

Laser Systems Help Improve Refractories Performance and Productivity

Laurel M. Sheppard, Contributing Editor

A laser, which stands for Light Amplification by Stimulated Emission of Radiation, consists of a cavity separated by plane or spherical mirrors. This cavity is filled with some type of material whose atoms can be excited to a semi-stable state by light or electric discharge. When the atom returns to its ground state, light is emitted and other atoms become excited, producing a light that continually increases in intensity. The light beam can be highly coherent or collimated, depending on the type of mirror.

Since the first laser was constructed in 1960, a myriad of applications has been developed for manufacturing, medicine and quality control, among others. Laser-based testing systems for research and quality control have become popular since they can provide a non-contact method that is usually faster and more accurate than conventional systems. In the refractories industry, laser systems are being used to measure creep and understand corrosion, as well as to monitor lining performance while in service.

MEASURING CREEP

Laser extensometers are being used for tensile creep displacement measurements at high temperatures (up to 1500 degrees C). These devices provide greater accuracy for data acquisition and can easily be interfaced with a personal computer for data collection and analysis. Commercially-available extensometers typically consist of a receiver, a HeNe laser, and a data processor whose output is continuously recorded by a personal computer. The laser scans in a vertical line over 100 times per second.

However, the stability and resolution of such an extensometer can be affected by fluctuations in air density (the refractive index) in the laser beam path during creep. These fluctuations are a result of local temperature differences along the laser beam path. The changes in refractive index cause beam scatter and thus affect the displacement measurements.

There are a number of approaches to stabilizing the ambient environment around the specimen and extensometer for reducing the measured displacement error. This error has been reduced to as low as +/- 0.5 micron. One approach uses the combination of minimizing the air seepage into the furnace, reducing the thermal gradient along the laser beam path (by shielding the laser), and averaging a large number of displacement scans. Another approach uses an inverted U-shaped water-cooled copper cover installed between the furnace surfaces and the laser and receiver as a shield. This approach does not require averaging the data.

The Orton Refractories Testing and Research Center has installed a laser-based testing system capable of testing either DIN 51053 (2-inch high samples) or ASTM C 832 (4.5-inch high samples). Both standards measure thermal expansion under load and creep properties of a refractory, which are then used to characterize the load bearing capacity of a refractory that is uniformly heated. The system combines a Series 2390 compression tester, a Series 3320 furnace (from Applied Test Systems) with a Model 2020 LaserMike unit from LaserMike, Dayton, OH, Figure 1. This

unit measures a part by sweeping a beam of laser light across its measurement area. Each sweep is called a scan and each part is typically scanned 100 times per second or more.

This testing system has been in continuous use for four years, typically testing two samples per week of alumina-silica or basic bricks up to 1650 degrees C, and is believed to be the first of its kind installed in the U.S. Figure 2 shows the correlation of the laser data to conventional ASTM C-832 data. Compared to conventional systems, the laser-based system does not require a system correction factor for baseline drift and is nearly maintenance free, according to Chuck Kistler, Senior Engineer. There are no push rods involved, which eliminates the need to apply any correction factors and the need for rod maintenance. Only cleaning of the laser's and receiver's windows is needed. The repeatability is within 0.0005 in. and the resolution is 1×10^{-4} . Resolution and accuracy can be improved significantly by using a laser with shorter gage length. Orton uses a thick block on each side of the sample rather than a thin disc since it can be reused more frequently without warpage, Figure 3.

UNDERSTANDING SINTERING BEHAVIOR

Laser extensometers are also being used to for dilatometry applications. Unlike conventional dilatometry, which provides only a spatially averaged response, the laser system can measure dimensional changes at a variety of different positions. Conventional dilatometry uses an LVDT connected to a push rod that is weighted to contact the surface of the sample over an area equivalent to the diameter of the rod. Therefore, results may be inaccurate if the expansion behavior is sensitive to pressure or specific events are obscured. Laser dilatometry, on the other hand, is a non-contact method, which is essential to detecting the dimensional change in samples that are very fragile.

Laser dilatometry thus becomes a useful tool, when correlated with X-ray computed tomography (CT), to better understand binder removal and sintering behavior. Using this approach, Ohio State University researchers led by Dr. John Lannutti have established that the combined effects of binder removal and density gradients do affect dimensional tolerance in a study of alumina (Figures 4 and 5). CT monitors internal structural changes, while laser dilatometry measures the impact on dimension. These internal changes cause considerable density variation during binder removal.

Binder redistribution and differential shrinkage is the result, which produces non-uniform dimensional changes that cause distortion. Overall, density undergoes a slight decrease accompanied by a 1% loss in dimensional tolerance. This and differences in CT images suggest that capillary forces generated during binder melting can change the density distribution.

The sintering study shows that microstructural packing controls both the macroscopic expansion at temperatures of 1000 degrees C or less and the onset of shrinkage. Neck formation initi-

ates during expansion and not just during shrinkage. Inter- and intra-agglomerate expansion/shrinkage proceed simultaneously. Thermal expansion in the presence of density gradients results in smaller values than well-sintered alumina, which is attributed to the type of bonding that exists between particles and grains.

For both studies, the researchers use a laser micrometer (LaserMike Model 501-195) with a repeatability within 0.0005 mm, integrated with a furnace. The laser beam is scanned through a collimator lens in a parallel path across the sample toward a receiving lens. The receiving lens focuses the radiation into a photo detector. When the beam encounters the sample, it disrupts that part of the beam curtain path, creating a space devoid of light. This space creates a signal that is processed and converted to a length measurement.

A positioning motor controls the sample's vertical position within the horizontal beam and is connected to the dilatometer output. The working distance is modified to allow for the insertion of the furnace. Accuracy is in the one micron range. Orton is developing a laser dilatometer based on this work for commercialization.

UNDERSTANDING CORROSION

A laser-based spectroscopy method, laser induced fragmentation fluorescence (LIFF), is being evaluated for the on-line process measurement of NaOH vapor concentration under oxyfuel glass furnace conditions, as part of a five-year research project. This project is a joint effort between Sandia National Laboratories and six companies: American Air Liquide; BOC Gases; Praxair, Inc.; PPG Industries, Inc.; Techneglas; and Visteon Automotive Systems. The University of Missouri-Rolla, Pennsylvania State University, Harbison-Walker Refractories, and Monofrax Inc. are also involved as subcontractors. These partners represent the glass and refractories industries, as well as oxyfuel suppliers. Funding is being provided by the Department of Energy's Office of Industrial Technologies and the six industry partners.

The LIFF data will be used to help develop strategies for minimizing corrosion of refractories in a furnace, as well

as to optimize refractory performance. Models are also being developed to predict corrosion rates after experimental characterization of corrosion processes. The major objective is to understand the mechanisms of corrosion in oxy/fuel glass furnaces.

LIFF was chosen because it provides a direct way to measure NaOH itself. Other methods only measure sodium atoms, and thus require a fairly sophisticated understanding of the other gases and their thermodynamics to determine NaOH concentrations. NaOH is also not a very strongly optically absorbing molecule unless it is excited by very high energy ultraviolet wavelengths. It is essentially transparent in much of the convenient part of the spectrum.

Since LIFF is a pulsed laser technique, it also eliminates the visible background of the furnace. Other advantages are its potentially high sensitivity (10 ppb) and its simplicity. The method involves only one laser, one detector & a small number of optics. Figure 6 shows a schematic of the system.

In LIFF, an ArF excimer laser is used to produce ultraviolet light of 193-nm wavelength. When the NaOH molecules become excited by this light at high temperatures, the molecule dissociates into OH radicals and electronically excited sodium atoms. The sodium atoms emit light at a wavelength of 589 nm and 818 nm, which is then detected. At low temperatures light of only 589-nm wavelength is produced. In order to selectively detect NaOH, the method takes advantage of the temperature dependence of the 818 line, which is not present in the LIFF spectrum of most other sodium-containing compounds. Once quantified, the LIFF technique will not only map the spatial variation in NaOH concentration, but may also be used as a temperature indicator.

The LIFF method was first tested in a flow furnace at 1345 degrees C. The spectrum contained a broad interfering background originating from the excimer laser and additional lines due to atomic oxygen. Improvements to both the detection system and optical configuration produced a spectrum without these artifacts at 1230 degrees C. However, the presence of CO₂ is a



Figure 1 The laser creep testing system at the Orton Refractories Testing and Research Center.

bigger problem since it causes major beam attenuation at 1600 degrees C.

The intensity dependence of the 589-nm line as a function of NaOH vapor concentration was measured and found to be nonlinear with a dampening effect occurring as the concentration is increased. This nonlinearity may be attributed to both the saturation of absorbers in the exciting beam propagation or atomic radiation trapping. The beam propagation problem is the most difficult to solve and is being investigated. Figure 7 shows the LIFF NaOH.

FROM THE LAB TO THE FIELD

The next phase of the LIFF project will develop a portable field instrument. Noise in the signal due to variations in laser power will be eliminated and the effect of this power and gas composition on the LIFF signal is being investigated. Attenuation resulting from the presence of O₂ and CO₂ will be characterized to quantify the expected response of this instrument.

The effect of laser pulse energy on the LIFF signal is also being investigated. Initial results have shown that a slight energy threshold must be reached to observe any signal at all. It is not clear whether this is real or an artifact of the background signal removal that is required with the lab configuration. If this is due to a laser propagation saturation, it can probably be quantified in the lab as a function of gas temperature.

If CO₂ concentration fluctuates wildly along the path in the furnaces, a test methodology will have to be developed in the field that is different from the lab methods. This test will involve mapping attenuation along the laser path. The solution to the threshold problem is important since the field instrument will likely use lower pulse energies than the laboratory setup.

The selection of the excimer laser is critical to the development of the field-portable unit. Small-sized easily portable ArF systems are now available that cost less than previous systems. However, compatibility of the performance of the laser needs to be matched with those of the experimental method, especially with regard to the propagation of the beam through the hot gases in the glass furnace.

A major issue will be how far away from the instrument a signal can be imaged and detected. If the goal of 10 meters is met, the instrument will be used to measure both temperature and NaOH profiles by placing the system at a furnace portal and directing the beam into the furnace. Details of how the system will be "aimed" are yet to be worked out. The instrument's initial purpose is to provide qualitative furnace fluctuation data. Again, the major limitation may be probing depth due to beam attenuation by hot CO₂ and O₂. Field testing is scheduled for 2001.

MONITORING LINING WEAR

Several different laser scanning systems have become available for measuring lining wear. These typically fall into two categories: a raster type system (point and measure) or one that is

imaged based. In the first type, the laser is moved electronically to one point at a time. The second type produces an image by moving a line of multiple points vertically. Laser systems can either be portable or permanently installed, depending on the system. Such systems provide fast, accurate scanning for monitoring lining wear and are relatively easy to use.

Rautaruukki Steel's Raahe plant in Finland has used several different laser systems, manufactured by Spectra Physics Vision Tech Oy, since the late 1980s. The Raahe plant has three 120-ton converters. The first system only measured individual points of the lining for controlling bottom wear. The second system was a mobile laser scanning unit for measuring the entire converter lining, as well as ladle linings. The third system was a fully automated and remotely operated ladle measurement system. Table 1 lists the converter lining materials.

The final system, the LR 2000 Sigma, is claimed to be the world's first completely automatic, permanently installed laser system. It was first installed on one converter in 1998 and by the end of the year automatic measuring units had been installed on the other two units. The measurement heads are installed about two meters from the converter's mouth and data can be viewed in the control room or elsewhere on the computer network. Lining thicknesses are displayed as a topographic map and can also be viewed as vertical or horizontal cross-sections (Figure 8). Wear trend data can also be generated.

The LR 2000 Sigma system has proved effective for monitoring lining wear and is currently being used for lining development, with a goal of increasing service life from 1560 heats to over 2000 heats by the end of 2000. Lining life has already improved by 12%, from 1567 to 1763 heats during 1998-1999. Refractories costs have decreased slightly and labor costs for brick laying have decreased about 15 percent.

The laser system is also used to optimize lance position and tapping angle. An automatic tapping system connected to the measurement system will eventually be installed. In addition, the Sigma provides simultaneous temperature measurements, which can be used for steel temperature modeling. Repair procedures have been improved, reducing wear rate of the charging area from 0.5-0.8 mm/heat to 0.1-0.3 mm/heat.

The LR 2000 Sigma system is user friendly, thereby allowing measurements to be taken every shift using a PC located in the converter control room. Converters can therefore easily be measured several times per day. Training of operators only takes several days. Real time information from each measurement is transported via the plant's network to production, who can then use this information for scheduling the different converter campaigns. Each measurement takes under five minutes, which includes tilting the converter, selecting the measurement plan, and generating the results. Accuracy is +/- 5 mm.

According to Hannu Nevala, Rautaruukki Steel's section manager of refractories, the return on investment

was two years. The system has also made it possible to select better material for critical areas. Converter breakdowns at the end of a campaign can be avoided since monitoring alerts users to abnormal wear. One limitation is that two measurement heads are required for measuring the upper cone diameter of the mouth due to its small size.

THE IMAGING APPROACH

One disadvantage of a raster type system is that, even with a fast servo moving from point to point, it can take more time to acquire the surface information than an image-based system. The data measurements are also few and farther in between, requiring interpretation about the interpolated space. Fewer data points are collected; for instance, a five minute system scan would generate less than a thousand measurement points on the vessel, whereas an image-based system from a similar fixed one image position would take in hundreds of thousands of points per two minute scan.

One such image-based system is the MarScan® patented thickness measurement system, introduced in 1998 by Martin Marietta Magnesia Specialties. It is comprised of a laser head with controller and a computer system for operating, recording, digesting and displaying range (measurement) and refractory lining thickness information. The components are installed in an electronic rack mounted on an electronic pallet mover that allows the unit to be moved from location to location. The system is also available with the sensor head/controller mounted remotely from the computer display assembly.

MarScan® uses several various imaging sensors capable of retrieving an image or a plurality of range data in a relatively short period of time. The speed of data acquisition and a complete surface measurement are two of the major benefits of this laser system over the typical point and measure or raster systems.

Several sensors were examined during the system's development before arriving at the current configuration. This sensor utilizes a single beam aimed onto a rotating polygon mirror. The multiple reflection of the laser beam provides a horizontal line of 1024 points. The horizontal line of 1024 points moved vertically to 1024 lines provides an image of 1024 by 1024 measurement points or 1,048,576 measurements in a 60 by 45-degree field of view. This equates to nearly 10,000 points per second.

The images once acquired are stored and used for processing measurements later. This approach takes full advantage of the fast data acquisition time of the system. In this way the images are taken when the vessel is available and processed after the vessel is back on line. Other point and shoot or raster measurement systems typically take much less surface data or much more time and generally give a less complete and therefore less accurate representation of the surface to be measured.

The measurement software condenses the millions of measurement points into surface tiles, typically (10-20,000), which are nominally five inch square surface areas. A typical ladle will

contain 8,000 tiles and a furnace 15,000, which cover the interior surface of the vessel. Sections of tiles in the vessel are grouped by the operator into regions. These regions are recorded for each saved measurement in text files. The text files can be exported into spreadsheet format and used in conjunction with the region statistics (minimum, maximum, average, and standard deviation) to track wear trends. The data can also be displayed as three-dimensional images (Figure 9), or axial and circular cutaways.

This full surface coverage allows two and one half and three-dimensional representation of actual measurement points and does not rely on interpretation or interpolation between widely spaced measurements points as provided by raster systems. The complete surface coverage is particularly important in situations where the lowest reading or most critical reading may fall between measurement points in other systems. Complete surface measurement coverage also allows for more accurate bath level calculation, a number that is used in determining the blow height of the oxygen lance in a basic oxygen furnace and relates directly to metallic yield productivity. The continuously moving beam contributes to improved safety, when compared to systems in which the beam can be directed and fixed or pointed directly into an operator's eye.

One limitation of this system is that it can only measure surfaces directly in a line from the laser beam source and detector; where an object does not impede the light. Therefore, the system will not measure objects or surfaces around a corner or through objects, steam, dust clouds, smoke curtains nor shiny specular objects. In order to avoid limited viewing angles in basic oxygen furnaces, several views of the surface from different positions are sometimes used and combined by the software into a single measurement.

When vessels become very hot, more smoke is produced that interferes with the light reflection of the laser. The software system will filter out these unacceptable measurements by blacking out the display for those represented areas, rather than showing an interpolated, or unmeasured value, as other systems may do.

A typical configured system costs less than \$500,000 and leases for \$10-\$20,000 per month. Most of the current systems in operation are under a lease system, which includes support for the system. For instance, USX is taking this approach at several of its plants. At the Gary plant, which has several 260-ton furnaces, a leased system has been in operation for about a year. According to Julio Martinez, section manager BOF, the response time of the previous raster-type system was inadequate so the switch was made to the Marscan system. The time to inspect an entire furnace has been reduced from 30 minutes to 10.

At Gary, a properly operating furnace is inspected once a day; a furnace having problems is inspected more frequently, up to three times a day. Gunning schedules can be adjusted accordingly and since the system pinpoints exactly where gunning material is needed, savings can be significant. The amount of such material can be reduced by as much as 50 percent. Another benefit of the laser system, according to Martinez, is how troubleshooting is handled. If the equipment malfunctions, it can simply be connected to a phone line and diagnosed remotely. The problem can be solved within a day, compared to the several days required with the previous system

Table 1 Properties of Converter Lining Materials, Rautaruukki Steel

Area	MgO	C	Fe ₂ O ₃	Al ₂ O ₃	CaO	SiO ₂	MgO, sintered	MgO, fused	Density g/cm ³	Porosity %
A	96	5	0.6	0.3	2.4	0.6	+	-	3.11	<7
B	97	9 0	3	0.2	2.0	0.5	+	-	3.00	<6
C	97	14 0	4 0	2	1.8	0.5	+	+	2.99	<11
D	97	5.5	0.4	0.2	1.8	0.6	+	+	3.17	<2
E	95.5	8	0.7	0.8	2.0	1.0	+	-	2.94	<8
F	97	5	0.3	0.1	2.0	0.3	+	-	3.12	<7

A=lower cone, mouth; B=lower cone, area above trunnions; C=trunnions; D=charging area (pitch impregnated); E=back wall, area between trunnions and charging area; F=upper cone

Continued on page 15

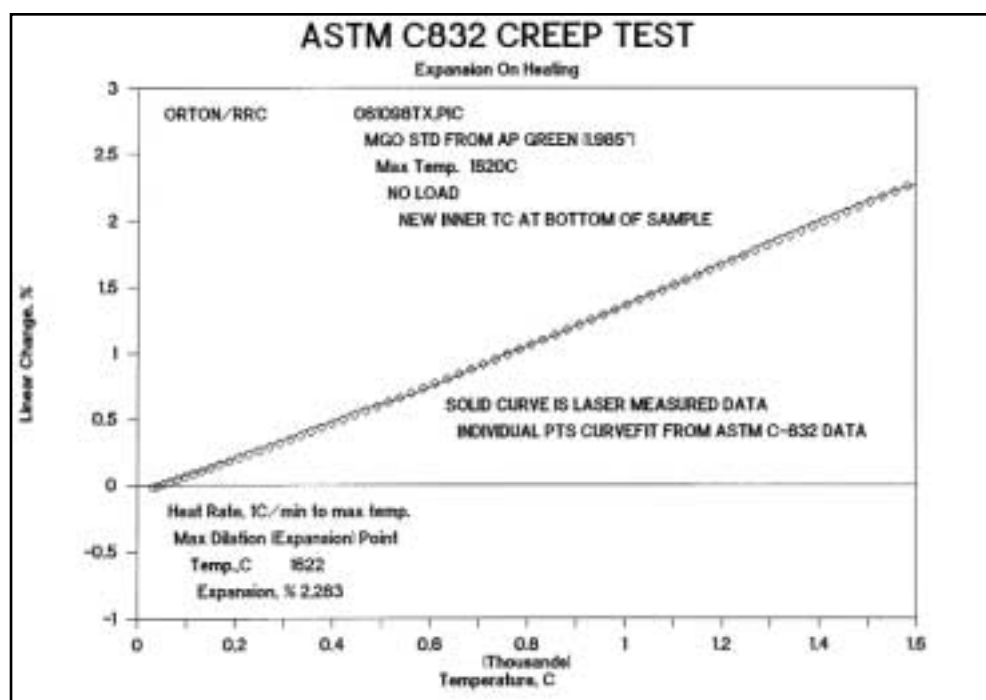


Figure 2 Linear change as a function of temperature for a MgO standard showing excellent correlation between laser data and standard data.

Continued from page 4

when a repair person had to visit the plant to determine what was wrong.

The laser system is also user friendly, since the software is designed with a graphical interface, accessed by simply touching a button. Therefore, operators can learn the system pretty quickly; at the Gary plant, training gunners only took a month. The software is currently configured, but not limited, for measuring surface thickness for basic oxygen and AOD vessels along with ladles of various shapes. Other refractory thickness measurement applications are certainly possible, but have not been undertaken for development.

At USX's ET works, laser systems have been in use for a number of years. When the previous system became obsolete and it became difficult to find replacement parts, the plant switched to the Marscan system. This system has been leased for the last several years



Figure 3 Close-up of the furnace and sample of the laser creep system at Orton Refractories Testing and Center.

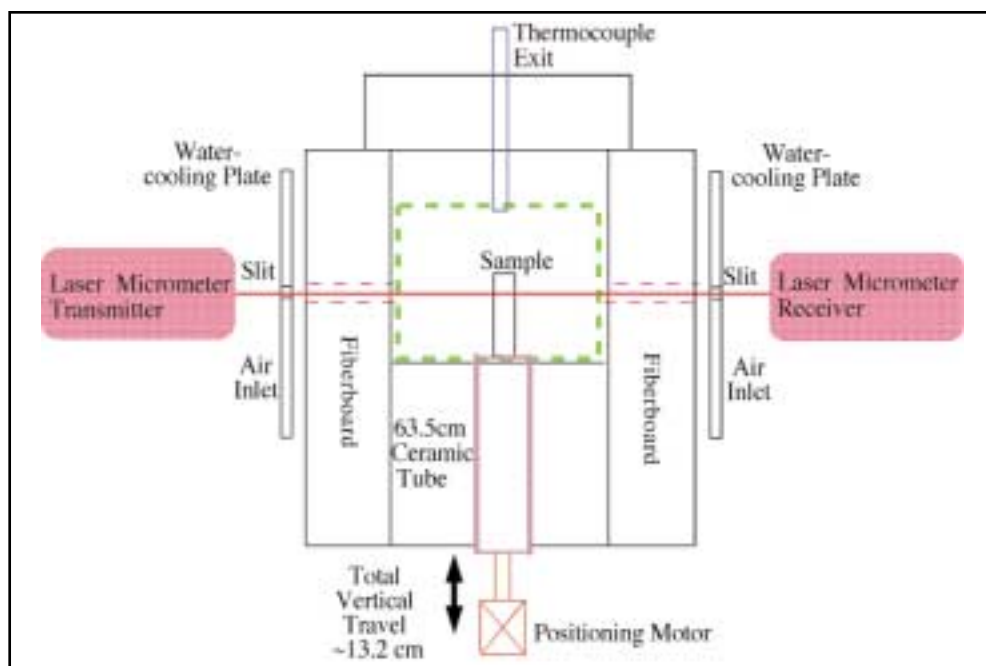


Figure 4 Laser dilatometry schematic showing the relative positions of the laser micrometer, the furnace and the sample positioning column at Ohio State University.

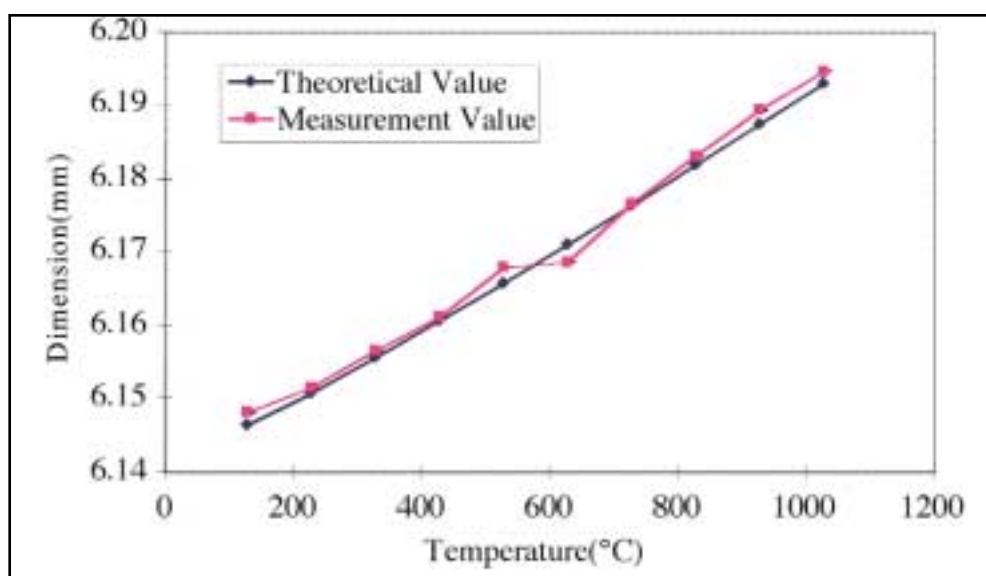


Figure 5 Comparison of theoretical and experimental values for dense alumina as measured by laser dilatometry.

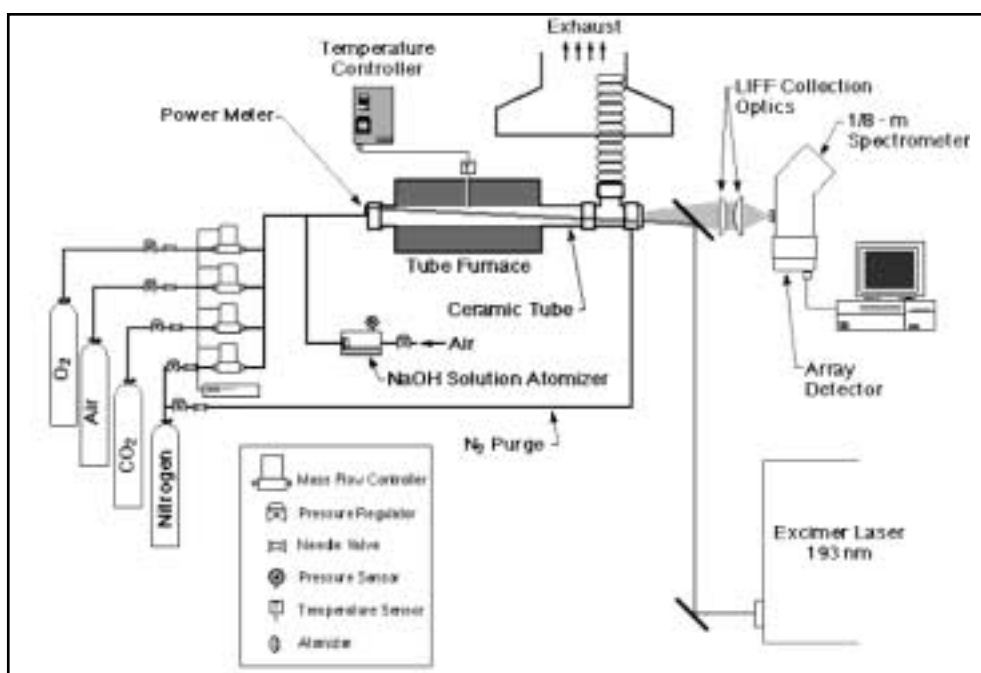


Figure 6 Schematic of the LIFF system at Sandia National Laboratories.

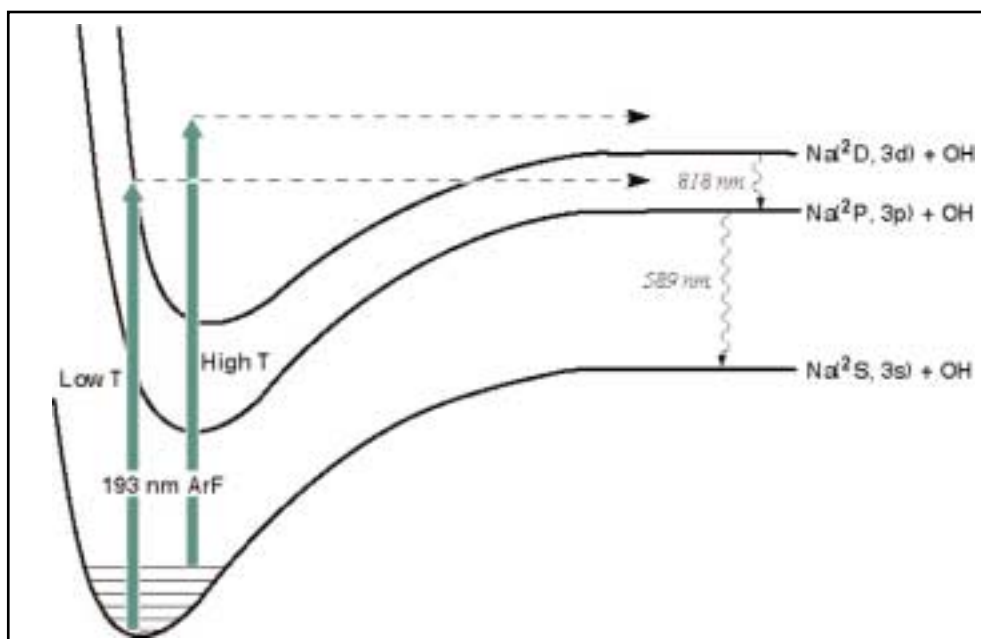


Figure 7 LIFF from NaOH with 193 nm ArF excimer laser.

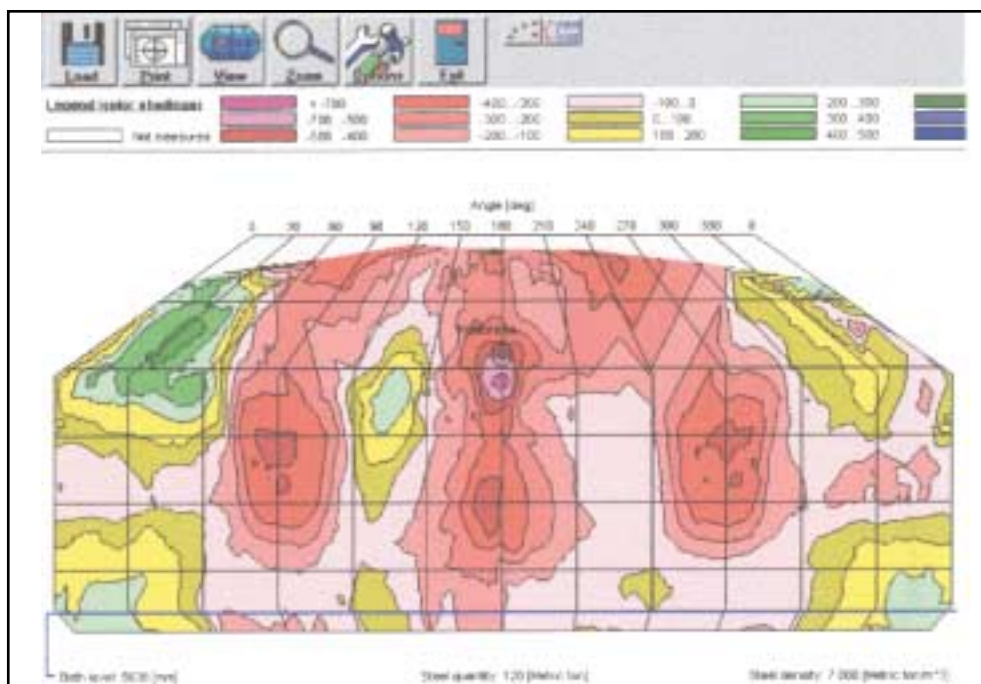


Figure 8 Color map of the lining thickness using the LR 2000 sigma system.

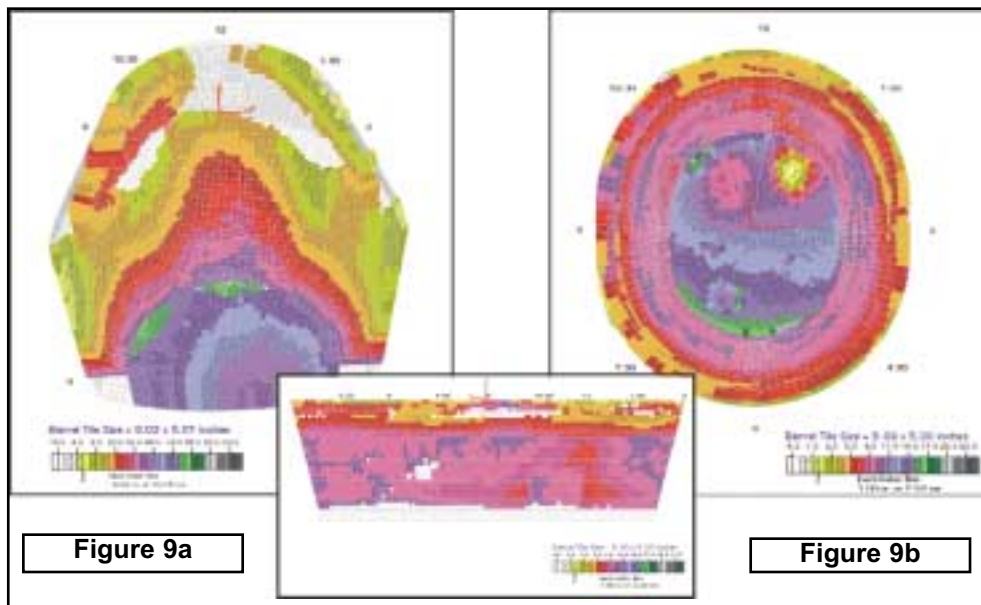


Figure 9a, b Measurements from the Marscan system can be viewed on the monitor or printed out in color displays. The 3D displays allows manipulation of the vessel in an XYZ coordinate system. The 3D bottom can be shown independently or with the sides in a 3D, a, or flat map arrangement, b. Thickness of refractories in the 3D display are represented by an operator varied color scale. The 3D mode allows display of assigned regions along with their measurement statistics.

for daily inspection of the two 225-ton vessels. A full scan takes 25 minutes since the system must be positioned in three different locations.

According to Jon Olszewski, section manager BOF, the system is being used to determine whether the oxygen lance is blowing at the correct height, in addition to checking for wear. Plans are underway to connect the laser machine to four production terminals and two in the systems group. This will allow operators to view the data directly and eliminate the paperwork associated with the printouts. The systems group will be able to use the data for testing and development.

EXPANDING APPLICATIONS

It is clear that laser-based monitoring systems such as those previously described will continue to find success in improving lining performance. The LIFF method will also soon be put to practical use. Other laser-based methods may eventually find their way into the refractories industry for testing or quality control applications.

FOR FURTHER INFORMATION

P. K. Lu and J. J. Lannutti, "Structural Evolution and Sintering Shrinkage for Compacts Formed from Spray-Dried Powders: I, the Expansion-Shrinkage Transition," submitted to the Journal of the American Ceramic Society.

P. K. Lu and J. J. Lannutti, "Structural Evolution and Sintering Shrinkage For Compacts Formed from Spray-Dried Powders: II, the Barrier to Full Density," submitted to the Journal of the American Ceramic Society.

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Steve Rice, Sandia National Laboratories, sfrice@sandia.gov or Mark Allendorf, (925)294-2895

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