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Abstract

A 135 GHz radiometer with a graphite waveguide/mirror system has been implemented on the Mark II DC graphite arc furnace for internal surface temperature measurements. Results are presented for the first low power test of Mark II which achieved a planned maximum temperature of 110° C in a clean soil fill. The radiometer performed well, providing the first complete temperature profile measurements inside a furnace. The non equilibrium distribution of the inside surface temperature was clearly detected.

Introduction

A pilot-scale DC graphite arc furnace, Mark II, has been constructed at the MIT Plasma Fusion Center and has commenced initial operational tests. The goal of this furnace is to evaluate DC graphite arc technology for the vitrification of wastes as part of the Department of Energy's (DOE) Buried Waste Integrated Demonstration (BWID) program. The construction of Mark II follows successful feasibility tests of Mark I, a 30 kW, 100 pound batch processing furnace [1]. Mark II represents a significant scale up to a maximum power of 1 MW and a 500 pound per hour continuous processing capability.

An important part of the Mark II program is to develop advanced diagnostics to better characterize furnace performance and to provide measurements to help in operation and control [2]. The first such diagnostic to be implemented is a millimeter-wave radiometer for spatially resolved surface temperature measurements inside the furnace. Millimeter-wave radiometry is a robust furnace temperature measurement technology because these wavelengths can readily penetrate cloudy, smoky atmospheres and are not significantly perturbed by thin deposition layers on window and mirror surfaces. In addition, waveguide and mirror components can be constructed from the

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same graphite material as the hearth. In this report we present the first results with this diagnostic during Mark II's first low power test.

Experimental Setup

The heterodyne receiver radiometer has a local oscillator (LO) frequency of 135.4 GHz and an intermediate frequency (IF) range of 0.4 to 1.5 GHz so that the emission was detected in the sidebands 133.9 - 135.0 GHz and 135.8 - 136.9 GHz above and below the LO. The measured noise temperature of this receiver was approximately 13,000 K double sideband. The theoretical minimum measurable temperature rise for such a receiver is 0.3° C for a signal integration time of one second [3]. There is no upper temperature limit, though in the unlikely case of temperature rises greater than the receiver noise temperature the nonlinear response of the IF detector diode would need to be considered. Measurements are always made relative to a room temperature reference which is provided by the blades of a chopper which periodically blocks the receiver field-of-view at 41 Hz. Millimeter-wave black-body material covers the chopper blades.

Figure 1 shows the temperature measurement setup in Mark II. The furnace cross section is shown at the height of the radiometer waveguide penetration into the furnace. The inner furnace chamber has a diameter of 36 inches and a height of 54 inches from the bottom of the hearth to the ceiling. The waveguide penetrates at a height of 38 inches above the hearth bottom in a direction that is parallel to a radial line but offset by 6 inches.

A unique feature of this furnace is the coaxial pair of graphite electrodes centered in the chamber which allows transfer and non transfer arc opertation [1]. The outer electrode outer diameter is 16 inches leaving a maximum space of 10 inches between the inner furnace wall and the electrodes. The protrusion of the radiometer waveguide into the furnace must be kept significantly less than this because the graphite electrodes are free to swing if hit by the waste feed In the present setup the maximum extension of the waveguide into the furnace is 4 inches. A flat graphite mirror in the end of the waveguide directs the radiometer field-of-view sideways at a 90° angle to the axis of the guide as shown by the arrow in Figure 1.

The waveguide itself is constructed from a 1.5 inch inner diameter graphite tube which is corrugated on the inside to propagate the HE_{11} waveguide mode [4]. This waveguide mode is the most efficient one for waveguides greater than one wavelength in diameter. It is the key reason why it was possible to construct an efficient waveguide from graphite. Also, the HE_{11} mode launches as a free space Gaussian beam which provides the best diffraction limited spatial resolution.

The length of the this graphite waveguide is 49.5 inches. An alumina tube with an outer diameter of 2.75 inches acts as a sleeve for support and electrical insulation to the outside of the furnace. The alumina sleeve is ten inches shorter than the graphite
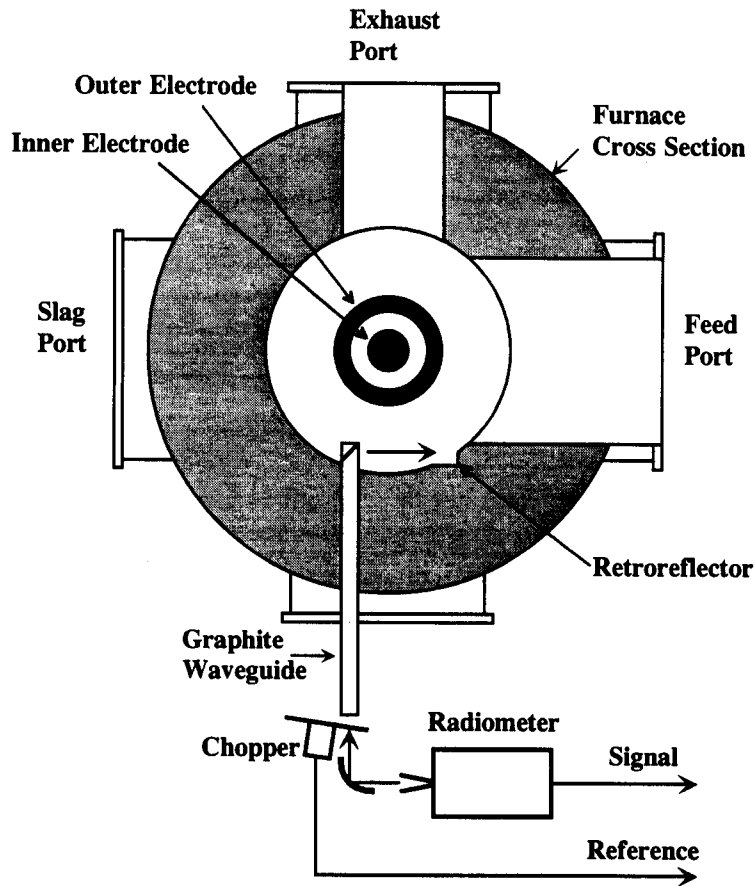
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Figure 1. Millimeter-wave radiometer temperature measurement setup in the Mark II arc furnace

waveguide and does not protrude into the furnace chamber. There is a break in the waveguide 7 inches from the output for a 0.25 inch thick Teflon window which acts as a seal and an electrical break. A 90° off-axis parabolic mirror is used to optimally couple the radiometer field-of-view as launched by its corrugated horn to the outside end of the graphite waveguide.

The graphite waveguide is rotatable so that the radiometer field-of-view can be continuously scanned from looking down at the hearth, at the walls, and up at the ceiling. This is illustrated in Figure 2 were approximately 0° corresponds to looking straight up and approximately 180° straight down. For an angular viewing range from about 0° to 45° the view is of the ceiling. For an angular viewing range from about 145° to 180° the view is of the hearth and waste inside. Actually the viewing locations are not this sharply defined because the field-of-view spot size is not a point. Figure 2 shows only were the approximate center of the viewing spot intersects the furnace surface.

The spatial resolution of the radiometer depends on the distance of the surface being viewed from the waveguide. The divergence of the launched Gaussian field-of-
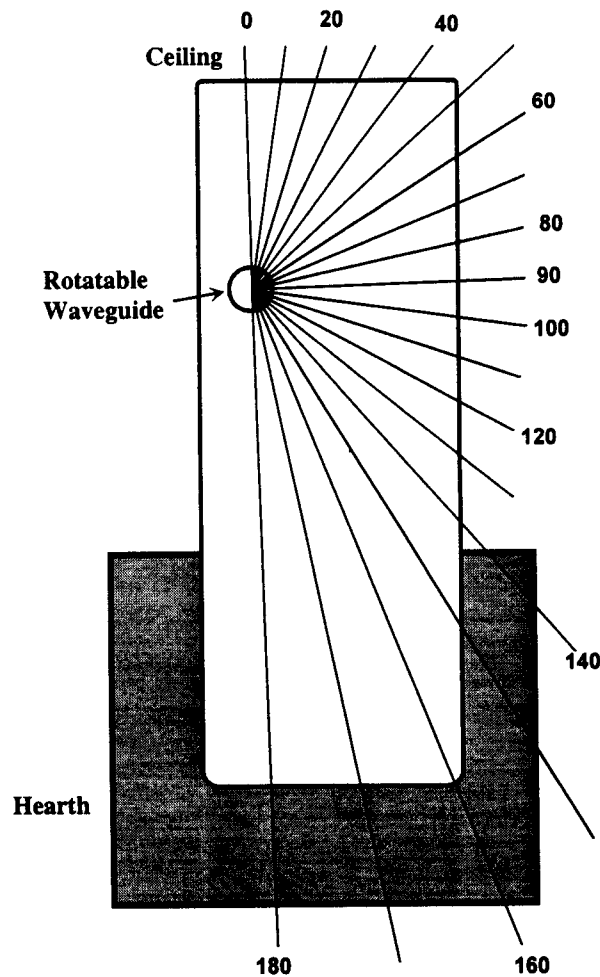
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Figure 2. Radiometer view directions and approximate intersection with the inside furnace surfaces

view beam is plotted in Figure 3. For a distance of 16 inches from the waveguide, which is the distance to the wall for the horizontal 90° viewing direction, the $1/e^2$ spot size (the diameter within which 87% of a Gaussian profile is contained) is about 2 inches. The furthest distance is to the bottom of the hearth, 38 inches, where the $1/e^2$ spot size is 4.8 inches. More typically, the hearth will have a fill of waste or soil, as it did for the present low power test, and the spatial resolution will be about 2.5 inches to the top of this fill. The spatial resolution on the ceiling is also about the same.

Calibration

The response of the radiometer to temperature differences, and the signal losses in the waveguide transmission system were calibrated with a liquid nitrogen cooled black-body. The radiometer responds to hot or cold temperature differences relative to the chopper blade reference. A liquid nitrogen cooled black-body source of extended dimensions which fills the entire radiometer field-of-view is readily obtainable and provides an accurately known temperature of 77 K for calibration. Commercially
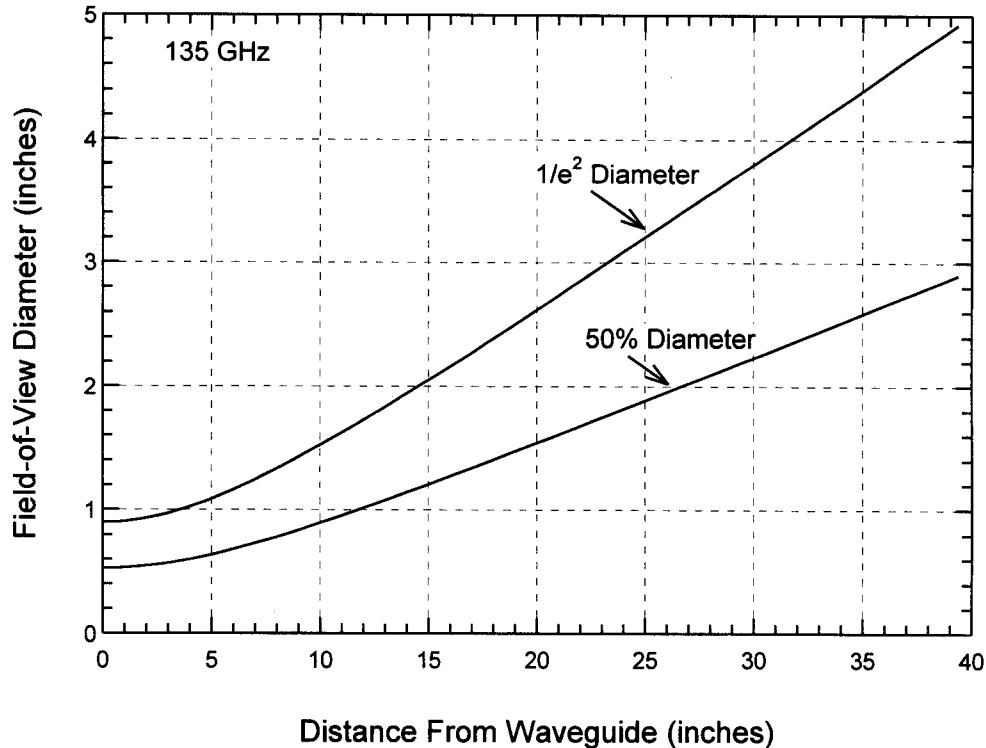
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Figure 3. Spatial resolution of the Mark II millimeter-wave radiometer. The field-of-view has a Gaussian profile and the curves show the diameters within which 87% and 50% of the sensitivity is located.

available Eccosorb™ [5], a millimeter-wave absorbing foam plastic, was used as the black-body material. It is the same material that covers the chopper blades.

The calibration procedure involved alternately holding a room temperature and then a liquid nitrogen cooled sheet of Eccosorb in the radiometer field-of-view. The room temperature measurement was used to determine the zero offset signal level and then the cold temperature measurement determined the response to a known temperature. This was done at two locations, between the chopper and the graphite waveguide at the outside of the furnace, and inside the furnace. The calibration to the outside of the graphite waveguide could be checked at any time during furnace operation. During the low power test of Mark II the calibration to this point was found to remain constant within 4% for the approximately 24 hour continuous temperature measurements.

The signal losses through the graphite waveguide and Teflon window were determined by comparing the cold black-body measurements at the outside of the furnace to those made inside the furnace prior to the Mark II low power test. These transmission losses were measured to be 15% or, in the terminology of microwave circuits, the waveguide/window insertion loss was -0.7 dB. Prior laboratory tests of this length of corrugated graphite waveguide without the window showed transmission

losses of less than 5%. Absorption and reflection due to the Teflon window alone does not account for the difference. Window reflection losses were minimized by window surface corrugations [6]. Therefore, most of the transmission line losses are probably due to mode conversion losses caused by the window gap in the waveguide and possible misalignment with the radiometer. These losses will be reduced for the next Mark II test, but for the present, the signals were corrected by the measured 15% loss factor.

Measurements

The goal of the first low power test was to warm up Mark II to approximately 100° C over four hours and then try to hold that temperature for one hour. No arcing was attempted. A carbon pile resistor consisting of alternating layers of steel plates and coke was stacked in the center of the hearth to a height slightly above the graphite hearth for resistive heating. The coaxial pair of graphite electrodes rested on top of this resistor. Clean soil from Idaho Falls with a 10% mix by weight of calcium carbonate filled the hearth around the carbon pile resistor.

The graphite waveguide was rotated to view straight down at the soil for all of the temperature measurements presented here except for two scans of the inside surfaces. Prior laboratory measurements of clean Idaho Falls soil with a 10% mix of calcium carbonate established the emissivity at 135 GHz to be 0.99 at room temperature. Similar measurements earlier established the emissivity of the alumina surfaced walls of the furnace to be 0.88 over a temperature range from room temperature to 900° C [2].

Temperature was displayed in real time on a computer monitor which read the output of a lock-in amplifier connected to the radiometer signal and referenced to the chopper frequency. Every minute the instantaneous temperature was stored to hard disk. Figure 4 shows this entire temperature record of the soil from 1.5 hours before the furnace was turned on to about 18 hours after turn off. The time scale is normalized to zero at furnace turn on. In addition to showing the temperature rise during operation, this figure shows the slow decrease in temperature after turn off. The next day, 18 hours after shut down, the soil temperature was still 10° C above room temperature. Another feature of these first temperature measurements is that the signal noise is much higher during furnace operation.

Figure 5 shows an expanded view of this temperature record during furnace operation. Major milestones in the run are indicated. The furnace was turned on with a 1000 Amperes of current, corresponding to about 17 kW of power which gradually decreased as the carbon resistor heated up. At 1.5 hours into the run the power was down to 14.5 kW. The noise was also particularly high at start up and decreased with temperature until the current was changed.
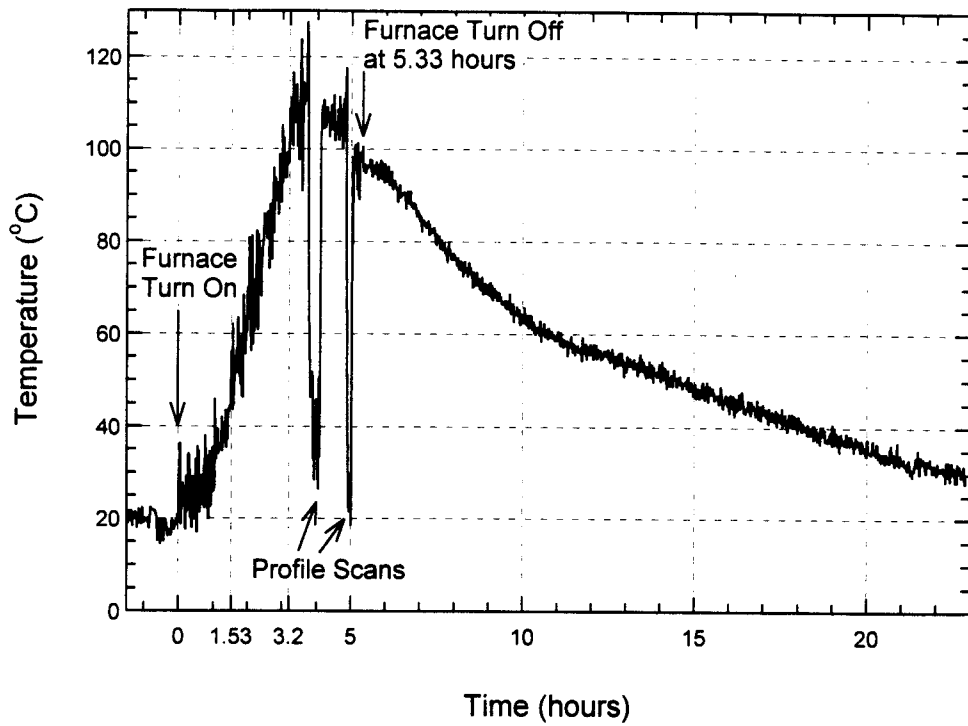
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Figure 4. Temperature record of the first low power test of Mark II. The radiometer was viewing down at the soil except during the profile scans.
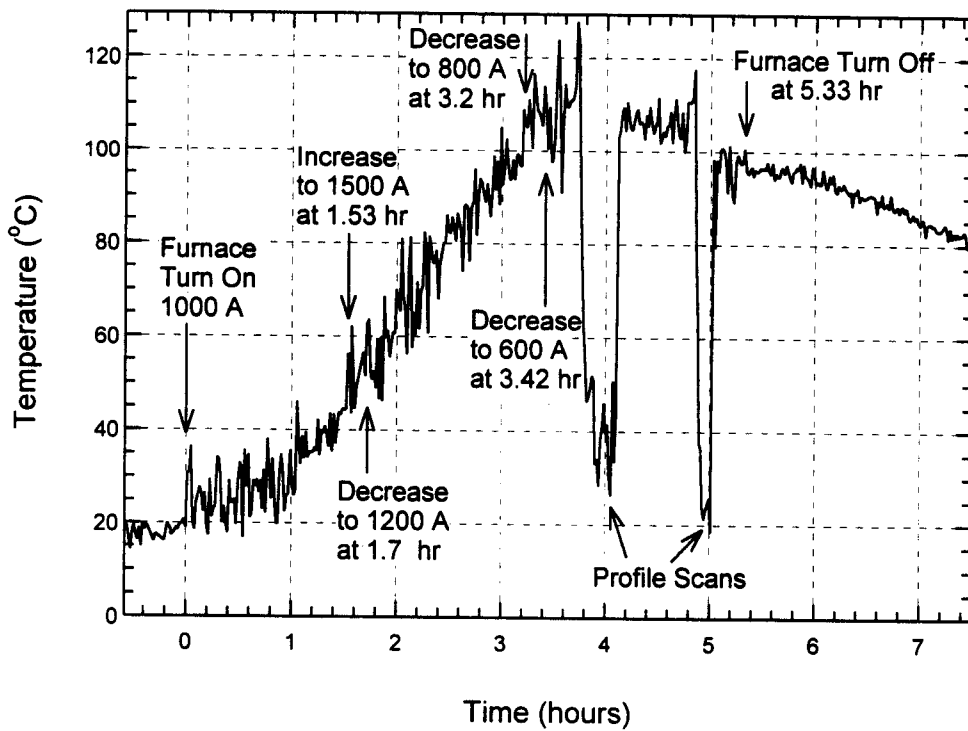

Figure 5. Expanded view of the temperature record during furnace operation for the first Mark II low power test.

At 1.53 hours into the run the current was increased to 1500 A and the peak power for this run of 31 kW was achieved. Ten minutes later the current was turned down to 1200 A and a power of 18.7 kW. A goal of this test was not to increase the temperature too fast and at the 1500 A setting it appeared as the temperature might be going up too fast. Also, the signal noise increased significantly and by turning down the current it was hoped the noise would also decrease for better temperature measurements. This did not turn out to be the case. The noise decreased only gradually with temperature once a current change was made.

At 3.2 hours into the run the power was down to 16.7 kW and a temperature of about 110° C was achieved. At this time the current was decreased first to 800 A at a power of 7.3 kW and then to 600 A at 4.4 kW. The power decreased to 4.1 kW at 600 A after about 25 minutes. It is evident from the temperature record that this power level was not sufficient to maintain equilibrium at 110° C soil temperature.

Further expansion of parts of the temperature record and calculating best fit straight lines allowed us to precisely determine the rates of temperature change for the various furnace power settings. Figure 6 shows the results of these calculations which will be of great value to planning the start up of Mark II's second test. At the start up 1000 A current and approximately 15 kW power level the soil temperature rise was 21° C per hour. At 1200 A and approximately 17 kW the temperature rise was about 32° C per hour, and finally at 600 A, 4 kW there was a temperature decrease from 110° C at about 3° C per hour. A desirable temperature rise for furnace warm up is 28° C per hour and these results indicate that about 16 kW will be required to achieve that rate in the temperature range up to about 110° C.

During lowest current operation at 600 A the graphite waveguide was rotated to scan the temperature profile inside the furnace. The drop in the temperature during the profile scans as shown in Figures 4 and 5 clearly shows that the rest of the furnace was much cooler than the soil. These temperature profiles are plotted in Figure 7. No corrections were made for emissivity in these plots. Such corrections would be very small in this case, less than 3° C for the walls and ceiling, and could be positive or negative depending on the exact angle of view. The soil temperature does not need correction because it is almost a perfect black-body.

This data shows there was a significant temperature gradient inside the furnace during this first low power test. The soil, which is in direct contact with the carbon resistor is the hottest measured surface (the carbon resistor, if viewed, would be hotter). The soil appears to have a hot spot in the 170° view direction. The surface temperature then drops sharply in scanning up the wall from the soil to the ceiling. At the ceiling there is a small rise in temperature. The second profile scan, taken about one hour after the first, shows a significant cool down of the furnace at the 4 kW power operation which would not be evident by monitoring the soil temperature only. In fact, the upper wall surface has returned to room temperature in this short time
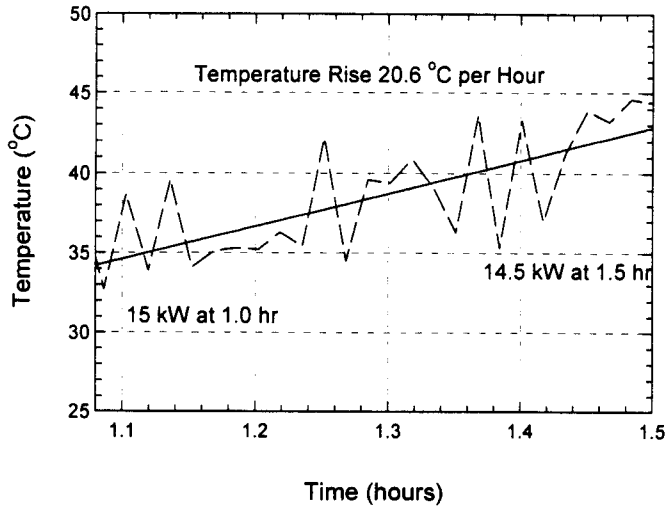
a. Soil temperature rise during 1000 A operation.
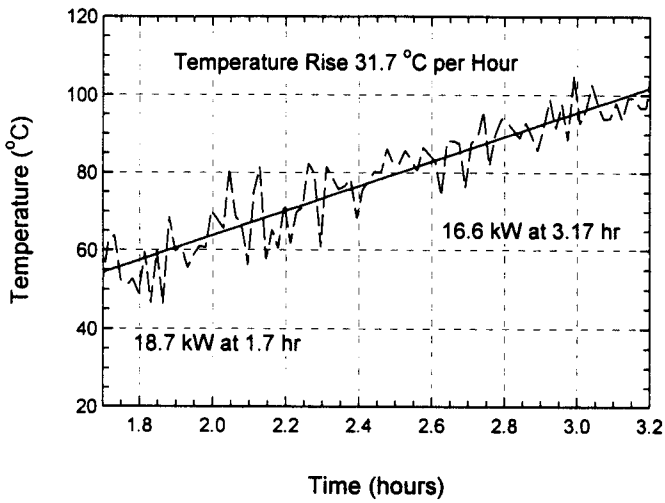
b. Soil temperature rise during 1200 A operation.
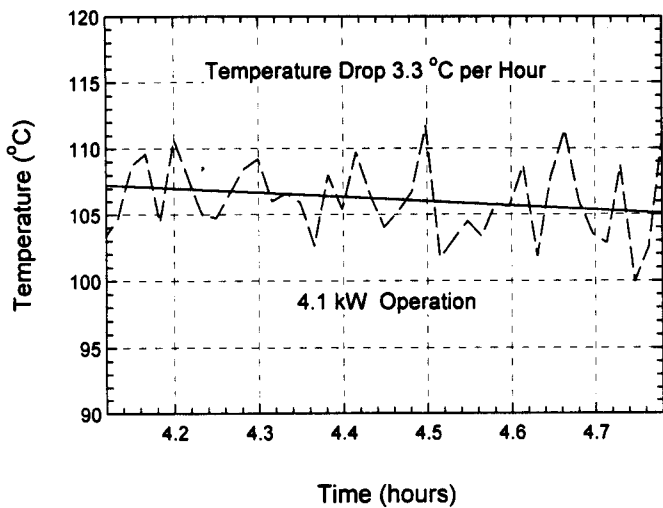
c. Soil temperature decrease during 600 A operation.

Figure 6. Rate of change of the soil temperature for the various furnace current settings during the first test of Mark II.
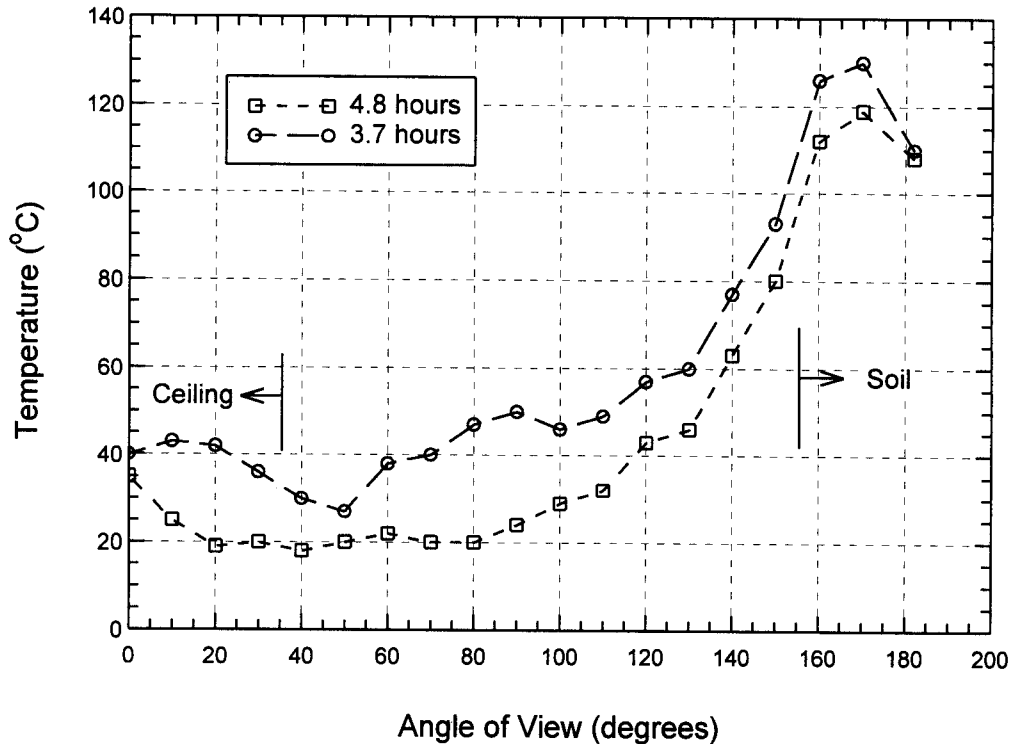
Figure 7. Radiometer scans of the internal surface temperature profiles inside Mark
II during 600 A operation.

before the furnace was completely turned off. The soil, on the other hand, remained
above room temperature for the next 20 hours.

The continuous internal surface temperature profiles provide valuable insight
into the operation and conditioning of Mark II. First, it shows that there is a great
thermal inertia in Mark II and that heating times greater than a few hours and power
levels greater than 4 kW will be needed to hold equilibrium on the large refractory
mass during early warm up stages. Second, it shows very good thermal insulation of
the hearth and soil waste inside. This is encouraging for efficient operation in the
future.

Discussion

This first test of the millimeter-wave radiometer temperature diagnostic has
been very successful. It provided useful information during the first low power test of
Mark II which was used to help control the test. The temperature data gathered from
this test is of great value for planning the next test and has generated confidence in this
diagnostic for providing the needed temperature measurements in the future. Also, it
demonstrated the powerful and unique capability for monitoring the temperature
distribution inside the furnace. This will be valuable for future studies of furnace
performance under various waste feed conditions.

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A number of modifications to this diagnostic will improve the accuracy and reliability of the temperature measurements. The most significant planned modification is to add a millimeter-wave probe beam superimposed on the radiometer field-of-view [2]. This will make possible the real time monitoring of the reflectivity of some the internal surfaces which is directly related to the surface emissivity. This will not only reduce the uncertainty of the temperature measurements at high temperature, but could also be useful for gaining knowledge of possible surface deposition chemistry inside the furnace during operation. A retroreflector, as shown in Figure 1, has been molded into the alumina wall refractory at the 90° viewing direction to facilitate a return reflection signal for these studies. Also, a return reflection from the waste fill surface will be possible where emissivity changes will certainly occur as the waste melts and the composition of the feed is varied.

The present graphite waveguide and Teflon window configuration will be modified to reduce transmission losses in this part of the radiometer system. The mode conversion losses due to the window gap in the waveguide will be eliminated by moving the Teflon window to the outside end of the guide. The waveguide\ window losses can not be easily checked during furnace operation and therefore reducing these losses to the lowest possible values will reduce their effect on the measurements if there are changes with temperature. The probe beam that will be added can be used to check the waveguide\ window transmission losses over the temperature range for which the emissivity of the refractory wall is known.

A finial modification will be to enclose all the data acquisition electronics inside an electrically shielded rack. For this first test the radiometer itself and the power and signal cables were shielded, and the power was obtained from an isolation transformer for all associated electronics with only one ground in the system. However, the data acquisition electronics including the lock-in amplifier were not shielded. It is obvious from this first test that there was electrical pick up noise from the furnace. This noise increased the temperature fluctuations in the measurements to as high as 20° C at some times during the test. With improved shielding of the electronics it is hoped that the temperature noise fluctuations will be reduced to less than 3° C during furnace operation.

The millimeter-wave radiometer temperature measurement instrumentation demonstrated here should find application to other high temperature furnaces. It should be applicable to both plasma and combustion furnaces, not only for waste remediation but for industrial processes as well. It will be particularly useful where a temperature measurement is needed and thermocouples or infrared pyrometers can not be used or are not sufficiently reliable.

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