Special workshop explores P91/T91 issues, impending ASME Code changes

By **Robert W Anderson,** chairman, HRSG User's Group

Problems in the fabrication, construction, and repair of 9Cr-1Mo steels have surfaced at many combined-cycle stations, raising safety concerns among plant owners and spurring efforts within ASME to revise its Boiler & Pressure Vessel Code. Last July, the HRSG User's Group assembled several of the world's leading authorities on P91/T91, including the chairman of the Code-revision Task Group, to discuss the problems as well as the Code changes needed to respond to them (Fig 1). Participants in the well-attended workshop, held in Philadelphia, included O&M personnel, manufacturers, fabricators, EPC contractors, constructors, welders, authorized inspectors, and R-stamp holders from 50 different companies.

Setting the stage

William F Newell, Jr, PE, IWE, vice president, EuroWeld Ltd, was the first speaker. His excellent overview of 9Cr-1Mo steels established a hard-hitting tone for the two-day seminar. Newell began with a concise history of the strong but easily degraded alloys, and explained why P91/T91 and other creep-strength enhanced ferritic steels are growing in usage.

The family of alloys traces its roots to the late 1970s, when it was being studied for possible use in the Clinch River Breeder Reactor. Researchers found that 9Cr-1Mo steels, compared to traditional 2.25Cr-1Mo ferritic steels and 300-series austenitic stainless steels, possessed lower thermal expansion, higher thermal conductivity, and improved oxidation resistance. These properties would enable the high-chrome alloy to minimize thermally induced stresses in powerplant components.

With the addition of niobium, vanadium, and nitrogen, Newell explained, the "standard" 9Cr-1Mo (ASTM P9/T9) also exhibited a substantial increase in

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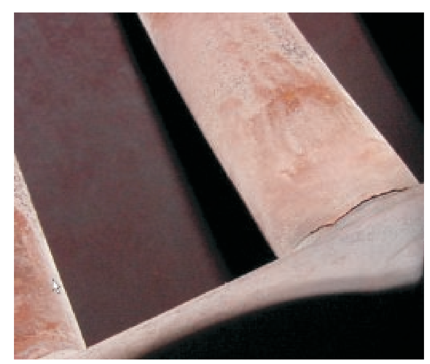
creep-rupture strength, compared to traditional steels, thus giving birth to the "modified" version of 9Cr-1Mo.

The impressive, new alloy was certified in the 1980s as ASTM A213 Grade T91 for tubing and ASTM A/Sa 335 Grade P91 for headers and piping, but another decade went by before it gained much acceptance. Initially, Newell explained, powerplant owners and constructors worried that the material was not



1. Cracking occurred at this tube-to-header connection in an HRSG reheater operating behind an F-class gas turbine. Both the tubing and piping are Grade 91 material, which many assumed would be a panacea for HRSG troubles

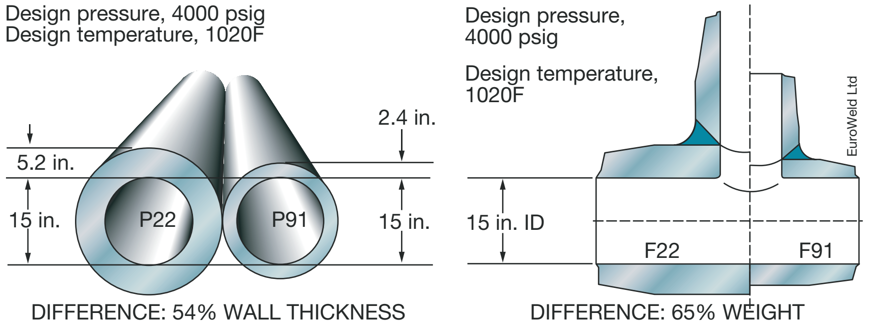
readily available, that all welds—regardless of thickness or diameter—would require post-weld heat treatment (PWHT), and that welds between dissimilar metals would cause problems.

Significantly, the few early adopters of P91/T91 and their suppliers paid great attention to these concerns, and as a result their field applications—at coal-fired plants like TVA's Kingston and Appalachian Power Co's Glen Lyn station—proved successful. "The designers, fabri-cators, and installers followed *all* the rules," Newell explained. They operated with conservative design margins (wall thickness), at reasonable steam temperatures (1050F or lower), and they carefully chose their steel producers and component fabricators. Newell smiled, "The low bidders were not involved yet."

It's not your father's Oldsmobile

In the 1990s, P91/T91 was seen by the booming combined-cycle industry as the cure-all for two major HRSG problems: *thermal fatigue* of thick-walled components, such as main steam piping and superheater headers, and *creep damage* in the superheaters.

The alloy's mechanical properties would allow pressure-containing components to be made in thinner sections, leading to smaller temperature gradients across the wall, reduced time for the metal to reach thermal equilibrium, and ultimately less thermal fatigue. For example, the upgrade of a typical HRSG superheater header from P22 to P91 can reduce wall thickness by 54%, and component weight by 65%



2. Specifying P91 for superheater headers enables the use of much thinner wall sections, hence thermal fatigue can be substantially reduced. However, manufacturers, constructors, and HRSG users often are unwittingly destroying the material's mechanical properties

(Fig 2).

In addition, the alloy's high creep-rupture strength and resistance to oxidation would minimize damage to superheater sections, particularly those coupled to the latest F- and G-class gas turbines that experience the highest metal temperatures.

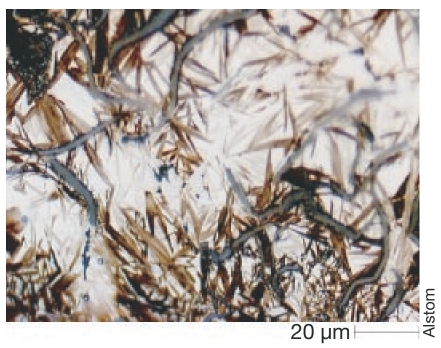
Unfortunately, Newell reported, many of the owners and builders of combined-cycle facilities downplayed the concerns of the early coal-plant adopters, and handled the advanced alloy as if it were an ordinary steel. Therein lies the rub. Newell stressed, "P91/T91 is not just another chrome moly!" It is a highly advanced material whose mechanical properties depend on its microstructure.

Because this fact was neglected, Newell continued, HRSG users began to experience failures in dissimilar metal welds and transition areas—often in less than 1000 hours—and failures caused by poor weld geometry or inappropriate heat treatment—typically in less than 5000 hours.

The following anecdote highlights the failures to which Newell was referring: At an earlier conference conducted by the HRSG User's Group, the approximately 200 users in attendance were asked how many had experienced piping failures of *any* material. Fifteen hands shot up. Next question: How many were with P91 material? Twelve hands remained in the air.

A common error, Newell reported, has been performing localized heating of the Grade 91 component with oxy-fuel torches. These are notoriously difficult to control and almost always provide destructive, non-uniform heating (Fig 3). Another common error is following an incorrect procedure for PWHT—temperature too high, temperature too low, or temperature not maintained for the correct duration. Even worse, some contractors are repairing P91 components without performing any PWHT at all. Paraphrasing a line from Apollo 13, a movie that concerned another engineering disaster, Newell stated that with P91 material, "PWHT is not an option!"

3. Localized heating using oxy-fuel torches is one way to damage the P91 microstructure. Yet it's been done many times in the fabrication, erection, and repair of combined-cycle plants



4. Martensite is a high-energy structure in which a dense array of sub-microscopic defects block easy movement of the lattice atoms along slip planes when stressed. Disruption of these defects—through improper heat treatment, welding, cold work, etc—will destroy Grade 91's mechanical properties

Code changes coming

Picking up where Newell left off was Jeff Henry, director of Alstom's Materials Technology Center and chairman of the ASME Task Group assigned to this issue. "The industry as a whole failed to fully comprehend these alloys," Henry asserted at the workshop. "Their metallurgy is fundamentally different from the 'traditional' low-alloy pressure-vessel steels."

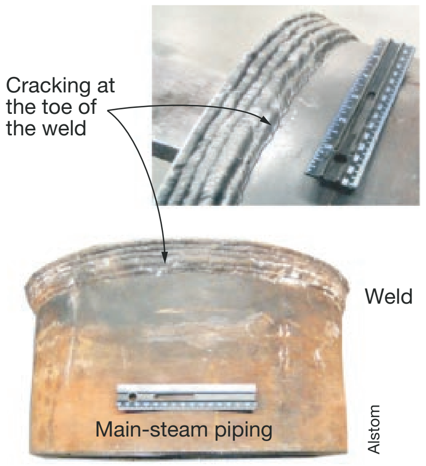
Henry then launched into a primer on materials engineering—a great review for those who don't want to admit how many decades ago they went to school—complete with iron-carbon phase diagrams, body-centered cubic vs face-centered cubic lattices, and martensitic transformation temperatures. While the metallurgy lesson was in-depth, Henry's message was grasped by all: The superior properties of Grade 91 depend on the creation of a precise condition of microstructure, and the maintenance of that microstructure throughout its service life.

Specifically, the properties require a controlled normalizing process to produce a complete phase transformation from austenite into martensite. This produces a hard steel with high tensile strength at elevated temperatures and with high creep resistance. A controlled tempering process must follow, to allow carbonitrides to precipitate at defect sites in the microstructure. This serves to anchor or "pin" the defect sites, thereby preventing future changes to the microstructure (Fig 4).

Failure to achieve this precise microstructure during original steel production or to maintain this microstructure during any subsequent action in the steel's life—such as the hot bending, forging, or welding that regularly occurs during component fabrication, plant construction, and steam-plant repairs—will cause a phase change away from 100% properly tempered martensite or will disrupt the precipitates, either of which will destroy the mechanical properties of the alloy (Fig 5).

Unfortunately, Henry explained, the existing ASME rules are not detailed enough to address this problem and prevent continued failures of P91/T91 components. In fact, Henry believes that today's problems will only get worse unless comprehensive, technically defensible, and widely accepted rules are established. That's why he is chairing a Task Group, working under the direction of the chairman of Section II (Materials) of the ASME Boiler & Pressure Vessel Code, to develop such rules for Grade 91, as well as other approved steels classified as creep-strength-enhanced ferritic (23, 92, 122, etc).

To date, Henry and his Task Group have identified eight specific



5. Type IV cracking—which takes place in the fine-grain section on the base-metal side of the heat-affected zone of a weldment—occurred recently on this section of P91 main steam piping at a US combined-cycle plant. Failures such as this have occurred at a relatively early stage in component life—20,000 to 40,000 hours

issues concerning the use of these alloys, and made recommendations for changes to the Code that will control their use more effectively. At the HRSG User's Group workshop, all eight were discussed in detail, with a great level of helpful interaction between Henry and the many P91 authorities in the audience. Space limitations, however, allow presentation here of only a sample of the issues discussed.

ISSUE: Intercritical exposure/over-tempering/under-tempering

One of the most significant problems with Grade 91 is post-production exposure to temperatures in the intercritical region. This is above the temperature where martensite begins to transform back into austenite (referred to as the lower critical transformational temperature or AC1) and below the temperature where phase transformation is complete (called the upper critical transformational temperature, AC3).

When Grade 91 is exposed to this intercritical region, the martensite is partially re-austenitized and the carbo-nitride precipitates are coarsened but do not fully dissolve back into solution. The resulting material, Henry pointed out, is a part austenite/part martensite metal that lacks the "pinning" effect of the precipitates, and, therefore, its creep-rupture strength is substantially reduced.

Exposure to the intercritical region and the resulting reduction in strength leads to the Type IV cracking found in many P91 welds. In a Type IV failure, cracking takes place in the fine-grain section on the base-metal side of the heat-affected zone of a weldment. Abrupt changes in wall thickness or other features that create high stresses in the region of the weld set up the conditions necessary for this type of cracking.

Type IV failures are a matter of significant concern because they occur at a relatively early stage in component life—20,000 to 40,000 hours—and at lower operating temperatures than the maximum design temperature of 1110F. In addition, they can initiate and grow sub-surface for some distance before breaking through to the surface. There have been about a dozen such failures in P91/T91 components, mostly in the UK where the alloy has been in service longer than in North America. However, the US may be poised to catch up. One American user at the workshop reported several P91 weld failures in steam piping of his company's relatively new fleet of F-class combined cycles.

Over-tempering occurs when Grade 91 experiences prolonged exposure to elevated temperatures below the lower critical transformation temperature. This does not affect the martensite, but it does cause coarsening of the precipitates, with a corresponding loss in creep-rupture strength due to the loss of their "pinning" effect. Over-tempering is a lesser risk during fabrication, Henry explained, because of the relatively short times of the thermal treatments. But in cases where multiple heat treatment cycles are applied in the fabrication of thick-walled components, weakening could become a significant issue at higher tempering temperatures.

Under-tempering also can jeopardize the high-temperature properties of Grade 91, since the required precipitation does not go to completion, and the precipitates either are absent or are of insufficient size to stabilize the structure. In addition to a loss of creep-rupture strength, risks associated with under-tempering are brittle fracture and stress-corrosion cracking.

Task Group response. In response to the issue presented above, the Task Group is recommending three actions:

- Impose an upper temperature limit on tempering and PWHT in order to avoid exposure to the intercritical region and the risk of over-tempering.
- Review the lower tempering limit.
- Prohibit localized heat treatments if temperature exceeds AC1.

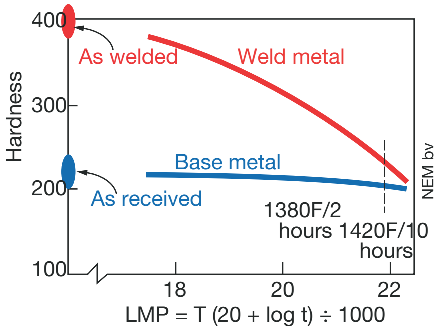
Specific limits being proposed are 1900-1975F for normalizing, 1350-1470F for tempering, 1325-1470F for PWHT of components equal to or thinner than 0.5 in., and 1350-1470F for PWHT of components thicker than 0.5 in. For any component in which a portion of the component is heated above 1470F, the component would have to be re-normalized and tempered in its entirety, or as an alternative, the heated portion could be removed from the component for re-normalizing and tempering and then replaced into the component.

ISSUE: Post-weld heat treatment

A second issue being addressed by the ASME Task Group is the effect of weld fillers on PWHT. Certain alloying elements in the filler—principally nickel and manganese—depress the AC1 and AC3 temperatures, as well as the martensite start (Ms) and martensite finish (Mf) temperatures. During PWHT, this presents the risks of intercritical heat-treat damage and untempered martensite in the weld metal. Henry noted that the AWS standards allow up to 1% Ni in weld metal, significantly higher than the 0.4% Ni maximum in base metal specifications.

In response to this issue, the Task Group has proposed stringent PWHT limits on Grade 91 components based on Ni + Mn content. Specifically:

- PWHT temperature range is 1350-1425F, if the chemical composition of the filler metal is not known precisely.
- For components less than or equal to 5 in. thick, minimum PWHT time is one hour per inch, with a minimum PWHT time of 30 minutes.
- For components thicker than 5 in., PWHT is five hours, plus 15 minutes for each inch over five inches.
- For weld thickness less than or equal to 0.5 in., minimum PWHT temperature is 1325F.
- If the chemical composition of matching filler metal is known precisely, the maximum PWHT temperature can be increased as follows:
  - If Ni + Mn < 1.50% but >



6. One European HRSG manufacturer uses a plot of LMP (Larson Miller Parameter) versus hardness to determine optimum time (t, hours) and temperature (T, deg Kelvin) values for post-weld heat treatment of Grade 91 material

1.00%, maximum PWHT temperature is 1450F.

- If Ni + Mn < 1.00%, maximum PWHT temperature is 1470F.

ISSUE: Control of properties through hardness testing

Another of the eight issues that Henry's Task Group is tackling is quality-assurance testing of the advanced alloys. In order to determine whether the processing of creep-strength-enhanced ferritic steels has been performed correctly, users need a tool that can quickly and inexpensively provide information on the overall material condition.

Because hardness provides a direct indication of a material's room-temperature tensile strength, which can be used to roughly estimate the elevated-temperature behavior of the material, portable hardness testing has been considered as such a tool. With that in mind, the ASME Task Group has considered developing specific hardness limits that, if exceeded, require the user to perform additional testing—such as metallurgical replication and destructive sampling—to demonstrate integrity of the material processing.

However, the Task Group believes further study is warranted because of the substantial variability in portable hardness test results. Henry pointed out that the variables include type of tester—rebound vs penetration—skill of the individual conducting the test, surface cold work, exposure to the intercritical temperature range, and surface decarburization.

Consider just the last variable: If the decarburized layer is not completely removed prior to testing, the hardness measured will be reduced by some amount corresponding to the depth of the layer affected and the depletion of the carbon. Note that even if ASME decides on specific hardness limits, they still would not address one variable: exposure to the intercritical temperature range. For material that has been exposed to temperatures in the intercritical range, hardness testing will not adequately indicate damage, since the re-formed martensite can mask the effects of the undesirable heat exposure.

Hardness help

The ASME Task Group is not the only group wrestling with the vagaries of hardness testing. In Europe, HRSG manufacturer NEM bv also has devoted much effort to the issue. The company's materials and welding engineer, Ing Patric de Smet, IWE, delivered an insightful presentation at the July workshop, providing an overview of European experience with advanced alloys and an in-depth discussion of hardness testing.

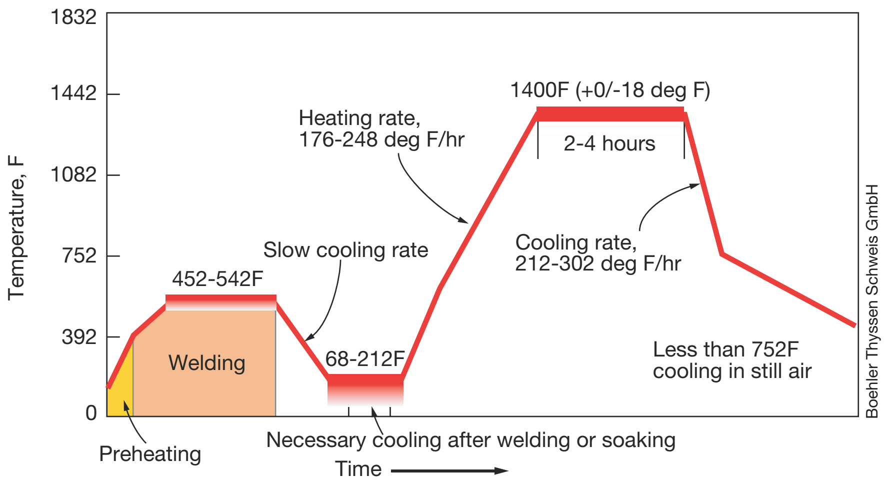
De Smet explained that, if the Grade 91 material has received proper heat treatment, hardness test results will be in a relatively tight range—not too high and not too low. NEM's rule-of-thumb for PWHT, for example, calls for a temperature range of 1380F to 1420F, and a duration of two to three hours. If this guidance is followed, de Smet said, the hardness will drop to 200-270 VHN (Vickers Hardness Number) and the ductility and high-temperature strength will be suitable for service.

De Smet's minimum hardness value certainly matches published data from the UK's West Burton Power Station, one of the first plants to receive replacement components of P91 in the 1980s. West Burton experienced numerous, well-publicized failures of its P91 components, and found that the failed components had hardness values of 10 to 20 points lower than 200 VHN.

NEM's guidance even goes beyond this simple rule-of-thumb. At the July workshop, de Smet introduced the Larson Miller Parameter (LMP) as a function of both heat-treatment temperature (in degrees Kelvin) and heat-treatment time (in hours). He then plotted LMP vs hardness value of both the weld metal and the base metal. His graphs show that hardness is very high in the as-welded condition. It decreases with increasing LMP; that is, higher PWHT temperature and/or longer holding time result in lower hardness. The optimum parameters, de Smet pointed out, are found around an LMP of 21, as indicated by the vertical green lines in Fig 6.

Tempering at relatively low LMP will result in too-high hardness of weld metal and heat affected zone; toughness is low. At the other extreme, PWHT at very high LMP values (high temperature for long duration) results in softening of both the weld metal and the base metal. De Smet emphasized that the LMP can be used only for heat treatments up to the lower critical transformation temperature, AC1.

Note that there are several different hardness instruments and scales applied in engineering practice. Instruments used in the laboratory include Vickers, Rockwell (both "B" and "C"), and Brinell. Portable hardness testers include Equo Tip, Rockwell, and TeleBrineller. The following Rockwell B values for portable tests have been adopted by one US power producer as a QA check on P91 materials:



7. A precise time vs temperature curve must be followed, not only during the production of Grade 91 steel but also during the welding of P91/T91 components in the field

- Higher than 285, reject.
- Between 255 and 285, investigate.
- Between 192 and 255, accept.
- Between 180 and 192, investigate.
- Lower than 180, reject.

Weldability a weighty issue

In another excellent presentation at the P91 Workshop, Dr Herbert Heuser of Boehler Thyssen Schweisstechnik Deutschland GmbH, tutored attendees on the specific challenges of welding P91/T91 components. Following a precise time vs temperature curve is one key to reliable welds, Heuser explained (Fig 7). He recommends cooling down after welding to temperatures of 176F to 212F before PWHT is initiated.

Another key to reliable welds, Heuser explained, is the proper matching of filler metals, which can be gleaned from the "B9" category of AWS tables. He cautioned, however, that there are restrictions to analysis tolerances to ensure that the mechanical values—in particular the notch toughness and creep rupture strength—are in accordance with the operational requirements. The notch toughness of the weld metal is influenced by the PWHT parameters, in addition to the chemical composition and the welding parameters.

Heuser also discussed the fact that field welding often requires joining P91 piping to piping of dissimilar alloys—such as P22 or austenitic stainless steel. In this application, the proper selection of filler metal becomes even more challenging. Dissimilar metal welds also present a challenge from a PWHT standpoint, because the PWHT schedules can be quite different for low Cr-Mo alloys versus the 9Cr-1Mo materials.

Heuser offered these suggestions for avoiding cracking when welding P91 components:

- Adhere to the specifications on preheating and interpass temperatures.
- Ensure equal temperature distribution over the cross-section of the parts with sufficient temperature control on the part during welding and heat treatment.
- Design according to stresses—specifically, avoid abrupt wall-thickness changes.
- Determine welding sequence with particular attention to residual stress.
- Pay attention to heat input. Don't exceed the interpass temperature.

Current status

The ASME Task Group has presented its recommendations on some of the eight issues it is studying to the Section II Committee. It is not clear when the Section II Committee will act on those recommendations with formal changes to the Code. In the meantime, the ASME Task Group continues to study the remaining issues it has identified regarding P91/T91 and other high-strength ferritic steels.

The HRSG User's Group will continue to track, on behalf of its 1100 members worldwide, the Task Group's efforts as well as industry experience. The organization will update members at future conferences and workshops (see sidebar).

Managing your materials

The HRSG User's Group workshop helped to advance the industry's understanding of P91/T91, but the organization's chairman remains concerned that the combination of the (1) recent "bubble" in combined-cycle construction, (2) the dominance of the low bidder, and (3) the sensitivity of Grade 91 materials to errors in thermal processing have positioned combined-cycle owners/operators for a wave of steam-plant failures. Managers of plants with P91 components are urged to establish a rigorous monitoring program—including routine visual inspections and nondestructive evaluation.

If a wave of P91 failures does emerge, the industry will need to manage potentially dangerous situations—such as leaking high-pressure steam pipes—to avoid catastrophic equipment damage, personnel injuries, and even death. If you have been in the power industry for several years, you may recall one or more tragic piping failures—such as the Mohave coal-fired plant's fatal steam rupture in the 1990s. While earlier accidents did not involve P91, the results at a combined-cycle plant could be the same if steam leaks are not properly managed.

The following safe action plan can help protect your personnel:

- **You must assume a leak** if you see steam, water, or heat waves coming from a high-pressure steam line.
- **Clear the area** immediately and keep all personnel well away.
- **Promptly depressurize the affected line** with minimal thermal shock to the system. This usually requires an unplanned shutdown of the entire plant.
- **Do not remove insulation** while the line is pressurized.
- **Only after the line is secure** should you allow personnel to enter the area, determine if you have a leak, and what appropriate response is required.

Such an approach may seem extreme, but less aggressive action—such as waiting for the weekend or the next scheduled outage before you shut down—could result in a catastrophic and fatal failure. It has happened before. CCJ

HRSG User's announces annual meeting; Steam Plant Workshop next on group's agenda

The HRSG User's Group, a professional association that's open to *all* combined-cycle/cogen professionals, announces that its 14th Annual Conference & Expo will be held March 13-15, 2006, at the five-star Broadmoor Resort in Colorado Springs. To register and/or exhibit, contact Lillian O'Connor (718-317-6737, lillian@cmimeetings.com).

Reminder. The group's next event, Steam Plant Workshop, is scheduled for December 6-7 in Las Vegas. It will tackle issues affecting the entire, integrated steam cycle—not just the HRSG. The focus of the first day's program is cycle chemistry; the second day, improving steam-plant O&M. Program details are in the User Group Activities section elsewhere in this issue and at www.hrsgusers.org.

Note that the HRSG User's Group is an approved "certified education provider" by a state board of professional engineers. Workshop attendees receive two continuing education credits.

The Steam Plant Workshop will be co-located with Power-Gen International, enabling registrants to participate in the focused technical seminar while also taking in the world's largest power-generation exhibition.