate of the melting interface for a burning metallic rod. The regression rates for burning iron rods in pure oxygen at different gauge pressures provided by the ultrasonic transducer compare excellently with published values and regression rates determined from standard posttest visual interrogation of a recorded image. In addition, the new measurement system has proven to be much more cost effective and significantly more sensitive and accurate than the visual techniques typically used to obtain this parameter.

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APPENDIX: UNCERTAINTY ANALYSIS

The major factor which determines the accuracy of the ultrasonic measurement system is the ratio between the individual wave propagation components that define the width of

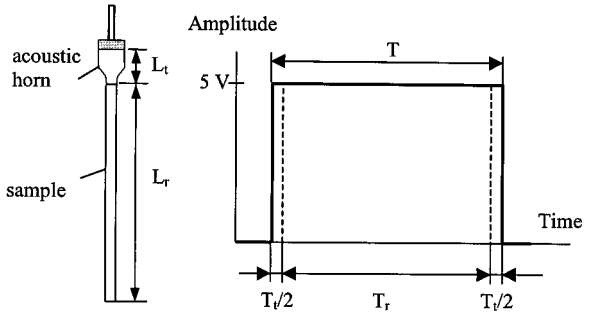

FIG. A1. Sketch of the wave propagation segments that contribute to the width of the rectangular peak detector output signal.

the rectangular peak detector output signal. As illustrated in Fig. A1, the pulse width is not only controlled by the time the pulse needs to travel along the rod, but also by the time required for the propagation within the transducer unit. Therefore, the assumption that a constant value of c_0 can be used to calculate the instantaneous rod length during the entire combustion period is strictly not correct.

In the initial, precombustion test, which is used to determine c_0, the time T_t is approximately 4% of the total time T if the rod length is 180 mm and the wave velocities within the metallic rod and the glass ceramic acoustic horn are assumed to be $c_r=5$ mm/μs and $c_t=12$ mm/μs, respectively. The velocity c_0 determined from the measurement is:

$$c_0=\frac{2L_r}{T}=4.8 \text{ mm}/\mu\text{s}. \tag{A1}$$

In comparison, T_t is approximately 6% if the rod is 120 mm long or, in other words, the instantaneous rod length is calculated to be

$$L_r=\frac{c_0 T}{2}=122.4 \text{ mm} \tag{A2}$$

if the c_0 value from above is used, which over estimates the real length by 2%.

In conclusion, considering an interrogation length of approximately 60 mm and typical wave propagation velocities for metallic samples, the maximum uncertainty for the measured rod lengths is less than 2%.

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