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Development of technically and economically viable processes for the conversion and utilization of fossil fuels is a major objective of both the DOE Fossil Energy program and EPRI. Many new and different processes are being investigated in areas of coal gasification and liquefaction, improved power generation and advanced combustion. As these processes evolve to the pilot plant stage and beyond, materials selection and component design become increasingly important for reliable and economical operation. The newsletter is intended to serve as a medium for exchange of information and experiences pertinent to the use of materials and components among the communities interested in the development of fossil energy systems.

ODS Alloy Heat Exchangers for Solid-Fuel Thermal Systems

A high-efficiency coal-fired power plant technology, the high-performance power system (HiPPS) concept developed as part of U.S. Department of Energy's (DOE's) Combustion 2000 program, involves the use of a combined cycle that consists of an indirectly-fired gas turbine using very-high-temperature but low-pressure air as the working fluid, and a steam bottoming cycle. The goals for the HiPPS system were 47% efficiency, with only one-tenth of the particulate, SO_x, and NO_x emissions allowed under the New Source Performance Standards, while reducing the cost of electricity by 10%. The Energy & Environmental Research Center (EERC) of the University of North Dakota worked with a team led by United Technologies Research Center (UTRC) in the development of this system.

The heart of the UTRC HiPPS system is a high-temperature heat exchanger (HTHX) that produces hot air for expansion through an aero-derivative gas turbine. Because of the need to maximize the temperature of the gas entering the turbine to achieve the highest efficiency, very crep-resistant materials are needed for the HTHX. The candidate materials are ceramics or oxide dispersion strengthened (ODS) alloys. Early in the program it was determined that the current state of the art for ceramic heat exchangers was insufficient to allow their use in the required time frame, so that effort was focused on the use of ODS alloys. A major characteristic of ODS alloys is useful creep strength at temperatures above the capabilities of conventional wrought alloys, which is derived from the distribution of fine particles of an inert oxide throughout the alloy matrix and the development of a microstructure in which large grains are developed. This alloy microstructure requires a powder metallurgical production route to be used, and also poses problems in joining of these alloys.

Pilot-Scale Testing of the HTHX

Tubes of an ODS-NiCr alloy (Special Metals alloy Inconel MA754: nominally Ni-20Cr-0.5Y_2O_3 in weight percent) were used in the construction of the HTHX. To protect the alloy tubes from corrosion by the products of coal combustion, UTRC designed the HTHX to include panels of corrosion-resistant ceramic between the alloy heat exchanger tubes and the flame, as shown in Fig. 1 (see also Materials & Components No. 136, Oct. 1998. pp.10-11).

A slagging furnace system (SFS), which is an integral part of the UTRC HiPPS design, was designed and constructed during the program. The SFS is designed to heat the HTHX under flowing slag conditions so that it can produce process air at 982°C (1800°F) and 1 MPa (150 psig). Although the SFS is designed for a maximum furnace exit temperature of 1593°C (2900°F), it is typically run at 1510°C (2750°F) at the exit in order to maintain desired slag flow characteristics while extending the furnace lifetime. The nominal firing rate is 586-879 kJ/s (2.0 to 3.0 x 10^6 Btu/hr) using a single burner, based on a bituminous coal (Illinois No. 6) and a nominal furnace residence time of 3.5 s. Resulting flue gas flow rates range from roughly 0.2 to 0.3 scm/s (425 to 640 scfm), with a nominal value

In This Issue

ODS alloy heat exchangers for solid-fuel thermal systems.....p. 1
P92 and P122 steels for superheater outlet collectors.....p. 5
Experience with internal airfoil coatings in industrial gas turbines...p. 7
Approaches for reducing scrap rates for advanced turbine blading...p. 10
Meetings calendar.....p. 13
Calls for papers..... ...p. 14
A word from our sponsors.....p. 16

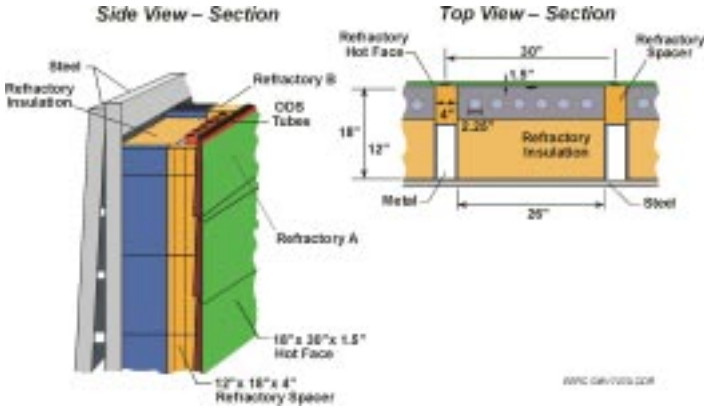

Figure 1. The UTRC high-temperature HTHX design

of 0.25 scm/s (530 scfm) based on 20% excess air.

The SFS was used at EERC to test the performance of the HTHX. In these tests, the furnace was oriented vertically (downfired). The burner design was based on a swirl burner currently used on two EERC pilot-scale pulverized coal-fired units that are fired at 176 kJ/s (600,000 Btu/hr). The furnace dimensions are 119 cm (47 in.) inside diameter by roughly 5.5 m (18 ft) in length. It is lined with three layers of refractory totaling 30.5 cm (12 in.) thick. The inner layer is composed of an alumina castable, developed by the EERC in cooperation with the Plibrico Company, that has been shown in laboratory tests to be extremely resistant to slag corrosion.

A key design feature of the furnace is accessibility for installation of a large HTHX test panel for testing material lifetimes and heat exchange coefficients. The size of the HTHX is 30.5 x 182.9 cm (1 x 6 ft.), which was based on manufacturing constraints identified by UTRC, the designer and builder. Air is delivered to the HTHX panel by an existing air compressor system (maximum delivery rate of 0.24 scm/s (510 scfm) and a maximum stable delivery pressure of 1.9 MPa (275 psig) and is heated from 538 to 982°C (1000 to 1800°F) as it passes through. A tie-in to an existing nitrogen system was also installed as a backup to the existing air compressor system to prevent the panel from overheating in the event of a power outage.

As the hot combustion gases leave the combustor, they pass through a slag screen to remove any entrained ash as a non-leachable slag and to reduce deposition on the convective air heater (CAH). The screen removes approximately 65% of the particulate matter from the gas stream. After the slag screen, the hot combustion gas is quenched using recirculated flue gas to 1010°C (1850°F) in order to make the ash less sticky and reduce deposition on the CAH. The quench zone is the only region in the furnace where hard ash deposits form, but they are easily removed by knocking them into a hopper at the bottom of the zone. The gases then pass over the CAH which heats air from 538 to 704°C (1000 to 1300°F). The hot combustion gases then flow through a series of heat exchangers and, finally, a baghouse on the way to the system stack.

In the HiPPS program testing the UTRC HTHX in the slagging furnace system performed well, typically producing 982°C (1800°F) air at 1 MPa (150 psig) for over 2,000 hours. For a short duration, air up to 1093°C (2000°F) was produced, which is believed to be a record for a coal-fired system. However, the ceramic panels were prone to failure through thermal shock and were significant impediments to heat flow. To determine if the HTHX could be operated without the ceramic panels, the EERC performed laboratory tests to determine if the MA754 alloy could be exposed directly to the products of coal combustion. Figure 2 shows the surface recessions of coupons of the MA754 exposed to Illinois No. 6 coal ash and flowing gas at 1000 and 1149°C (1832 and 2100°F). The data indicated that, as long as the surface temperature of the alloy was kept below the solidus temperature of the fuel slag, corrosion rates of the MA754 would be commercially acceptable and the bare alloy tubes could be directly exposed to the products of coal combustion.
Although the Combustion 2000 program has ended, the DOE is continuing the development of the very-high-

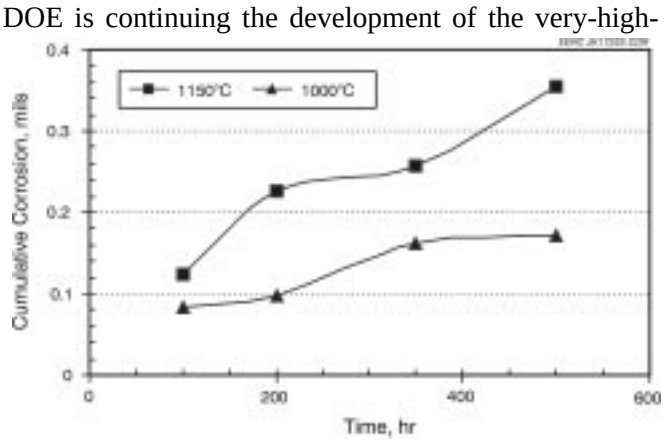

Figure 2. Surface recession rates for MA754 exposed to Illinois No. 6 ash and flowing gas

temperature heat exchanger concept, both through funding the EERC directly for continued testing and through other programs such as the DOE Vision 21 program.

Thermal Performance of the Bare Tube HTHX

Initial tests of the bare-tube configuration showed that without the ceramic panels the heat exchange coefficients were sufficiently high that not enough cooling air could be provided with the existing equipment. Therefore, the initial tests were done while firing the SFS at much lower rates than the normal operation, while changes were made to the system to allow firing at higher rates while still cooling the surface temperature of the alloy to 1093°C (2000°F). The changes culminated in reducing the surface area of the exposed tubes by encasing the bottom half of

the HTHX in alumina insulation and refractory. The HTHX is typically operated with process air flow rates of 0.165 to 0.172 scm/s (350 to 365 scfm) at 1 MPa (150 psig). Under these conditions the inlet process air temperatures are 538 to 552°C (1000° to 1025°F) and alloy tube surface temperatures are 752 to 1099°C (1385° to 2010°F). The low end of the alloy tube surface temperature range represents the back side of the tubes at the process air inlet, with the high end of the range representing the front side of the tubes at the center of the HTHX. Process air temperature at the outlet ranged from 766 to 860°C (1410° to 1580°F). Heat recovery rates ranged from 60 to 71 kJ/s (206,000 to 241,000 Btu/hr).

One of the first issues to work out with the bare-tube design was whether or not hot spots, possibly leading to strong thermal stresses, developed in the structure because of its exposure directly to the coal flame. Since instrumentation of the HTHX with multiple thermocouples is not sufficient for detecting such hot spots, the assistance of the NASA Johnson Space Center was requested in the form of an infrared camera and operator. Figure 3 shows an infrared (IR) image of the tubes while firing natural gas, along with the calculated temperature distribution along the surface of the middle tube. The data show that no hot spots developed on the tubes because of incomplete air distribution, and that circumferential and axial temperature distributions were smooth and should not cause undue stresses in the tubes.

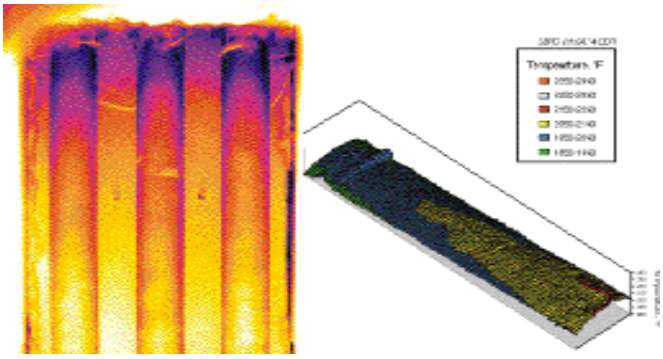

Figure 3. IR image and temperature distribution of the upper portion of the middle tube in the HTHX while firing on natural gas

The longest test of the HTHX while firing coal at the maximum level was made in November and December of 2001. The heat recovered by the HTHX decreased as a function of time, nominally from 71 to 61 kJ/s (241,000 to 209,000 Btu/hr), or 13%, during the first 70 hr of coal firing. Heat recovery appeared to be stable during the last 30 hr. Therefore, if adequate process air were available and half of the HTHX were not insulated, the resulting heat recovery rate would be 120 to 123 kJ/s (410,000 to 420,000 Btu/hr) at a nominal furnace temperature of 1538 to 1554°C (2800° to 2830°F).

HTHX heat removal data as a function of furnace temperature are summarized in Fig. 4 on an equivalent-surface-area basis for selected test periods. The data for the June, August, and November/December 2001 tests of the bare-tube design are represented by open symbols and are connected by lines for natural gas-fired tests. Data resulting from coal-fired tests are simply open symbols. The 2001 data are compared to data in the lower right of the graph, represented by closed symbols, for tests performed in 1999 and 2000 in which the original ceramic panels were in place. The data clearly show that for a given furnace temperature, removing the ceramic panels from the heat exchanger increased the heat removal rate by a factor of almost five. This means that the heat exchanger could be as small as one-fifth of that originally proposed. Factoring in the price reduction from not requiring the ceramic panels and the unprotected heat exchanger panel could cost as little as one-tenth of the original tubes-in-a-box design.

Alloy Performance

Measurements of MA754 tube diameters after coal firing indicated no recession or significant dimensional variations compared to the measurements before the test. Ash depositing on the tube formed a sintered powder layer of fly ash between a brittle slag layer and the alloy surface. Total thickness of the sintered powder was several tenths of a millimeter, while the slag layer varied from 2 to 5 mm thick. The lightly sintered nature of the inner layer indicated that its corrosivity toward the alloy should be low, while the slag layer formed running drips, indicating that it had reached its maximum thickness and had begun to flow off the tube. The brittle fused slag/sintered ash layer was easily removed from the alloy surfaces, indicating little interaction between the alloy and the ash.

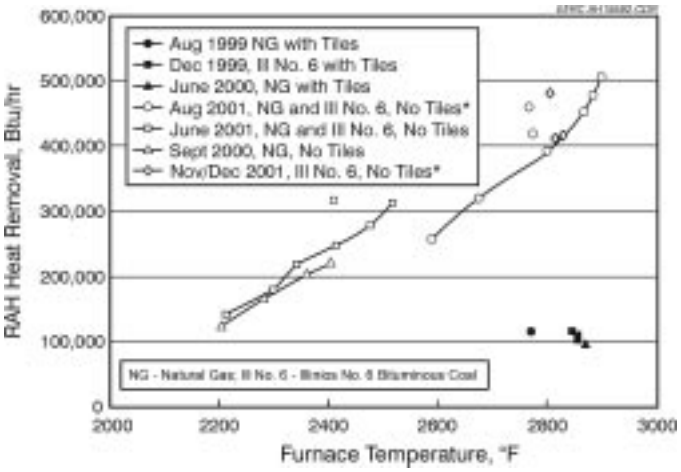

Figure 4. Heat removal as a function of furnace temperature on an equivalent surface area basis

The development of the sintered ash overlaid by the slag layer is considered to be the primary reason for the 13%

decrease in heat recovery during coal firing. This illustrates one of the main advantages to operating the HTHX at such high temperatures: that only a very thin layer of ash develops before it becomes molten and flows off. In essence, the tubes become self-cleaning. The 13% drop in heat recovery is less than one-third of the typical 50% drop seen when much thicker sintered ash deposits develop on heat-transfer surfaces. Hence, it is the insulating effect of the ash deposits that causes the need for up to twice as much heat exchange surface to be installed in a furnace than would be required if the ash did not insulate the tubes. Given the self-cleaning nature of the thin deposits forming on the bare-tube HTHX, the excess surface area needed would only be approximately 20% compared to 100% excess for conventional heat exchangers operated at ash sintering temperatures.

Corrosion Probe Tests

In order to perform detailed analyses of ODS alloys after exposure in the SFS, short disposable air-cooled probes are made and inserted into the slagging zone while firing on coal. Two alloys have been tested in the probes to date: Special Metals alloy Inconel MA754, and Special Metals alloy Incoloy MA956, which is nominally Fe-20Cr-4.5Al-0.5Y_2O_3 (in weight percent) that forms a protective alumina scale if prepared correctly.

In one such test, an MA754 probe was left in place at nominally 971 to 1093°C (1780° to 2000°F) as a function of probe insertion depth and a process air flow rate of 0.04 to 0.05 scm/s (95 to 100 scfm). Measurements showed an average surface recession of approximately 60 µm (0.002 in) in 130 hours, although loss of cooling air to the probe for several hours while preheating on natural gas may have caused an excessive oxidation rate. The end of the probe that was not efficiently cooled had melted, but corrosion was minimal up to the point where melting occurred. The slag layer that had formed on the surface of the tube during the test was only approximately 1.5 mm (0.06 in.) thick and was composed of three layers. A schematic diagram of the layers is shown in Fig. 5. During cooling, the slag layer spalled from the tube, indicating that it was not intimately bonded to the tube. The innermost layer was sintered and approximately 50-250 µm thick. The fact that it was sintered implies that the ash would be relatively solid; therefore, corrosion of the alloy by this inner layer of ash would be expected to be low.

On top of the sintered layer was a fused but porous layer approximately 800 to 1,750 µm thick. The fact that the layer was fused indicates that it would have a high thermal conductivity, but the porous nature indicates that it would not be flowing and so would provide a relatively permanent corrosion protection layer. The outer layer was fused

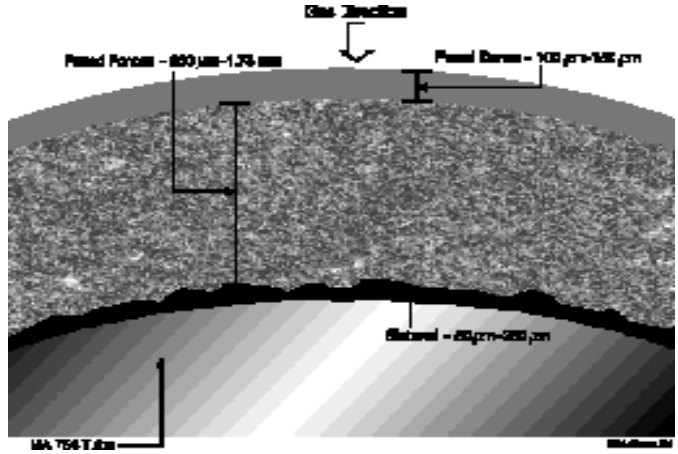

Figure 5. Schematic of the layers that formed on the cooled MA754 probe exposed directly to the coal flame in the SFS

and dense. It was approximately 100 to 150 µm thick. Its density indicates that it was likely molten at temperature and would, therefore, be constantly flowing off, preventing any greater buildup of ash.

In another SFS test performed with Illinois No. 6 coal, a similar probe of MA956 was exposed to flame conditions for 100 hours while the surface was cooled to nominally 1093°C (2000°F), but loss of cooling air shortly after the start of the test resulted in alloy temperatures as high as 1427°C (2600°F) for a period of 2 hours. Because of this loss of cooling, the ash in contact with the probe fused into a solid mass. Since MA956 has a higher melting point than MA754, and it also forms an alumina surface scale, it was protected from the fused slag attack. The absence of any porosity in the slag indicated that it had reached the fusion temperature and a relatively uniform 3 to 5 µm-thick alumina scalewas formed on the surface on the alloy. Between the alloy surface and the fused slag, there was indication of an Fe-Al transition layer tending toward a Ca-Al silicate matrix with scattered iron oxide-rich and iron-calcium silicate crystals.

Effect on Cost of Electricity

The use of the bare tubes in the heat exchanger would not have a significant effect on the overall efficiency of a power system compared to the tubes-in-a-box design, although the HTHX would be considerably less expensive. While the radiant heat-transfer rates to the tubes would increase, the air outlet temperature is still determined by the maximum tube wall temperature, which is governed by stress and corrosion considerations. Thus no changes are anticipated in the estimated 47% higher heating value (HHV) efficiency of the bare tube HTHX using a state-of-the-art turbine as compared to the tubes-in-a-box HTHX. Figure 6 shows the efficiencies of a current pulverized coal-fired plant compared to four different bare-tube HiPPS configurations, an integrated gas-

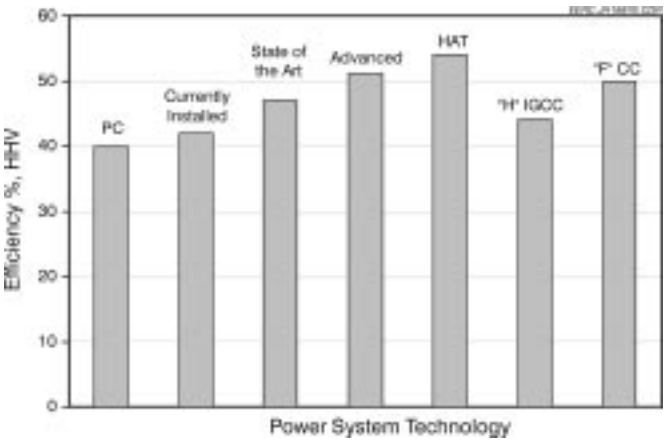

Figure 6. Higher heating value efficiencies for pulverized coal, HiPPS, IGCC, and natural gas-fired combined-cycle plants

ification combined cycle (IGCC) plant using an H-class turbine, and a natural gas-fired combined-cycle plant using an F-class turbine. The four HiPPS configurations include using 1) currently installed turbine technology, 2) state-of-the-art turbine technology, 3) near-term advanced turbine technology, and 4) an advanced humid air turbine (HAT). The data show that by using state-of-the-art turbine technology, the efficiency of a HiPPS system employing a HTHX is similar to that for IGCC or gas-fired combined-cycle plants. Using advanced turbines, efficiencies can be higher.

Although efficiencies for HiPPS plants rise with the turbine technology employed, the cost of electricity (COE) can actually drop, assuming existing or projected prices for the systems. Figure 7 shows the relative COE for a modern pulverized coal-fired plant (assigned a

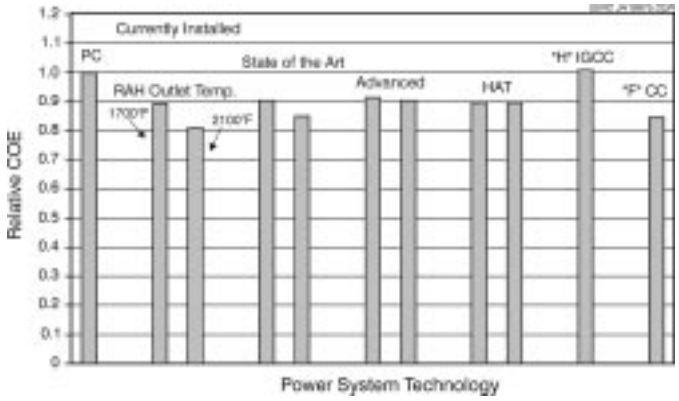

Figure 7. Relative cost of electricity for pulverized coal, HiPPS, and natural gas-fired combined-cycle plants

relative cost of unity) compared to that for the four HiPPS systems (with two HTHX process air temperatures for the currently-installed technology), and the IGCC and natural gas-fired plants. A 20-year levelized cost of coal of $0.99/million Btu and for gas of $3.29/million Btu was used. These data show that the lowest relative COE for these systems is for a HiPPS using a HTHX producing 1149°C (2100°F) process air and a current technology turbine. The second lowest is for a similar system producing 927°C (1700°F) air. This implies that a cost-competitive HiPPS system could be built with available HTHX and turbine technology.

From: J. P. Hurley, K. D. Williams, G. F. Weber, and M. L. Jones, *UNDEERC*; and F. L. Robson, *KraftWork Systems*, "Very High-Temperature ODS Alloy Heat Exchangers for Solid-Fuel Thermal Systems," paper presented at the 27th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Florida, 2002.

Fabrication/Installation of P92 and P122 Steels for Superheater Outlet Collectors

Two martensitic 9 and 12%Cr advanced high-temperature steels: NF616 (P92) and HCM12A (P122), were developed as the result of a project initiated by EPRI for alloys for use in thick-section steam generator components and steam lines in ultra-supercritical (USC) power plants. The project was finalized at the end of 1994 with ASME code approval for both steels (ASME Code Case 2179 for P92, and 2180 for P122). Further qualification of the two 9-12%Cr steels was completed in a succeeding project (EPRI WO 9000-38), which involved trial production of headers made from both alloys for installation in a coal-fired USC steam generator with steam parameters close to 300 bar (4,350 psi) and 600˚C (1112°F). The only steam generators available to host trial headers operating at advanced steam conditions at that time were two identical USC units ordered by the Danish utility Elsam to be commissioned in 1997 and 1998. The unit at Nordjyllandsvaerket (steam parameters 290 bar/580˚C/580˚C/580˚C, or 4,206 psi/1076°F/1076°F/1076°F) to be commissioned in 1998 was chosen as the host site.

Demonstration Project

The original superheater outlet header and collector design is shown in Fig. 8. Twenty eight smaller steam collectors are used to gather steam from the final superheater. These collectors are connected to two main outlet headers, 14 to each header. The final superheater is made of the austenitic steel TP347HFG, and all the collectors and headers are made of P91.

In order to allow participation of three boiler manufacturers in the project [Rolls-Royce-International Combustion (RR-IC); ABB-Combustion Engineering (ABB-CE); and Mitsubishi Heavy Industries (MHI)] it was decided to replace four of the smaller collectors originally designed in P91 by

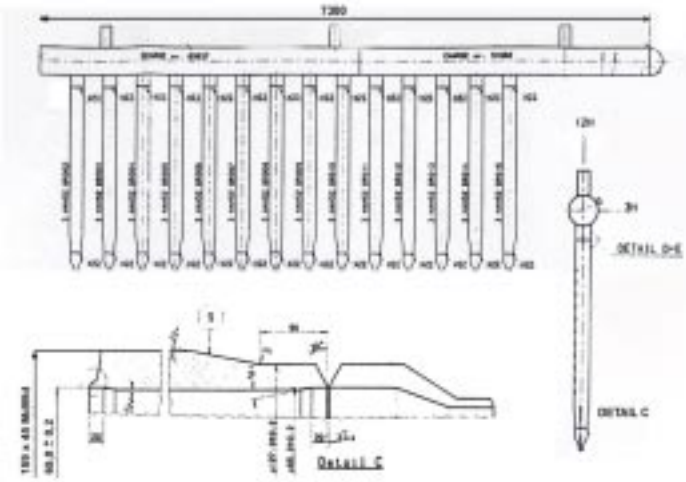

Figure 8. P91 superheater outlet header anf collector design

four trial collectors redesigned using P92 and P122 respectively. RR-IC and ABB-CE each redesigned and manufactured one of the trial collectors in P92 and P122, respectively, while MHI redesigned and manufactured the remaining two trial collectors, one in P92 and one in P122. All stubs and transition pieces that would form welded connections on site were made from P91 to make the mounting of the trial collectors equivalent to the P91 collectors, and thereby avoid any problem with dissimilar site welds during installation of the trial headers.

The Danish authorities accepted the demonstration project under the following conditions:

- header design should be in accordance with ASME Boiler and Pressure Vessel (B&PV) Code, Section 1, using the materials properties for P92 and P122 given in B&PV Code Cases 2179 and 2180, respectively;
- fabrication of the headers should be in accordance with the Danish Power Companies' *Joint Conditions for Welding on Pipe Systems*;
- welding procedures, procedure qualification, and welder qualification were to be witnessed by third-party inspectors before approval;
- final quality control of the headers based on non-destructive testing (NDT), heat treatment, and hydrostatic testing, was to be witnessed by a third-party inspector before approval; and
- inspection of the headers was mandated, including NDT on specified welds every two years after commissioning.

Design and Manufacture of the Superheater Outlet Collectors

The four headers in P92 and P122 were designed based on the specifications for the P91 collectors, and the design drawings and calculations were reviewed by a third-party inspector before being submitted for approval by the Danish authorities. The P92 and P122 collector design by MHI is shown in Fig. 9. Nippon Steel and Sumitomo produced the necessary P92 and P122 pipe materials in the required dimensions, as well as forged material to be used for the

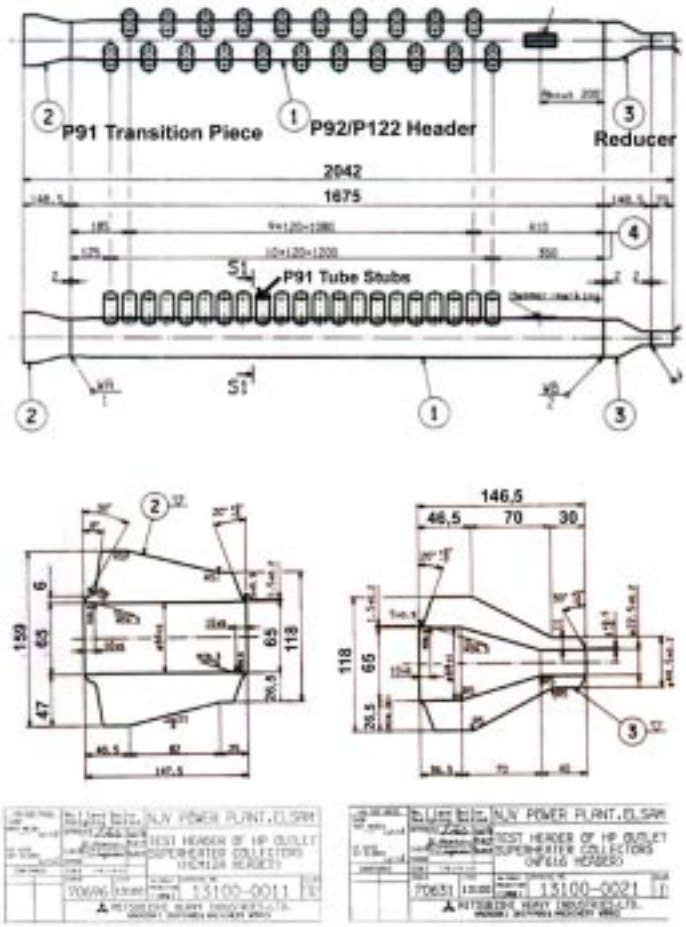

Figure 9. P92 and P122 collector design by MHI

reducers of the collectors. Before fabrication of the collectors, all three manufacturers had to set up and qualify a welding procedure. Since the welding procedures developed in the original EPRI project were qualified to the requirements of ASME IX (which are less demanding than the Danish requirements), it was necessary to set up new procedures meeting the requirements of European Standard EN288. This necessitated all-weld tensile tests in the P92 and P122 weld metal, macro and hardness surveys, and Charpy tests in the weld.

The NDT applied to the welds in the collectors was far in excess of the requirements of ASME I, partly to meet the Danish requirements but, more importantly, to fully categorize and examine all weldments since they were experimental/trial collectors. Before heat treatment all butt welds were subjected to radiography and ultrasonic examination scanning for longitudinal and transverse defects over 100% of their length. All stub-to-collector welds were subjected to 100% ultrasonic examination, and all welds were subjected to external surface examination using magnetic particle methods (MPI).

After post-weld heat treatment, all NDT examinations, radiography, ultrasonic and MPI were repeated. Finally, the collectors were hydro-tested to 1.5 times the design pressure using hot water with a temperature about 50˚C (122°F).

Installation and Service Exposure of Collectors

Because of incomplete documentation of the production procedures required by the Danish authorities for the collector fabricated by ABB-CE, it was possible to install only the three collectors made by RR-CI and MHI during the construction of the steam generator. The collector from ABB-CE was later used in a full-size exposure test run at elevated temperature and pressure by MHI in Nagasaki, Japan. The three collectors were successfully installed, as illustrated in Fig. 10. The power plant was commissioned during the spring of 1998 and has been in operation since then. All three headers were inspected during the summer overhaul in August 2000. MPI and surface replica inspections of one of the butt welds and selected stub welds at each collector did not reveal any cracks or microstructural degradation.

Figure 10. Installation of one of the trial collectors

Abstracted from: R. Blum, *Elsam, Denmark*, "Fabrication and Installation of Demonstration Superheater Outlet Collectors of Steels P92 and P122 in a USC Coal-Fired Boiler," pp. 229-225 in Proc. of the 3rd EPRI Conference on *Advances in Materials Technology for Fossil Power Plants*, R. Viswanathan, W. T. Bakker, and J. D. Parker, Eds., The Institute of Materials, London (Book 0770), 2001. Published by permission of the Institute of Materials.

Experience with Internal Airfoil Coatings in Industrial Gas Turbines

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Abstracted from: G. A. Kool, *National Aerospace Laboratory, The Netherlands*; K. S. Agema, *KEMA*, and J. P. Buijtenen, *Delft University of Technology, The Netherlands*, "Operational Experience with Industrial Coatings in Aero- and Industrial-Gas Turbine Air Foils," Paper No. GT-2002-30359, presented at the ASME Turbo-Expo 2002, June 3-6, 2002, Amsterdam, The Netherlands.

Approaches for Reducing Scrap Rates for Advanced Turbine Blading

The generation of gas turbines that has entered the market in recent years has incorporated new technologies that permit cycle efficiencies of over 58% to be delivered in combined-cycle operation. As some of the technologies from programs such as the U.S. Department of Energy's Advanced Turbine Systems Program and from the European and Japanese equivalents are incorporated into land-based gas turbines, the combined-cycle efficiency is expected to approach 60%. As reported elsewhere, the first of the General Electric H Class machines is scheduled to commence operation this year. A major contributor to the increased cycle efficiency has been the increased temperature capability of the hot gas path components and, in particular, the introduction of directionally-solidified (DS) and single-crystal (SC) airfoils, and the reliance on thermal barrier coatings.

In some cases, however, the turbine blades exposed to the highest temperatures suffer from scrap rates of 25-50%. The highest scrap rates, therefore, typically involve DS and SC blades and, since these have a value of over 5,000 Euros each, the scrap rate of these components can have a dominant influence on life-cycle costs.

A complicating factor is the liberalization of the electricity markets, which has put great pressure on the life-cycle costs of the new gas turbine types. Hence, it is no longer acceptable to have unplanned outages and high scrap rates for expensive gas path components due to poor design. Neither will the market tolerate the lack of operational experience with these new components, or the absence of the technologies needed to repair these advanced machines. Given this scenario, together with the dramatic grown in the application of gas turbines for power generation, the situation in the repair and refurbishment industry has changed dramatically in the last few years. The main drivers are:

- Increased desire by gas turbine users to transfer the financial risks of post-repair problems to the original equipment manufacturers (OEMs) and the repair shops—this typically takes the form of long-term service agreements and operational and maintenance contracts.

- Because of the stiff competition in marketing new gas turbines, the major OEMs have recognized the need to capture gas turbine repair and refurbishment work, which is seen as a major potential source of profit.

- Repair and refurbishment of the new technology blades and vanes represent technical problems that may be beyond the experience of independent repair shops. As a result, there is keen interest in the development and introduction of innovative repair and refurbishment techniques.

Features of Advanced Blading

The main features that have been introduced into the hot sections of advanced gas turbines in the past 3-5 years are:

- Film cooling
- Reduced blade wall thickness
- DS and SC alloys
- Thermal barrier coatings (TBCs)

Film cooling is achieved by means of numerous perforations of the blade walls. The efficiency of this cooling technique is greatly affected by factors such as the accuracy and reproducibility of the hole size, and the shape of the hole, which can change from essentially cylindrical (resulting from laser drilling) to special trapeziform shapes. Reduced blade wall thicknesses are desired together with complex internal cooling channel structures to minimize blade temperatures. This approach, however, is not applicable to areas that experience high thermal-mechanical stresses or where there is insufficient cooling air available, such as at blade tips and vane platforms. The temperature capability of the first and second stages of airfoils has been increased by the introduction of SC alloys, and DS alloys have been applied to the latter turbine stages. This application is intended to increase the thermal fatigue resistance, but some of the increased properties have to be sacrificed to overcome the notch effect of the film-cooling holes, and the metallurgical imperfections caused by the laser drilling process.

A potential problem is that these higher-strength alloys (increased volume fraction of the γ' phase with a concomitant reduction in Cr content) have poor resistance to hot corrosion, and so must rely on coatings for environmental protection. Since the predominant turbine fuel is natural gas, the gas turbine conditions are expected to be chemically less aggressive than when using liquid fuels, though even sporadic use of 'dirty' fuels would risk hot corrosion damage. Thermal barrier coatings (TBCs) have been applied as a design feature, that is, the thermal protection that they provide is now relied upon to allow a reduction in cooling air flow to the airfoils, which is a significant step from their use in current turbines as a means of life extension. In this scenario, the oxidation resistance of the bond coating is extremely important, since it may experience a significant increase in operating temperature in areas where the outer ceramic layer of the TBC may be lost. Significantly upgraded metallic coatings, typically MCrAlY-type coatings (where M is Ni and/or Co) have been applied as bond coatings in the TBCs, as well as to the later stage airfoils, replacing diffusion-type coatings.

Coatings also are being used to protect the internal passages in the blades and vanes from oxidation. This is important, given the reduction in wall thickness. Although the temperature of the cooling air is relatively low (compared to the combustion gas), less material degradation can be tolerated in these passages due to the prevailing tensile stresses, and the danger of critical crack growth on the internal surfaces. The internal coatings are typically aluminides, applied by chemical vapor deposition.

Although many of these new technologies have been derived from existing aircraft engine practice, a considerable ongoing research and development effort is required to adjust the systems to the different requirements of land-based gas turbines. Important differences are longer times at higher temperatures, longer periods between overhaul, and possibly more hostile environments. The scaling aspects from aircraft-sized components to land-based gas turbines also are important. For instance, some low-pressure plasma spray-coated parts may weigh more than 30 kg, and these together with the masking and fixturing tools result in a mass of more than 50 kg that must be heated up and maintained at the coating temperature. Further, coating facilities specialized for small aircraft components are not really suitable for coating land-based turbine components.

Challenges Posed by the New Technologies

The application of these new technologies under conditions hitherto unknown in land-based gas turbines have resulted in forms of damage or degradation that pose challenges to established repair and refurbishment technologies. Some of these damage features have been observed after relatively short operating times (between 25 and 33 kh engine operating hours). Some examples are:

- Cracking adjacent to the cooling holes that results from thermal stresses. Such cracks usually show subcritical growth behavior, and so seem to be repairable at least in the case of stationary blading. However, nondestructive testing methods such as eddy current and dye penetration must achieve lower detection limits to detect all the cracks present. Because of the thin blade walls, blending of cracks and/or of worn areas must be done with minimum energy input. In addition, to ensure reproducible results, appropriate inspection instrumentation for wall thickness measurement, for instance, must be identified and qualified. Welding and brazing methods must be developed for these new alloys that result in high strength bonds. In fact, the development of techniques for welding relatively high gamma prime alloys has made good progress. In these alloys, repairable cracks must be completely cleaned of debris and of any oxides that may have grown on the alloy, and this is best done by chemical means employing Hf. Brazing is the technology of choice to fill narrow cracks without blending.

- Premature failure of the coating sometimes linked to poor cooling can result in excessive oxidation of the thin blade walls. In such cases, these must be carefully blended out down to certain minimum levels (which

must be established). The aerodynamic surface then has to be recontoured by, for instance, weld overlay, welding, brazing, or parent metal thermal spray. Since none of these repair methods will attain the original base metal strength (60-70% is apparently achievable by welding and brazing) the extent to which such damaged surfaces can be repaired is limited.

- Recontouring of blended areas by overlay welding or preferably by overlay brazing need not necessarily meet high strength requirements, but must result in good bonding to the substrate, and must be machinable to the final shape. In addition, heat input during the repair must be kept as low as possible to avoid recrystallization of the DS or SC substrates. In addition, hot tearing (cracking formation) and incipient melting must be completely avoided.

- Rubbing of the tips of the rotor blades on the clearance coating on the inside of the casing is a common occurrence, since good sealing between the rotor tips and the casing is required to minimize gas leakage and improve overall efficiency. In case of DS and SC blades, repair of damage to the blade tips by rubbing must be done in such a way that avoids recrystallization, and/or the formation of secondary grain boundaries. There are several patent applications pending in this area.

- Following blade repairs, representative areas of single crystal castings must be checked for recrystallization in areas where deformation has occurred by, for instance, foreign object damage. The OEMs have established conservative limits for the recrystallization effect.

- The ceramic layer of a TBC usually can be stripped by mechanical means, such as grit blasting, or by chemical means using a salt bath, with no major complications. However, removal of the bond coating (which typically consists of high-Al MCrAlY or aluminide coatings) may be difficult to achieve mechanically without causing unacceptable damage to the thin walls of the airfoils. Since the adherent alumina scales formed by the bond coatings are resistant to simple acid stripping, more sophisticated methods such as high-pressure water jet cleaning, or other proprietary processes, must be used.

- Recoating of film-cooled blading currently is the main problem in refurbishment. Typically the techniques used in refurbishment are the same as those used for coating new parts, although additional considerations are required to take into account the fact that the repaired parts may have different surface properties, requiring special measures. Further, some parts have a different production sequence in the new and refurbished condition. For instance, the recoating must be done with existing cooling holes whereas, on new parts, the holes are usually drilled after deposition of the TBC. In addition, thermal spray coating methods (such as low-pressure plasma spray or the deposition of MCrAlY coatings) are line-of-sight processes, so that there is a tendency to build up coating material in areas where it is not desired, such as in cooling holes. As a result, recoating of such parts requires special care to avoid plugging of the holes. This problem may be overcome by modification of the programming of the coating robot, or by the use of a non-thermal spray process such as TRIBOMET™ (an electrochemical process), or by using a diffusion process.

Recoating of the ceramic layer by EB-PVD does not have these problems, since in this vapor process the coating is only deposited where solid material exists. With APS coating processes, the cooling holes can be protected by plugging by the use of elastic sticks that are applied to the holes before spraying.

The condition of the coatings on the internal passages can only be checked through the use of destructive examination of a representative part. In principle, the internal coating can be protected from removal during the stripping of the external bond coating, but an economic judgment is required concerning the desirability of allowing this relatively low-cost coating to run for a second duty cycle. The technique for stripping internal aluminide coatings is well established in the aircraft industry, and should not cause problems on industrial gas turbine parts. Recoating is possible as on new parts, provided that the stripping has been successful and the refurbishment sequence is appropriate.

Suggested Refurbishment Sequence

The techniques required for repair and refurbishment of advanced gas turbine blades involve a complicated sequence of inspections, chemical and mechanical operations, welding and braze repair and recoating. A typical sequence of operations needed might be as follows:

1. Visual inspection to identify parts that have undergone exceptional degradation (including recrystallization of SC blades following foreign object damage) to identify components that must be scrapped.
2. Removal of cooling inserts and baffles.
3. Chemical or mechanical removal of the TBC (different processes for the ceramic outer layer and the bond coating).
4. NDT examination of the effectiveness of the stripping.
5. Visual inspection to detect obvious cracking.
6. Dye penetrant testing to locate cracking.

7. NDT (such as eddy current) to find microscopic and subsurface cracks and other defects.
8. Documentation and evaluation of the findings to determine which components can be refurbished.
9. Specification of the procedures and repair steps for each component depending on its condition.
10. Mechanical machining for blending of cracks and removal of deteriorated material.
11. Ductilization heat treatment in preparation for weld repair.
12. Weld repair procedure (TIG or laser).
13. Cleaning to remove oxide debris where applicable using HF.
14. Narrow-gap brazing of cracks, including hot tears from weld repair.
15. Wide gap brazing to fill up blended material.
16. Parent metal low-pressure plasma spray coating to rebuild the structure where applicable.
17. Machining to recontour air-flow surfaces.
18. Recoating of internal coating passages where applicable.
19. Recoating with overlays (MCrAlY and TBC, where applicable). Note that the preconditioning of the surface to be recoated depends heavily on the TBC application method.
20. Reassemble with cooling inserts and battles.
21. Visual and dye penetrant inspection.
22. Application of outer diffusion coating where applicable.
23. Final heat treatment where applicable.
24. Final inspection and documentation.
25. Return parts to service.

Although not unexpected following the introduction of major new technologies, the scrap rates experienced with the new gas turbine components (from rejection of new parts that do not meet specifications as well as from the high fraction of parts (25-50%) that are designated to be unfit for repair and refurbishment) have resulted in a very high cost burden for the gas turbine operators, in terms of life cycle costs. As a result, there are attempts to off-load some of the financial risks onto the original equipment manufacturers through long-term operational and maintenance contracts but, ultimately, the main load will be carried by the operators. The goal of the increased emphasis on improved repair methods and more sensitive NDT is to reduce the existing scrap rates in the short term (for instance by 50% in two to three years). It is anticipated that this can be achieved through the adaptation of existing aircraft technology by the repair and coating shops that are experienced in refurbishment of land-based turbines. Further, all of the production sequences indicated above need not necessarily be carried out in one place, so that a production chain of highly specialized companies performing specific steps could be visualized. The introduction of innovative repair and refurbishment techniques can also entail some additional technical risks but, with a semi-conservative approach as suggested here, it is anticipated that the financial benefits will greatly out weigh the cost.

Abstracted from N. Czech, *N. C. Consulting, Dorsten, Germany*, "Reducing Scrap Rates for Advanced Turbine Blading," Modern Power Systems, December 2001, pp 31-35. Published by permission of Wilmington Publishing.

Meetings Calendar

November 20, 2002: A one day meeting on the Microstructure and Performance of Joints in High-Temperature Alloys will be held at the Institute of Materials, Minerals and Mining, 1 Carlton House Terrace, London, SW1Y 5DB. Presentations will cover aspects of microstructural interpretation, modeling, and the relationship with performance in the context of alloy joints for elevated-temperature applications. Emphasis will be on welding, but other joining methods including brazing, friction processes, and diffusion bonding also will be addressed. The focus will be on nickel-based alloys and steels of interest to the power generation and aerospace industries. For further information, contact: Professor H.K.D.H. Bhadeshia, Department of Materials Science and Metallurgy, Cambridge University, Pembroke Street, Cambridge, CB23QZ, England; 'phone: 011-44.122.333.4301; or e-mail: hkdb@cus.cam.ac.uk.

November 28-30, 2002: The National Convention on Corrosion/Corcon 2002/The NACE East Asia Pacific Regional Conference, Goa, India. See Materials & Components, No. 157 for details.

December 2-6, 2002: The Fall Meeting of the Materials Research Society will be held in Boston. Featured topic areas are: Polymers and Biomaterials; Nanomaterials and Technology; Electronic and Photonic Materials; Spin, Superconductivity and Ferroelectricity; Surfaces, Interfaces and Membranes (interfacial issues for oxide-based electronics; morphological and compositional evolution of thin films; surface engineering 2002-synthesis, characterization, and applications; structure-property relationships of oxide surfaces and interfaces; membranes-preparation, properties, and applications); Metals, Alloys and Inorganics (including: materials for fuel cells and fuel processors; fiber-reinforced cementitious composites; high-temperature thermal spray coatings-thermal barrier coatings); and Materials Science and Society. For further information, contact: Materials Research Society, 506 Keystone Drive, Warrendale PA 15086-7573; 'phone: 724.779.3003; fax: 724.779.8313; or internet: webmaster@mrs.org.

December 2-6, 2002: A symposium on High-Temperature Thermal Spray Coatings-Thermal Barrier Coatings, will be held as part of the Materials Research Society's Fall Meeting, in Boston. This symposium will focus on the processing, characterization, and modeling of high-temperature thermal spray coatings with emphasis on thermal barrier coatings and oxidation-resistant coatings. These coatings are used, for example, in the hot sections of gas turbines and diesel engines to improve efficiency, performance, and durability by protecting the metallic components from the harsh high-temperature environment. For details, contact: Y. C. Lau, General Electric Global Research Center, K-1 MB243, One Research Circle, Niskayuna, NY 12309; 'phone: 518.387.6017; fax 518.387.7495; or e-mail: lau@crd.ge.com

March 2-6, 2003: A symposium on "Materials Processing Under the Influence of Electrical and Magnetic Fields," held in conjunction with the 132nd Annual Meeting & Exhibition of TMS, San Diego, California, USA. See Materials & Components, No. 157 (Calls for Papers) for details.

March 2-6, 2003: A symposium on Computational Phase Transformations will be held at the 132nd TMS Annual Meeting & Exhibition, San Diego Convention Center, San Diego, California. Six to eight sessions are anticipated addressing the following topic areas: thermodynamic properties of equilibrium and nonequilibrium phases; atomic transport in multicomponent solids; databases for computational thermodynamics and diffusion modeling; kinetics of nucleation, growth and coarsening; fundamental behavior of surfaces and interfaces; microstructural evolution during solid-state reactions, solidification and crystallization; effect of defects (dislocations, surfaces, interfaces, grain boundaries, et. al.) on phase transformation and microstructural evolution; transformation under stress, electrical/magnetic fields and highly nonequilibrium conditions; and recent advances in computational methods and algorithms for modeling phase transformations and microstructural evolution. For details, contact: Yunzhi Wang, Dept. Materials Science and Engineering, The Ohio State University, 2041 College Road, Columbus, OH 43210; 'phone: 614.292.0682; or e-mail: wang.363@osu.edu

March 16-20, 2003: CORROSION NACExpo 2003 will be held in San Diego, California. Technical symposia will be sponsored by the following committees, and include: Surface Tolerant Coatings; Methods of Corrosion Control for Threaded Fasteners; Pipeline Coatings and Linings; Tank Lining; Recent Advances in Water Treatment; Cathodic Protection in Natural Waters; Pipeline Integrity; Materials Technology Developments for Incinerators and Waste Fuel-Fired Processors; Advances in Electrochemical Techniques for Monitoring of Corrosion and Corrosion Control; Plant and Field Applications of Electrochemical Noise; Corrosion Sensors; Corrosion in Gas Treating; Heat Recovery Steam Generator (HRSG) Boiler Tube Failure Analysis; Advances in Materials and Corrosion in Fossil Fuels Conversion and Combustion; Environmentally Assisted Cracking; and New Technologies in Chemical Cleaning of Boilers. For details, see the ANCE website at: http://nace.org/NACE/Content/Conferences/c2003/TechnicalSymposia.ASP

April 7-9, 2003: The Fifth International Conference of the Engineering Integrity Society, "Fatigue & Durability Assessment of Materials, Components and Structures," Queens' College, Cambridge, England. See Materials & Components, No. 157 for details.

December 1-4, 2003: The World Conference on Corrosion and Corrosion Maintenance Expo and Celebration of the Ninth Corrosion Awareness Day, Mumbai, India. See Materials & Components, No. 157 (Calls for Papers) for details.

Calls for Papers

January 30-31, 2003: A Workshop on Metal Dusting, Carburization and Nitridation (European Federation of Corrosion-Event No. 258) will be held at DECHEMA, Frankfurt am Main, Germany. This meeting incorporates a large number of papers intended for a workshop planned for May 2002 in Pamplona, Spain, that was cancelled. Further papers are sought in the general topic areas indicated by the Workshop title. Abstracts should be sent, by 25 November 2002, to: Prof. H. J. Grabke, Max-Planck-Institut für Eisenforschung, P. O. Box 140444, 40074 Düsseldorf, Germany; fax: 011.44.211.6792.277; or e-mail: grabke@mpie.de.

March 10-13, 2003: The 28th International Technical Conference on Coal Utilization & Fuel Systems, Theme: Coal: Energy Security for the Future, will be held at the Sheraton Sand Key Hotel, Clearwater, Florida. See Materials & Components, No. 157 (Calls for Papers) for details.

April 7-9, 2003: The Fifth International Conference of the Engineering Integrity Society, "Fatigue & Durability Assessment of Materials, Components and Structures," will be held at Queens' College, Cambridge, England. See Materials & Components, No. 157 (Calls for Papers) for details.

April 28-March 2, 2003: ICNCTF 2003: The International Conference on Metallurgical Coatings and Thin Films, will

be held at the Town and Country Hotel, San Diego, California. Abstracts are requested by October 1, 2002 on the topic areas: coatings for use at high temperatures; hard coatings and vapor depositions technology; optical thin films; carbon and related materials; tribology of coatings and thin films; coating and thin film characterization; applications, manufacturing, and equipment; new horizons in coatings and thin films; principles of pulsed plasma; self organization and surface response effects in thin film technology; computational studies in thin film research. Abstracts may only be submitted electronically to the conference website at http://www.abs.org/conferences/icmctf/call/2003. Information is also available from the conference administrator: Mary S. Gray, 14001-C St. Germaine Drive, Suite 136, Centerville, Virginia 20121; 'phone: 703.266.3287; fax: 703.968.8877; or e-mail: icmctf@mindspring.com.

April 28-March 2, 2003: There will be a special session at the ICNCTF 2003, San Diego, devoted to Wear and Friction Mapping of Coated Surfaces. The scope of the session includes sliding wear, erosion, abrasion (including micro-abrasion) and fretting wear. Papers involving interactions with dry and wet corrosion are also of interest. The nominal abstract deadline is October 1st 2002. However, papers in mapping tribological phenomena are being keenly sought, so to submit a paper, please contact: Prof. Margaret Stack, Director of Research, Department of Mechanical Engineering, University of Strathclyde, James Weir Building, 75 Montrose St., Glasgow, G1 1XJ, Scotland; 'phone: 011.44.141.548.3754; fax: 011.141.552.5105; e-mail: m.m.stack@mecheng.strath.ac.uk. Further details can be found on the conference website http://www.avs.org/conferences/icmctf/call/2003.

May 19-22, 2003: The fourth DOE-EPRI-USEPA-Air & Waste Management Association Power Plant Air Pollutant Control 'Mega' Symposium will be held in Washington, DC. The Symposium will showcase the latest developments and operational experience from fossil-fired boilers. The topic areas to be covered include: NO_x control; SO_2 control; multi-pollutant controls (combines SO_2, NO_x, PM, Hg); particulate control; and mercury/air toxins controls. Abstracts for papers should be submitted by November 1, 2002 via: www.awma.org/events; or contact Denise Stotler, A&WMA technical programs manager, at dstotler@awma.org.

June 8-13, 2003: The Third Mediterranean Combustion Symposium (MCS-03), will be held in Marrakech, Morocco. All topics and all the scientific/technological approaches in the combustion field are pertinent to this Symposium. The technical program will consist of invited lectures by eminent specialists from all over the world, oral presentation of the contributed papers and posters of the work-in-progress. Colloquia will be held in the following topic areas: flame structure and dynamics; solid fuels and waste combustion; sprays and gas combustion systems; internal combustion engines; optical diagnostics and radiative transfer; pollutants; fire and explosions; kinetics; and turbulence combustion and modeling. Further information is available from: Martine van Hapert, Istituto di Ricerche sulla Combustione – CNR, P.le V. Tecchio 80, 80125 Napoli, Italy; 'phone: 011.39.081.768.2263; fax: 011.39.081.593.6936; or e-mail: martine@irc.na.cnr.it. The conference web site is at: http://www.combustioninstitute.it or http://www.ichmt.org

September 1-5, 2003: Euromat 2003, The European Congress on Advanced Materials and Processes, will be held in Lausanne, Switzerland. This is the seventh in a series initiated in 1989, and will be structured into eighteen topic areas that, in turn, will each include 3-5 symposia. Topic areas of interest are: information technology (electronics, photonics, spintronics, packaging); modeling on all length scales; biomimetic and bio-inspired approaches to inorganic and functional hybrid materials; bio-functional materials and surfaces; nano-structured materials; thermal mechanical coating; functional coatings; energy and transportation; near-net shaping and rapid prototyping; materials for light design; assembling and joining; non-crystalline, quasi-crystalline and complex intermetallic materials; building materials (cement, concrete, steel); ceramic materials; polymers; phase transformation; design and prediction of fundamental and constitutional properties; and materials characterization (microstructure, NDT, mechanical properties, residual life). Abstracts should be submitted by January 31, 2003, to the Euromat 2003 Congress Office, c/o Deutsche, Gesellschaft für Materialkunde, Hamburger Allee 26, 60586, Frankfurt, Germany; 'phone: 011.49.69.7917.747; fax: 011.49.69.7917.733; e-mail: Euromat@Fems.org.

A Word From Our Sponsors...

The 28th International Technical Conference on Coal Utilization & Fuel Systems, Theme: Coal: Energy Security for the Future, will be held on March 10 - 13, 2003 at the Sheraton Sand Key Hotel, Clearwater, Florida. The Conference Committee is seeking papers that will deal with technical solutions to problems; specific strategies; projects; innovations; industry trends; and/or regulatory compliance. The goal is to present an extensive overview of emerging, evolving, and innovative technologies, fuels and/or equipment in the power generation industry, through the presentation of accomplishments, opportunities and challenges in the areas of: environmental & health aspects; advanced power systems & green coal technologies; utility perspectives on coal-based fuels; opportunity fuels; domestic & worldwide coal resources quality issues; transportation issues; international programs – technical developments/policy issues. A one-page abstract should be sent via email, by October 31, 2002, to: Coal Technology Association, 601 Suffield Drive, Gaithersburg, Maryland, USA 20878; attention: Barbara A. Sakkestad (CTA), 'phone: 301/294-6080; fax: 301/294-7480; e-mail: BarbaraSak@aol.com; or Web site: www.coaltechnologies.com.

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