APPLICATION OF ULTRASONIC THERMOMETRY
IN LMFBR SAFETY RESEARCH*Gary A. Carlson
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ABSTRACT

Ultrasonic thermometry has many potential applications in reactor safety research, where extremely high temperatures and lack of visual access may preclude the use of conventional diagnostics. An application (the in-core molten fuel pool experiment) will be described in which thoriated tungsten ultrasonic thermometers were used to measure temperatures in UO_2 to incipient melt (2860°). Each thermometer included five sensor elements 10 mm long, providing five temperatures within the UO_2 at various axial locations. The 10 mm spatial resolution is about five times better than previous applications of the technique. Temperature resolution of $\pm 10^\circ\text{C}$ was indicated by calibration data. Besides providing temperature data approximately 1000°C higher than were obtained with thermocouples, the thermometer yielded valuable axial temperature profile data. Details of the sensors, exciting coils, and signal conditioning electronics will be given.

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Introduction

Ultrasonic thermometry is a method of temperature measurement based on the principle that the acoustic velocity in all materials is a function of temperature.¹ Although the application of the method is relatively involved, requiring sophisticated electronics and often utilizing small, fragile sensing elements, it has been very useful in certain applications for which other thermometry methods could not be used. For example, there have been several successful applications of ultrasonic thermometry to the measurement of nuclear reactor fuel pin centerline temperatures.^{2,3,4} Here, the very high temperatures (to 2500°C), high radiation fields, and lack of visual access precluded the use of thermocouples or optical pyrometry.

In the present application, similar constraints of extremely high temperatures, radiation fields, and no visual access have suggested the use of ultrasonic thermometry for temperature measurements. The possibility of temperature profiling (making several temperature measurements at adjacent spatial locations using a single sensor line) was an additional incentive for its use.

The present study, entitled the "Molten Fuel Pool Program,"⁵ is part of an extensive LMFBR safety research program being conducted at Sandia Laboratories. The study is designed to simulate that portion of a hypothetical accident in which the entire reactor core fails and falls onto the base of the reactor vessel or eventually onto the reactor substructure. The goals of the study are to determine heat transfer rates from the molten or near-molten fuel to its surroundings and to measure the rates of ablation of the steel supporting structure. The experiments are conducted in the Annular Core Pulse Reactor at Sandia, used in the steady-state mode to provide fission-heating of the fully enriched UO_2 . This simulates the decay heating which would occur in an actual reactor accident.

This paper describes the development of ultrasonic thermometers and associated electronics for the in-core molten pool experiments and reports preliminary results from the first three experiments, two involving only UO_2 and the third looking at steel melting by fission-heated UO_2 .

Development Work

Figure 1 shows schematically the central portion of the in-core molten fuel pool experiment package, and one of the ultrasonic thermometers used to monitor the axial temperature profile in the fuel (not drawn to scale). The ultrasonic thermometer functions by generation of an acoustic pulse in a magnetostrictive rod using an electrically pulsed coil to generate a pulsed field in the rod; propagation of that acoustic pulse through a transmission line welded to the magnetostrictive rod; reflection of the acoustic pulse from several impedance discontinuities (notches) near the end of the transmission line; acquisition of the reflected signals as induced pulses in the pulse coil; and measurement of the time delay between successive reflections, which is then translated into a temperature by means of a calibration curve.

In applications of ultrasonic thermometry to fuel pin centerline temperature measurements, the temperature field was relatively uniform over hundreds of millimeters. Thus, sensor element lengths of 50 mm or so were commonly employed, along with the appropriate signal-conditioning electronics and acoustical signal generators. For the present study, steep temperature gradients were expected (up to 30°C/mm). This necessitated the use of much shorter sensor elements, higher frequency acoustical signals, and higher frequency response electronics.

Although the molten pool studies were designed to attain higher temperatures than measured previously ($\sim 2900^\circ \text{C}$, versus $\sim 2500^\circ \text{C}$), it was felt that the thoriated tungsten sensor rods used successfully by others⁴ would also be well suited to this program. It was determined that 10-mm length sensing

elements would give adequate temperature profile information, allowing the use of five elements through the 55-mm height fuel bed.

In order to attain the much higher frequency acoustical waves required because of the reduction of the sensor lengths from 50 mm to 10 mm, modifications suggested by delay line technology were employed.⁶ Short (2 mm) pulse coils were employed, with ferrite end checks to confine the magnetic field to a short length of the remendur magnetostrictive rod. Coils with 100-150 turns of #44 copper wire gave satisfactory acoustical signals with the relatively long (7 m) cables required for the in-core experiments between the electronic coil pulser and the coil. The diameter of the tungsten sensor line (0.5 mm) was chosen to maximize signal amplitude while minimizing the loss of the high frequency components of the acoustical waves which occurred with larger diameter lines.

The ultrasonic thermometry electronics were designed for measurement of the time delay between microsecond-width signals separated by a few microseconds, with a few nanoseconds time resolution. As shown in Figure 2, the electronics package consists of five modules; (1) an electronic coil pulser and preamp, (2) a bandpass video amplifier and limiter, (3) six gate control servos, (4) a multiplex system and (5) an electronic timer. The basic functions of each module are as follows:

The coil pulser contains a delay line type pulse generator to provide short duration, high current drive pulses to the pulse coil. The unit also contains a signal preamplifier and a sync amplifier. Although the preamplifier provides some signal gain, its primary function is to provide impedance matching to the long coaxial cable used to transmit the return signal from the coil pulser to the signal processing system. The sync amplifier provides a zero-time signal for use in the gate control servos.

The video amplifier/limiter consists of a two-stage non-saturating limiter amplifier, followed by a high speed integrated circuit sense amplifier. The two input stages provide a relatively narrow band-pass characteristic to reduce system noise and to improve overload recovery time. The amplifier output is a TTL logic compatible switching signal where the switch transitions correspond to the zero crossings of the input signal.

The gate control servos generate a gate signal (~ 0.75 μ s wide) which can be centered on the desired video zero crossing signal. Once the desired zero crossing is selected in this manner, the servo loop is engaged, causing the gate pulse to track the selected zero crossing signal. The zero crossing signal within the gate pulse is used to drive an "AND" gate, the output of which can be used as a start or stop signal to an electronic counter.

Only one pulser and one amplifier are needed for each multi-element sensor. However, each sensor discontinuity requires a separate gate control servo. The servo output (gate "AND" video signal) may be used as either a start or stop signal, depending upon the selected element. The multiplex system sequentially selects elements and routes the appropriate servo start/stop signals to a single start and a single stop terminal so that one timer can sequentially read all the elements on the sensor. The present system is designed to sequence through either one or two sensors, where either sensor may have from one to five elements.

The timer in the present system is a commercial time interval counter, having BCD output to provide direct interfacing to an on-line computer. The computer uses a polynomial fit of a calibration curve to convert the time interval data into temperatures, which are displayed on a TV monitor for the experimenter.

Prior to the in-core experiments, a number of studies of sensor performance were conducted in a high-temperature helium-gas-filled furnace. In these studies it was determined that the thoriated tungsten sensors could be used to measure temperatures in UO_2 to above the UO_2 melting point

($\sim 2860^{\circ}\text{C}$), provided a protective sheath was used to prevent acoustical interference. It was found that protective sheaths of ThO_2 were superior to sheaths of tungsten-rhenium alloys as others have employed, due to the lack of interaction between ThO_2 and tungsten. However, the period at high temperatures with ThO_2 sheaths is somewhat limited due to migration of ThO_2 from the sheath to a lower temperature portion of the sensor line through an evaporation-condensation process. The condensed ThO_2 provides a new reflective discontinuity which may affect subsequent measurements. This effect was not a problem for the present studies because of the relatively short times at high temperature ($\sim 5 - 10$ minutes).

Calibration curves for the ultrasonic sensors were established in the furnace experiments, using an optical pyrometer as the primary temperature monitor. A typical calibration curve for a 10 mm sensor element is shown in Fig. 3. Since the data showed a considerable change in slope near the middle temperatures, the high and low temperature segments were fit with separate fifth-order polynomials. The standard deviation of the high-temperature data segment (1400 to 2850°C) typically was near $\pm 10^{\circ}\text{C}$. The accuracy of the temperature calibration data was limited primarily by the accuracy of the optical pyrometer measurements to about $\pm 15^{\circ}\text{C}$ above 2000°C .

Heat transfer calculations were run to determine the effect of axial thermal conductivity in the sensor and sheath on the accuracy of temperature measurements. These showed that for a 0.5 mm diameter tungsten sensor and a 0.85 mm ID x 1.70 mm OD ThO_2 sheath, in a UO_2 bed with a temperature

gradient of $20^{\circ}\text{C}/\text{mm}$ (500°C from bed center to top and bottom), the errors in temperature measured due to heat losses through the sheath and sensor would be less than 15°C , or smaller than the measurement uncertainty.

In-Core Temperature Measurements

Following the laboratory development program, three in-core molten pool experiments were run. In each experiment, two ultrasonic thermometers were positioned near the axial centerline of the fuel bed. Each thermometer had five sensor elements with lengths of 9 to 10 mm. A single calibration curve for all the sensor elements on a given thermometer was used in the first two experiments, MP-1 and MP-2. However, it was determined after these experiments that there was sufficient variability in calibration curves for adjacent sensor elements to warrant the use of individual calibration curves for each element, and this was done for the final in-core experiment (MP-3S). The variability apparently reflects axial variations in the composition of the thoriated tungsten rod.

The data acquired during the first two in-core experiments were much less satisfactory than from the laboratory experiments due to the more complex physical arrangement of the in-core experiments. Data from one sensor in MP-1 are shown in Fig. 4. Temperature measurement errors up to 100°C (based on calculated temperature histories), are believed present during the reactor-powered portion of the run (0-20 minutes), while even larger errors are apparent following the reactor shutdown. The other sensor in MP-1 and both sensors in MP-2 gave less accurate data. For these in-core

experiments, the sensors were contained within 150 mm long ThO_2 sheaths for protection from contact with the UO_2 bed. Because the sheaths were generally somewhat warped, there was some binding between the sensor and sheath. Further, in the initial experiment configuration, it was necessary to put an S-bend in each sensor line near the top to accommodate a feedthrough in the lid of a steel containment vessel. This caused additional binding between sensor and sheath which may have been accentuated during the experiment by the uneven thermal expansion of various parts of the experiment capsule. Finally, the large temperature gradients in the fuel bed during the in-core experiment may have caused non-uniform fuel motion which could have further warped or even broken the ThO_2 sheaths during the later portions of the experiments.

Although the experimental data from MP-2 for the individual sensor elements were not as good as hoped, the average data from each ultrasonic thermometer (total sensor length 50 mm) were quite good and provided a useful record of the average temperature of the fuel bed during the experiment. Figure 5 shows the average temperature data measured during MP-2 by the two ultrasonic thermometers. As seen, there is very little difference in the temperatures recorded by the two sensors until about 2750°C . At this time, fuel melting and motion began to occur in the middle of the fuel bed. This apparently caused some perturbation of the sensor elements, seen as a deviation in the data traces which eventually becomes a total disruption of data from one of the sensors at later times.

For the final in-core experiment of the present series, modifications were made to allow for straight, parallel sensor lines with a minimum of contact between sensor and sheath. Somewhat larger reflection coefficient notches were also employed (30-35%, vs 20% for MP-1 and MP-2), to minimize the effect of spurious reflections due to binding of sensor and sheath. These changes were quite helpful, and the data obtained from MP-3S were much more satisfactory than the previous two experiments. MP-3S was a somewhat different experiment, with a 12.7 mm thick stainless steel disc below a 44 mm thick UO_2 bed. The purpose of this experiment was to study the melting of the steel disc by the overlying fission-heated UO_2 bed. In MP-3S, one element of each sensor was within the steel disc (in a drilled hole), while the other four elements were in the fuel bed. Figure 6 shows the ultrasonic data from one of the sensors, compared with the response of the bed and steel calculated using a two-dimensional heat transfer code.⁷ As seen, with the exception of some spurious data early in the experiment on sensor elements 4 and 5, the agreement between calculations and measurements of steel temperature and maximum fuel temperature is quite good. A temperature arrest in the steel at 1410°C corresponding to the steel melting transition is clearly seen. The lower measured rate of rise in the fuel temperature above 2100°C is believed to be real, but cannot be explained at this time.

Figure 7 shows the power of the ultrasonic technique for measuring temperature profiles. Here, the temperature profiles in the steel-fuel bed measured by each ultrasonic thermometer are compared to calculated values at several points in time during the experiment. The agreement is in general very good except for high steel temperatures measured by one sensor, and a discrepancy between measured and calculated fuel temperatures at later times, as previously discussed.

Summary, Conclusions, and Future Studies

Ultrasonic thermometry has been utilized to make temperature and temperature profile measurements in a UO_2 bed to the UO_2 melting point within a nuclear reactor. These measurements could not have been made with any other known thermometry technique.

For these studies, it was necessary to improve the spatial and temporal resolution of the method by about a factor of five. This was accomplished by application of delay line technology to miniaturization of coils and sensors, and by use of integrated circuit technology to develop advanced signal conditioning electronics.

While some experimental difficulties were encountered in the early in-core experiments, the latest experiment suggests that good to excellent temperature data may now be obtained in subsequent studies. Data from future experiments, involving an array of ultrasonic thermometers deployed in a radial array, will be essential in defining the heat transfer characteristics of molten fuel pools, information which may be vitally important to the determination of the safety of the LMFBR.

The techniques developed during this study are believed to have a broader range of application in the LMFBR safety research area. Use of the method for measuring temperatures in liquid sodium and sodium-fuel mixtures (in the "Debris Bed" experiments) is being evaluated. Applications to measurement of temperatures in concrete-molten core and concrete-steel studies are also under investigation.

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Figure 1 5-Element Ultrasonic Thermometer in UO₂ (Schematic).

Fig. 2 Ultra sonic Thermometry Electronics (schematic)

CALIBRATION CURVE FOR 2% THORIATED TUNGSTEN ULTRASONIC THERMOMETER

ULTRASONIC THERMOMETER RECORDS FOR FIRST IN-CORE MOLTEN POOL EXPERIMENT

Fig 4

MP-2 Ultrasonic Thermometry Data
Averaged Fuel Bed Temperature

Fig 5

Figure 46 Ultrasonic thermometry data from MP-3S, sensor 2. Sensor elements 1-5 are each approximately 9 mm long. The elements are positioned near the axial centerline of the thorium crucible, with elements 1 to 4 running sequentially from the top of the fuel bed to the bottom, and element 5 within the steel disc.

Figure 5. A comparison of measured and calculated temperature profiles at various times during MP-3S. Solid line - calculation; x - UT1; o - UT2.